

A Performance Improvement of V/f Control using a Disturbance Observer

Jun-ichi Itoh*, Tetsuma Hoshino*, Takayuki Kaneko**

*Nagaoka University of Technology, Nagaoka, Japan

**Fuji Electric Advanced Technology Co., Ltd, Tokyo Japan

Abstract— This paper proposes a dead-time compensation method with a disturbance observer and a current controller for V/f control. Dead-time compensation is very important to improve motor drive performances in the low speed region. The proposed compensation method is composed in the d-q rotational frame. The ripple of the d-axis current caused by the dead-time is suppressed by an auto current regulator, the ripple of the q-axis current according to the dead-time is suppressed by the disturbance observer. The control of the d-axis current is added the auto current regulator to the V/f control. As a result, the magnitude of the motor current can keep more than the rated exciting current in spite of the low speed region with the V/f control. The control of the q-axis current only uses the disturbance observer to suppress the voltage error of the dead-time. In this paper, the performance of the proposed controller in the low speed region is discussed based on the experimental results. The proposed method can improve the current distortion to less than quarter against the conventional method. Although the disturbance observer requires motor parameters, it is not so sensitive.

I. INTRODUCTIONS

In order to realize energy saving in recent years, general-purpose inverters are widely used in industry applications. Particularly, an induction motor controlled by the inverter is widely applied to adjustable speed drive. V/f control method of the induction motor is more suitable to general applications than a speed sensor-less vector control system because the V/f controller is very simple, and robust for parameters variation of the motor. In other words, the speed sensor-less vector control system needs the many control parameters agreeing with the motor parameters to obtain high performance.

A voltage source type inverter has to make dead-time between upper arm and lower arm to avoid a short circuit of dc voltage. The dead-time occurs output voltage error because the output voltage during the dead-time period depends on the direction of a load current. The voltage error of the dead-time is constant regardless of the magnitude of the output voltage. As a result, the voltage error caused by dead-time period affects in low voltage output area such as low speed. Thus, in case of the V/f control, it is very difficult to smoothly work in low speed region due to no current controller. Therefore the dead-time compensation techniques are very important to realize a low cost motor drive system.

The voltage error compensation method is feed forward compensation for the output voltage command according to the sign of the load current and the magnitude of the voltage error[1]-[8]. This is very simple and the most

popular compensation method. However, this method can not compensate in low speed region because it is difficult to detect the load current sign. As a result, the dead-time error is generated current stagnation around zero-crossing point. In open loop control such as especially the V/f control, the speed and torque ripple in low-speed region becomes very large. In addition, if a pulse modulation method is changed, for example, from a three-phase modulation method to a two-phase modulation method, then the compensation values has to change depending on the modulation method.

On the other hands, on-line dead-time compensation methods are proposed in [9]-[10]. The voltage error is estimated by a disturbance observer using motor parameters. In those papers, the disturbance observer is composed for the sensor-less vector control system of a permanent magnet motor in a rotational frame or a three-phase frame. However, the V/f control of the induction motor is not considered.

This paper proposes the dead-time compensation method with the disturbance observer and the current controller for the V/f control. The proposed method is composed in the d-q rotational frame. The ripple of the d-axis current caused by the dead-time is suppressed by an auto current regulator, the ripple of the q-axis current according to the dead-time is suppressed by the disturbance observer. The control of the d-axis current is added the auto current regulator to the V/f control. As a result, the magnitude of the motor current can keep more than the rated exciting current in spite of the low-speed region operation of the V/f control. The control of the q-axis current only uses the disturbance observer to suppress the voltage error of the dead-time. Although the disturbance observer requires the motor parameters, it is not so sensitive. In this paper, the performance in the low speed region is discussed based on the experimental results. The proposed method can improve the current distortion to less than quarter against the conventional method.

II. PROBLEMS OF DEAD-TIME AND CONVENTIONAL COMPENSATION METHOD

Figure 1 shows behavior of the voltage error during the dead-time. The 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 of u_p and u_n are adjusted during T_d as shown in Figure 1(b).

The voltage error during the dead-time depends on direction of flowing current. When the output current of the leg is flowing to positive, the current in the leg flows through the FWD of the lower arm during the switch off.

