Output Voltage Correction of an Induction Motor Drive Using a Disturbance Observer with Speed Sensor-less Vector Control Method

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Abstract-**This paper applies and evaluates a method for error voltage correction using a disturbance observer for an induction motor where will be controlled by speed-sensor-less vector method. The disturbance observer uses a fast-response observer, which responses ten times as fast as a current controller in sensor-less vector control. The voltage error is efficiently corrected by using the proposed method. The proposed method is validated on the basis of the experimental results. This method can reduce the current distortion to about 1/3 times smaller.**

I. Introduction

Recently, control method of an induction motor for variable speed driving has continuously been improved. *V/f*, vector and sensor-less vector-control method are popular control methods for induction motor driving. Especially, sensor-less vector control method is particular used for difficult application, which *V/f* control method cannot be applied, e.g. constant torque without speed sensor.

All voltage source type inverters require a dead-time to prevent a short circuit for switches and capacitors. However, the dead-time results output voltage errors and significant distortions on the current waveform, which caused torque ripples. When using the sensor-less vector-control method for induction motor driving, there are current regulators on the d and q axes to correct an error voltage. In low-speed region, the performance of the error voltage correction is degraded by the decreasing of the output command voltage that is as small as the error voltage. And in the middle-speed and high-speed range, fast-response current regulator is needed to suppress the distortion of the waveform of the current because frequency of the error voltage is raised with frequency of the output voltage. Therefore, the error voltage correction is an important issue to reduce torque ripples, especially for conveyers or elevators.

Many dead-time compensation methods using a disturbance observer have been previously proposed [1-10]. The most common method detects the direction of motor current and decides the correction voltage according to direction of the current, then adds the correction voltage to the command voltage. If delay of the polarity detection or mismatching of the correction voltage was occurred in the correction process, the happen of torque ripple and distortion of the current waveform are because of the remained error voltage. Especially, to detect the polarity is very difficult in low-speed region because transition of the polarity is slowed down. Therefore, the correction method using polarity detection has a limitation. On the other hand, error correction method by using disturbance observer for estimation of disturbance voltage is proposed for vector-controlled systems[1, 9]. The disturbance-observer based method is a useful method because the method corrects the saturation voltage drop of switching devices and also the dead-time error voltage.

Methods of dead-time error voltage correction using disturbance observers have ever been proposed were using observers for only estimation of averaged error correction voltage, then the estimated voltage is added to the command voltage according to the direction of the current[1]. This method is still based on the polarity detection and difficult to solve the problem in low-speed region. On the other hand, direct estimation method of error voltage using disturbance observer was proposed in PMSM drive[9]. However, there are no further discussions about the error voltage correction of disturbance observer by using no polarity detection on sensor-less vector control for induction motor.

This paper applies and evaluates the error voltage correction method by using disturbance observer without the polarity detection. The advantage of this method is easy to determine unique control system by the motor model. And, this method can be used to decrease the current distortion to 1/3 times lesser. At the result, advantages of using no polarity detection method were obtained, and compared to the method depend on polarity detection.

II. Principles of the Disturbance Observer for a Dead-time Error Voltage Correction

A. Problems of dead-time and conventional compensation

Fig. 1 shows the behavior of the voltage error during the dead-time period. Switch off time, it is so called dead-time, is added to gate pulses of u_p and u_n in order to avoid the short circuit between an upper arm and a lower arm. To obtain dead-time period, the turned-on timing of the gate pulse u_p and u_n are delayed during T_d as shown in Fig. 1(b).

The voltage error during the dead-time depends on the direction of a flowing current. When the output current direction of the leg is positive which is defined from the leg to load, the current in the leg flows through the free wheeling diode (FWD) of the lower arm during the dead-time period. Thus, the output voltage is decreased by the dead-time period. On the other hands, when the output current direction is negative, the current in the leg flows through the FWD of the upper arm. Thus, the output voltage increased. The value of the voltage error depends on the dead-time period and dc-link voltage as shown in Fig. 1. Finally, the voltage error is calculated by (1).

$$\Delta V = -f_s V_{dc} T_d \cdot \mathrm{sign}(i_u) \tag{1}$$

where, f_s: switching frequency, V_{dc}: dc-link voltage, T_d: dead-time period, i_u: output current of the leg, sign(x):sign function. If $x>0$ then sign(x) =1, if $x<0$ then sign(x) =−1, if $x=0$ then sign(x) =0.