Thus, the output voltage is decreased by the dead-time period. On the other hands, when the output current is flowing to negative, the current in the leg flows through the FWD of the upper arm. Thus, the output voltage increases. The value of the voltage error depends on the dead-time period and dc-link voltage. Finally, the voltage error is decided by Equation (1).

$$\Delta V = f_s V_{dc} T_d \cdot \text{sign}(i_u) \quad (1)$$

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

It is noted that the magnitude of the voltage error does not depends on the amplitude of the output voltage and load 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 large.

Figure 2 shows the conventional compensation method of the dead-time voltage error. The compensated voltage command $v_u^{**}, v_v^{**}, v_w^{**}$ are obtained by adding the voltage error calculated by Equation (1) to the basic voltage command v_u^*, v_v^*, v_w^* . Since this method needs only detect current direction, it is very simple. However, if all legs are not the same modulation e.g. the two-phase modulation, then the compensation value has to distinguish the switching leg and the stop leg.

Figure 3 shows the stagnation of the load current in the low speed operation of the motor in case of the conventional compensation method. The positive load current is decreased by the dead-time voltage error, and the negative load current is increased by the dead-time error. As a result, the stagnation of the load current is generated around the zero-crossing point of the load current. Since the direction of the load current is not clearly, it is very difficult to compensate the dead-time voltage error around the current zero-crossing point.

III. PRINCIPLE OF PROPOSED COMPENSATION METHOD

Figure 4 shows an equivalent circuit of the induction motor on d-q rotating frame. This paper proposes a dead-time compensation method with a disturbance observer. The voltage error of the dead-time is estimated by the load current and the motor parameter. The relation between the motor voltage v_1 and current i_1 is obtained by Equation (2).

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

where, R_1 : primary resistance, R_2 : secondary resistance, $p = d/dt$, L_m : magnetizing inductance, L_σ : equivalent leakage inductance, ω_1 : primary angular frequency, ω_m : rotor angular frequency.

From Equation (2), when d-axis corresponds to vector of the secondary flux ϕ_2 , the q-axis component ϕ_{2q} is equal

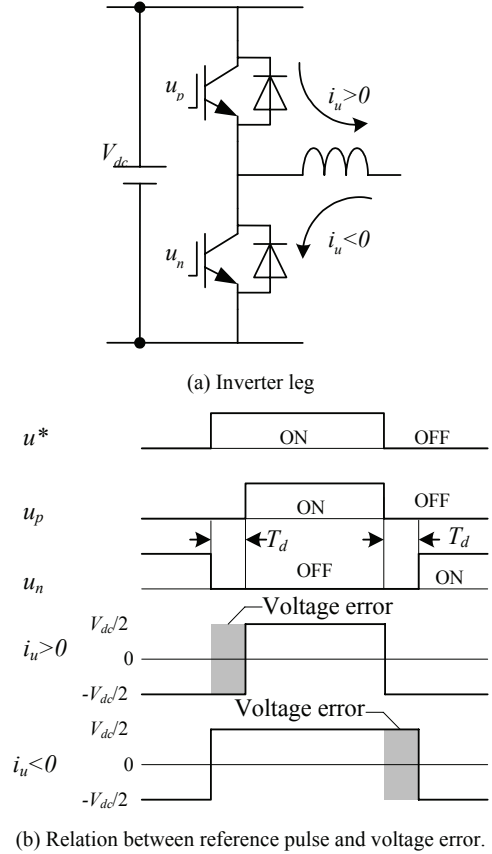


Fig. 1. Output voltage error by dead-time

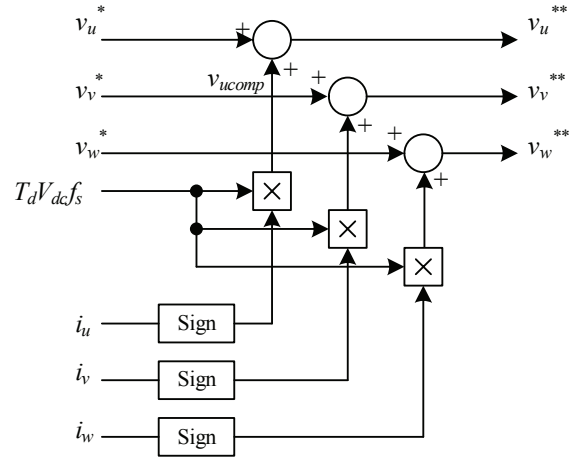


Fig. 2. Conventional compensation method of dead-time voltage error.

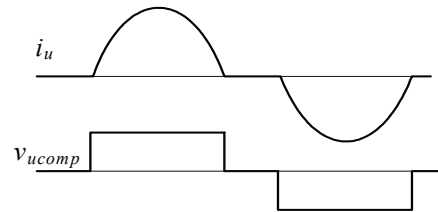


Fig. 3. Current waveform and compensation voltage in case of very low speed region.

to zero and the q-axis voltage v_{1q} is calculated as

$$v_{1q} = (R_1 + R_2 + pL_\sigma)i_{1q} - \omega_1 L_\sigma i_{1d} + \omega_m \phi_{2d} \quad (3).$$

The transient response of the load current for the output voltage is constrained by time constant $T_e = L_\sigma / (R_1 + R_2)$.

Figure 5 shows the configuration of the disturbance observer based on Equation (3). It is very simple idea to use the inverse system to calculate the terminal voltage of the motor as shown in Figure 5(a). However, the inverse system includes the pure differential calculation. It is difficult to calculate the pure differential calculation without the error due to the noise in an actual system. Thus, the terminal voltage of the motor in the proposed method is calculated as Figure 5(b). In case of the low speed operation, ω_1 and ω_m becomes the small to other terms. Thus, those terms can be neglected. Finally, The voltage error is estimated by Equation (4).

$$\Delta \hat{V} = \frac{k}{1+sT} (R_{1c} + R_{2c} + sL_{\sigma c}) I_{1q} \quad (4)$$

where, suffix c : controller parameter, T : time constant of the observer, k : observer gain, s : Laplace parameter.

The transfer functions to the output voltage V_q from the voltage error ΔV or from the command voltage V_q^* are obtained as

$$G_1(s) = \frac{V_q(s)}{\Delta V(s)} = \frac{L_\sigma T s^2 + ((1-k)L_\sigma + RT)s + (1-k)R}{R+k(R_c - R)} \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (5)$$

$$G_2(s) = \frac{V_q(s)}{V_q^*(s)} = \frac{L_\sigma T s^2 + (L_\sigma + RT)s + R}{R+k(R_c - R)} \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (6)$$

where $R = R_1 + R_2$, $R_c = R_{1c} + R_{2c}$, the damping factor ζ and the natural angular frequency ω_n of Equations (5) and (6) are obtained as Equation (7) and (8).

$$\omega_n = \sqrt{\frac{R+k(R_c - R)}{L_\sigma T}} \quad (7)$$

$$\zeta = \frac{1}{2} \frac{L_\sigma + k(L_{\sigma c} - L_\sigma) + RT}{\sqrt{L_\sigma T \{R+k(R_c - R)\}}} \quad (8)$$

From Equation (5) and (6), the steady state value of output voltage V_q for the step input of the voltage error ΔV or the output voltage command V_q^* becomes Equation (9) and (10).

$$G_1(s \rightarrow 0) = (1-k) \frac{R}{R+k(R_c - R)} \quad (9)$$

$$G_2(s \rightarrow 0) = \frac{R}{R+k(R_c - R)} \quad (10)$$

From Equation (7) and (8), except controller gain $k=0$, the mismatch of controller parameters affects the damping factor and the natural angular frequency.

The proposed method is robust to change of motor parameters R_c and $L_{\sigma c}$ as shown in Equation (9). The voltage error rejection needs only set to observer gain $k=1$. On the other hands, Equation (10) represents that the output voltage is equal to the command voltage under $R_c=R$. It also shows that $k=1$ cannot cancel the affect from mismatch of motor parameter R_c to controller DC gain.