It should be noted that the magnitude of the voltage error does not depends on the amplitude of the output voltage and the output current. Therefore, when the output voltage is small such as a low speed operation, the affect of the dead-time is strongly appeared because the ratio of the voltage error to the output voltage becomes larger.

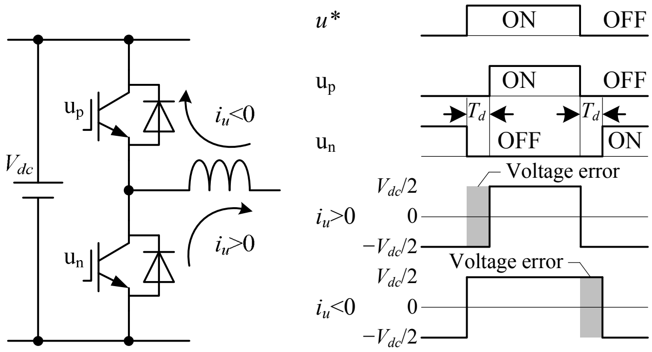
Figure 2 is a control block diagram of an error voltage correction according to the current direction. The error correction voltage is calculated from $K_{FF} i_u$ limited to -1 and 1, where K_{FF} compensates the gain to keep linearity at zero-crossing point for hunting prevention.

B. Dead-time correction method using disturbance observers

This paper proposes a dead-time compensation method with a disturbance observer. The voltage error of the dead-time is estimated by the output current and the motor parameters shown in Fig. 3, which is the equivalent circuit of an induction motor on d-q rotating frame, converted a secondary leakage inductance into a primary side. The estimation using the formula of relation between the motor voltage v_1 and current i_1 is obtained by (2).

$$\begin{bmatrix} v_{1d} \\ v_{1q} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + pL_\sigma & -\omega_1 L_\sigma & p & -\omega_1 \\ \omega_1 L_\sigma & R_1 + pL_\sigma & \omega_1 & p \\ -R_2 & 0 & \frac{R_2}{L_m} + p & -\omega_1 + \omega_m \\ 0 & -R_2 & \omega_1 - \omega_m & \frac{R_2}{L_m} + p \end{bmatrix} \begin{bmatrix} i_{1d} \\ i_{1q} \\ \phi_{2d} \\ \phi_{2q} \end{bmatrix} \tag{2}$$

where,
R_1 is the primary resistance,
R_2 is the secondary resistance,
p is differential operator $p = d/dt$,
L_m is the magnetizing inductance,
L_σ is the equivalent leakage inductance,
ω_1 is the primary angular frequency,
ω_m is the secondary angular frequency,
i_{1d} is d-axis components of the primary current,
i_{1q} is q-axis components of the primary current,
v_{1d} is d-axis components of the primary voltage,
v_{1q} is q-axis components of the primary voltage,
ϕ_{2d} is d-axis components of secondary flux,
and ϕ_{2q} is q-axis components of secondary flux.



(a) An inverter leg
(b) Relationship between reference pulse and voltage error

Figure 1. Relations between reference pulse and voltage error.

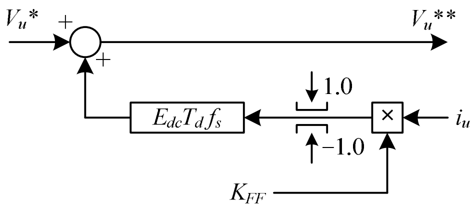


Figure 2. Conventional error voltage correction method according to the direction of motor current.

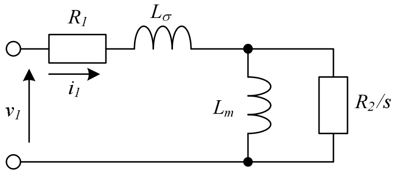


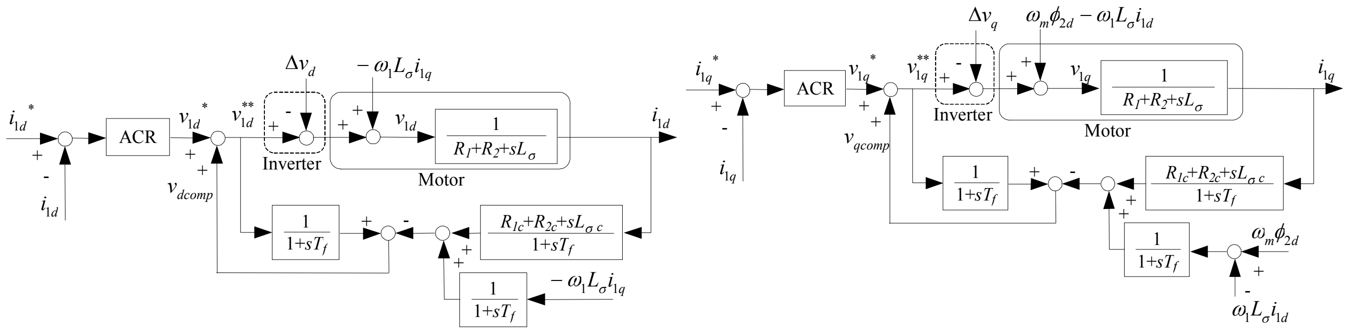
Figure 3. Equivalent circuit of induction motor.

Figure 4 shows a block diagram for vector control method using the proposed error voltage collection method. The disturbance observers calculate difference between command voltage and actual output voltage of the inverter and estimate the amount of disturbance voltage. The estimated disturbance voltage is added to the voltage command as disturbance correction voltage V_{comp} which is calculated using (3).

$$\begin{aligned} v_{dcomp} &= \frac{1}{1+sT_f}\left\{v_{1d}^{**} - \left(\left(R_{1c} + R_{2c} + pL_{\sigma c}\right)i_{1d} - \omega_1 L_{\sigma c} i_{1q}\right)\right\} \\ v_{qcomp} &= \frac{1}{1+sT_f}\left\{v_{1q}^{**} - \left(\left(R_{1c} + R_{2c} + pL_{\sigma c}\right)i_{1q} - \omega_1 L_{\sigma c} i_{1d} + \omega_m \phi_{2d}\right)\right\} \end{aligned} \tag{3}$$

where, the suffix $_C$ means controller parameter.

In the equation (3), the 1st trm of the right side is the command value adjusted by V_{comp}. The 2nd term is the back EMF of the *RL* based on the inverse system of the motor. The 3rd term is the cross term between d- and q- axis. The 4th term is the speed electromotive force. If the command voltage was collected by 2nd term only, the 3rd and 4th term will be estimated as



(a) d-axis (b) q-axis

Figure 4. An error voltage correction method using a disturbance observer.

disturbances. So the system is instable because correction voltage is exceeded in actual disturbance voltage Δv shown in figure 4. These terms should be calculated, measured or estimated.

Additionally, it is desirable that the disturbance observers responses faster than the current regulator. If the disturbance voltage was corrected by the disturbance observer, output of the current regulator is considered to be an actual output voltage of inverter. Then the output-voltage- and speed-sensor-less vector control will be achieved. So, this method is able to use in *V/f* or vector control method. In latter section, results and notes of these control method are shown.

C. Using disturbance observers for V/f control method

This subsection describes the way to use the correction method to *V/f* control method. It is difficult to separate primary current into field and torque components because *V/f* control method does not estimate secondary-side flux. Instead of flux estimation, a current controller was used to determine the flux component of the motor current. On the other hand, *V/f* control and the correction method were used in orthogonal axis. It should be noted that the axis using current controller and disturbance observer is called d- and q- axis, respectively.

Fig. 5 shows a block diagram for the proposed compensation method using *V/f* control. The feedback filter using the T_f (fast response disturbance observer) estimates the back EMF in addition to the disturbance voltage. To estimate only the voltage error from dead-time in the middle- or high-speed range, the feedback filter of the T_s (slow response disturbance observer) is used to cancel the back EMF. On the other hand, the ACR on the d-axis corrects the dead-time voltage error on d-axis and maintains the rated excitation current of the motor.