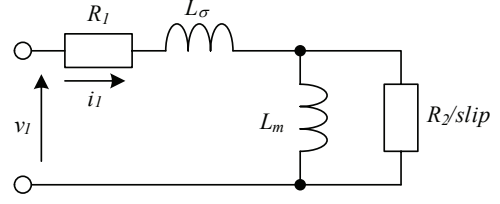
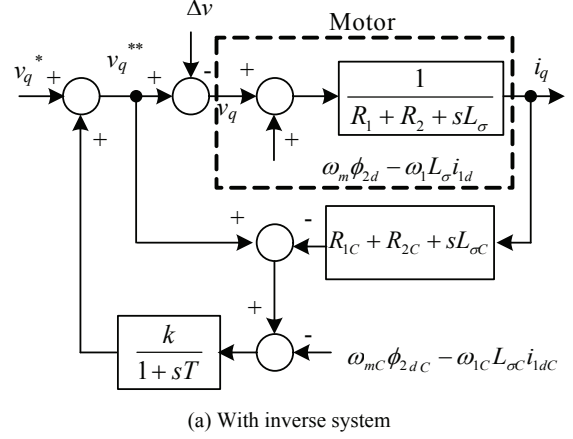
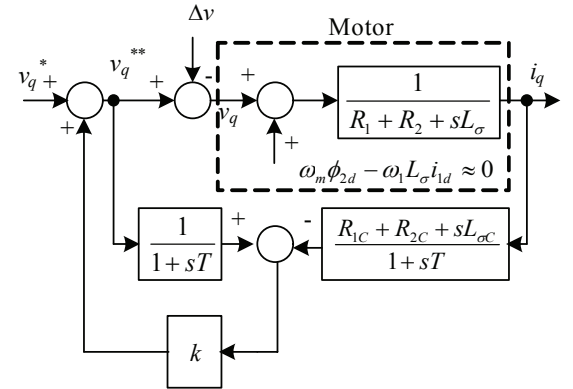


Fig. 4. Equivalent circuit of induction motor.



(a) With inverse system



(b) Without pure differential calculation

Fig. 5. Configuration of disturbance observer.

Figure 6 shows a bode diagrams of Equation (5) and (6). A solid line shows under ideal condition that $k=1$, $R_c=R$ and $L_{\sigma c}=L_\sigma$. And dashed lines show under various conditions that either R_c or $L_{\sigma c}$ equals to R or L_σ multiplied or divided by 10. The other parameters in use to calculate bode diagrams are shown in Table. 1.

From Figure 6, parameter mismatch of $L_{\sigma c}$ does not affect the gain of the controller in high- or low-frequency region. However, the parameter mismatch of R affects the gain of the controller as inversely proportional to R_c/R at low-frequency region. Therefore R_c must be decided with consideration for error of R .

If parameters have an ideal condition, i.e. $k=1$, $R_c=R$ and $L_{\sigma c}=L_\sigma$, then the transfer function of Equation (11) is obtained by Equation (5).

$$\frac{V_q}{\Delta V} = \frac{sT}{sT+1} \quad (11)$$

Thus, the time constant of the observer is set out according to frequency of the voltage error due to dead-time. Since the voltage error on q-axis has 6 times frequency of the output frequency. And the voltage error has been neglected after 3 times time constant, the time constant of the disturbance observer is obtained by Equation (12).

$$T < \frac{1}{18f} \quad (12)$$

Figure 7 shows the control block diagrams in the proposed V/f controller. The d-axis current is controlled by auto current regulator e.g. PI controller. The d-axis current command can be decided since the rated exciting current is known from the motor parameters. The current control boosts the output voltage at a low speed, and keeps the exciting current for the induction motor.

The proposed controller in Figure 7 is very simple controller compared with sensor-less vector control system. It is noted that the proposed dead-time compensation method can be used together with the conventional method as shown in Figure 2. Since the disturbance observer also cancels electromotive force in the middle and high-speed region, the proposed method gradually adjusts the disturbance observer gain k to small according to the increase of the motor speed.