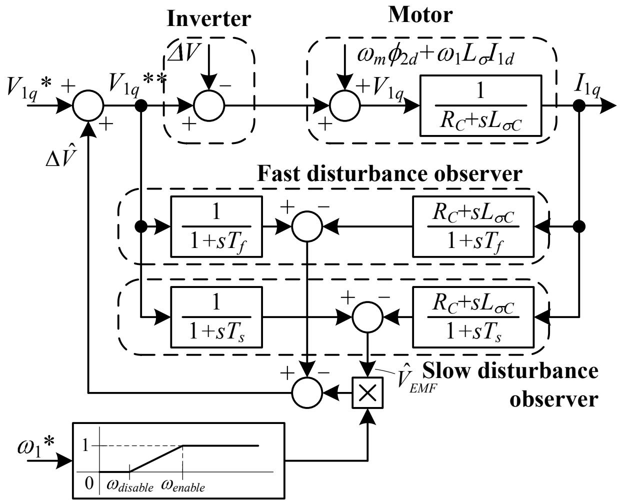


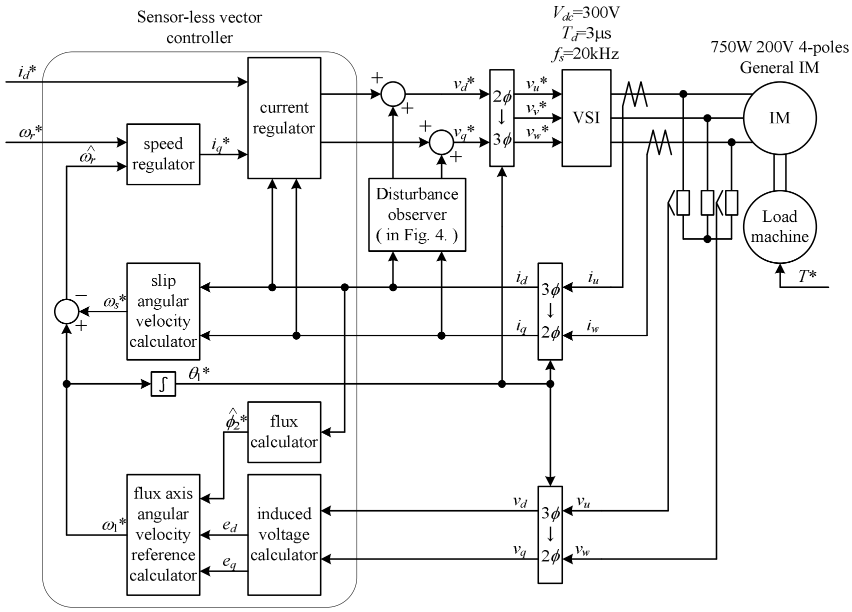
Figure 5. Block diagram of error voltage correction system for *V/f* control.

III. EXPERIMENTAL RESULT

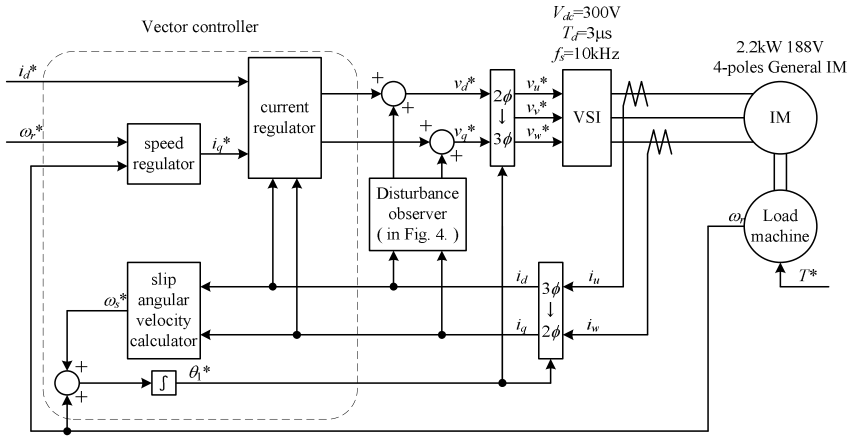
A. Error voltage correction for sensor-less vector control

Fig. 6(a) shows a block diagram of an experimental system. The experimental system is composed of a general induction motor and an inverter. The motor is controlled using speed-sensor-less vector control to keep at constant speed. The sensor-less vector control shown in figure 6(a) is based on reference (10). This method obtains zero-volt for d-axis induced voltage.

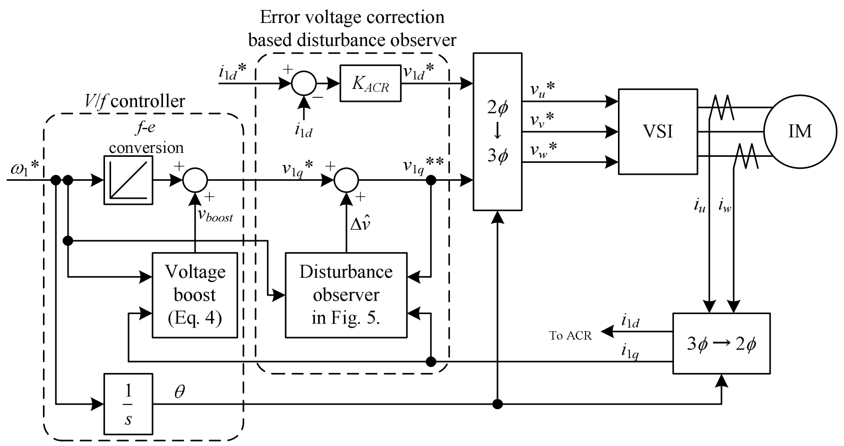
Fig. 7 shows the waveforms of motor speed, d-axis, q-axis and u-phase current under conditions where the motor speed is 300r/min with the rated load torque (1.0pu). It should be noted that result shown in figure 7(a) is not using error voltage corrections and 7(b) is using the disturbance observer based on the error voltage correction method, respectively. In Fig. 7(a), the current distortion occurs on the zero crossing point of the u-phase current because the error voltage is changing significantly at this point. In contrast, the distortion is almost corrected in Fig. 7(b) by the fast response disturbance observer. And the total harmonic distortion (THD) of the current shown in Fig.7(b) is 1.20%, with a 1/3 reduction from the result as shown in Fig. 7(a).



(a) sensor-less vector control type

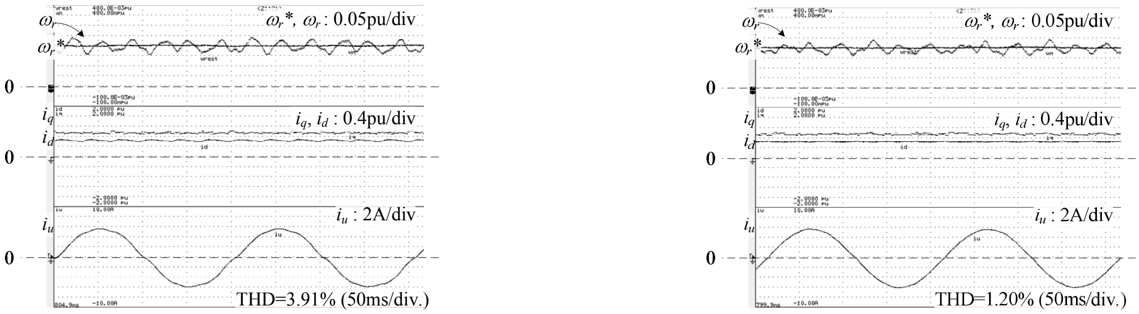


(b) vector control type



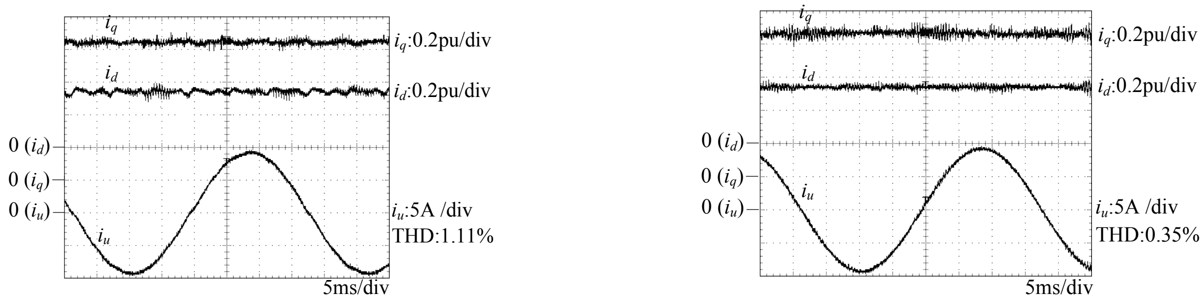
(c) V/f control type

Figure 6. Evaluation systems of correction performance.