IV. EXPERIMENTAL RESULTS

Figure 8 shows the experimental results of the conventional compensation method as shown in Figure 2. The tested motor and inverter as shown in Table 1 are used in the experiment. The time division is 200ms/div., the current division of i_u is 2A/div. and i_d or i_q is 0.2pu/div. The output frequency is 1Hz (2% to rated frequency), at no load. Then, T.H.D. is 14.4%, and the current magnitude is 0.51A in the conventional compensation method. Though the voltage command is compensated the voltage error of the dead-time by following Equation (1) makes the exciting current greatly reduced. Particularly, the q-axis current is decreasing. There are two reasons in these results. First, the actual dead-time is not only T_d due to including the delay of a switching device and a gate drive circuit. Second, it is difficult to detect the direction of the load current at the low speed region.

Figure 9 shows the experimental results of the proposed compensation method. The time division is 200ms/div., the current division of i_u is 2A/div. and i_d or i_q is 0.2pu/div. The experimental condition is the same as Figure 8. Then, T.H.D. of 1.7% and the fundamental current magnitude of 2.87A are obtained by the proposed method, respectively. The d-axis current is kept the constant at the rated exciting current by the PI controller. The ripple of the q-axis current is suppressed by the proposed disturbance observer. T.H.D. is improved less than a quarter, and the rated exciting current is almost obtained.

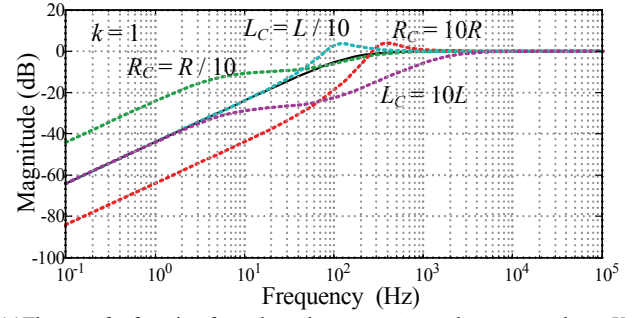
Figure 10 shows the comparisons under variations of controller parameters; k , R_c , $L_{\sigma c}$, and T_i in order to discuss influence of parameter mismatches through the experimental result.

References:

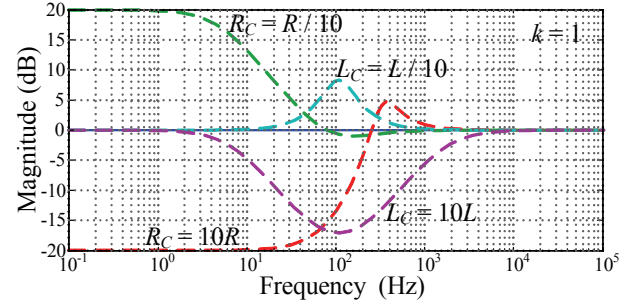
Conventional method: Figure 10 (a)

Proposed method: Figure 10 (b)

These waveforms are same to Figure 8(a) and Figure



(a) The transfer function from the voltage error Δv to the output voltage V_q



(b) The transfer functions from the command voltage V_q^* to the output voltage V_a

Fig. 6. Bode diagrams of proposed controller.

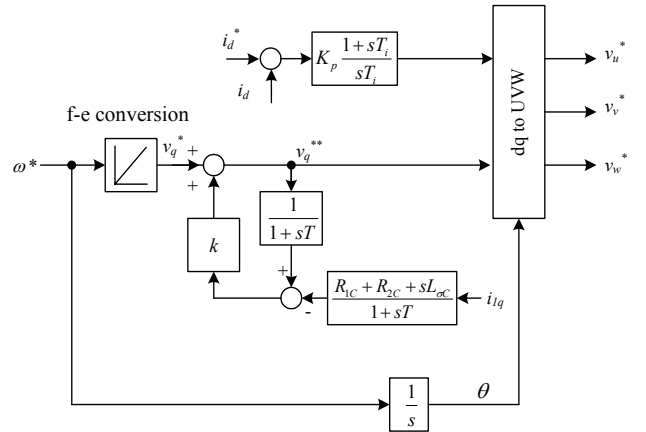


Fig. 7. Control block diagrams of the V/f control with the proposed dead-time compensation method.