(a)No correction method (b)Correction method based on disturbance observer

Figure 7. A Comparison of Correction performance for a disturbance observer on sensor-less vector control method.



(a)No correction method (b)Correction method based on disturbance observer

Figure 8. A Comparison of Correction performance for a disturbance observer on vector control method.

(a)No correction method (b)Correction method based on disturbance observer

Figure 9. A Comparison of Correction performance for a disturbance observer on V/f control method.

Table 1. summary of current THD on each control method

Control method	A: No correction	B: Correction method based on disturbance observer	B compared with A
Sensor-less vector	3.91%	1.20%	≤1/3
Vector	1.11%	0.35%	≤1/3
V/f	8.91%	0.98%	≤1/9

B. *Error voltage correction for vector control*

Fig. 6(b) shows a block diagram of an experimental system. The 2.2kW motor is controlled using the vector control to keep at constant speed.

Fig. 8 shows the waveforms of d-axis, q-axis and u-phase current under conditions where the motor speed is 750r/min with rated load torque (1.0pu). The current distortion on the zero-crossing point of the u-phase current is also suppressed when using the error voltage correction method based on the disturbance observer. And the total harmonic distortion (THD) of the current shown in Fig.8(b) is 0.35%, with a 1/3 reduction from the result as shown in Fig. 8(a).

C. *Error voltage correction for v/f control*

Fig. 6(c) shows a block diagram of an experimental system. The 750W motor is controlled using *V/f* control to keep at constant primary frequency. In Fig. 6(c), the boost voltage is calculated as

$$v_{boost} = R_1 i_{1q}\left(1 - \frac{\omega_1^*}{\omega_n}\right) \quad \text{..(4).}$$

Fig. 9 shows the waveforms of d-axis, q-axis and u-phase current under conditions where the primary side angular frequency is 1Hz with no load torque. The current distortion on the zero-crossing point of the u-phase current is also suppressed when using the error voltage correction method based on the disturbance observer. And the total harmonic distortion (THD) of the current shown in Fig. 9(b) is 0.98%, with a 1/9 reduction from the result as shown in Fig. 9(a).

D. *Comparisons of each result*

In former sections, the correction method using disturbance observer was applied into sensor-less vector, vector and *V/f* control method. The stability of the correction method is discussed in the following sentences.

First, the combination of such system and disturbance observer will be a stable system. The vector control method calculates accurately d- and q- axis of motor from current and speed of a motor, then the stability of the correction method will be obtained.

Second, we discuss about the sensor-less vector control method. When a sensor-less control is worked properly, the axis of motor and controller will be same. Then the correction method will also work properly. It should be noted that the voltage sensor using the sensor-less control only has minimum speed of response to estimate the motor speed, which means insufficient to correct error voltage.

Last, a V/f control will not equate the axis of motor and controller. So the current regulator on d-axis retains excitation current to obtain the stability of correction. And it is difficult to calculate important terms to prevent over correction, which are the speed-EMF and cross term. Instead of calculation, the important terms are estimated by the disturbance observers which have the fast and slow response.

Table 1 shows a summary of current THD on each control method. The correction method using disturbance observer reduces the distortion of current on any control methods. Especially, THD reduction on *V/f* control was marked because original *V/f* control method has no current controllers. So, the THD on original *V/f* control is higher than others. As the result, THD reduction is achieved evenly on vector and sensor-less vector control. Therefore the voltage error correction method is effective on any control method.

IV. CONCLUSIONS

A disturbance observer, used for dead-time error voltage correction, was applied to sensor-less vector controlled in an induction motor. Then the THD of the motor current was evaluated. At the result, this method is able to decrease the current distortion to 1/3 times smaller than the original method.

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