Table 1 Calculation and experimental conditions

Items(motor)	Values	Items(motor)	Values
Rated power	750W	Poles	4
Rated Voltage	200V	Rated Frequency	50Hz
Rated Current	3.6A	Rated speed	1420 r/min
Rated exciting current	2.0A	Primary resistance	2.78Ω
Leakage inductance	11.0mH	Secondary resistance	2.44Ω

Items(controller)	Values	Items(controller)	Values
Dc voltage	280V	Observer Gain	1
Dead-time	3.0μs	Time constant of LPF	1ms
Switching frequency	20kHz	d-axis ACR	used

9(a). The following discussion is based on waveforms Figure 10(a) and (b).

Changing Time constant T:

T multiplied by 10: Figure 10 (c)

From Equation (11), cut-off frequency is pulled to low frequency by time constant. Thus, a high frequency component such as the ripple of q-axis current is increased.

No A.C.R. on d-axis: Figure 10 (d):

The disturbance observer on q-axis obtains q-axis current. However, d-axis current includes the ripple because of d-axis current controller lost.

Changing observer gain k:

k is set to 0.5: Figure 10 (e)

k is set to 1.5: Figure 10 (f)

From Equation (9), the DC gain of the dead-time error correction has been changed, Figure 10(e) is reduced or Figure 10(f) is exceeded. Thus, the voltage error due to the dead-time affects to output voltage.

Changing controller parameter R_C :

R_C is set to $2/3R$: Figure 10 (g)

R_C is set to $1.5R$: Figure 10 (h)

$k=1$ rejects the voltage error of the dead-time. But, from Equation (10), parameter mismatch of motor resistance changes DC gain of controller. Then, the DC component of q-axis output current is increased in Figure 10(g) or decreased in Figure 10(h).

Changing controller parameter $L_{\sigma C}$:

$L_{\sigma C}$ is set to $1/2L_{\sigma}$: Figure 10 (i)

$L_{\sigma C}$ is set to $2L_{\sigma}$: Figure 10 (j)

From Equation (9) and (10), DC gains are robust to a change of the inductance of the motor. Thus, Figure 10(i) and Figure 10(j) are similar result to Figure 10(b).

As a result, too small parameter R_C causes increasing of current amplitude. So, be careful to set R_C . And observer time constant T gives a good result in shorter value. The other parameter $L_{\sigma C}$ is not critical to disturbance rejection characteristics. These experimental results are according to analytical results. It says a validity of the analysis.

V. CONCLUSIONS

In this paper, several new approaches to improve the performance based on V/f control have been proposed and tested, with the disturbance observer, d-axis current regulator. Summary of the outcomes indicated in this paper is as follows:

- The conventional dead-time compensation is not effective in the low speed region.
- The disturbance observer can cancel the voltage error of the inverter dead-time.
- The d-axis current regulator is very effective based on the V/f control.
- T.H.D. is improved less than a quarter against the conventional compensation method, and the rated exciting current is almost obtained by the proposed dead-time compensation.

The V/f control is very important in the general-purpose inverter. It is noted that the dead-time compensation is also

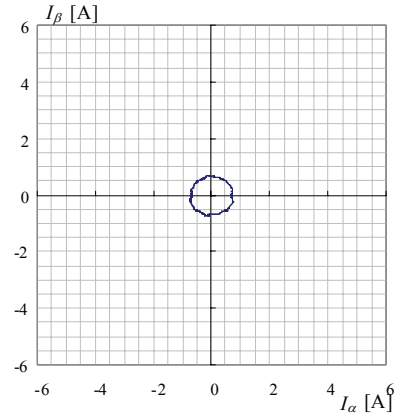
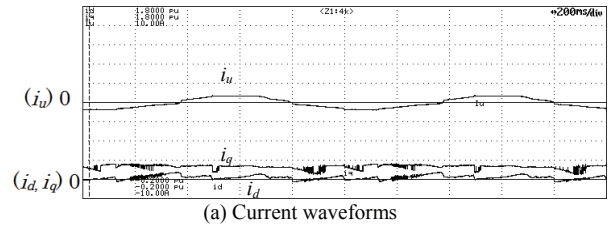


Fig.8 Conventional compensation method. (Output frequency 1Hz, no load, 750W induction motor)

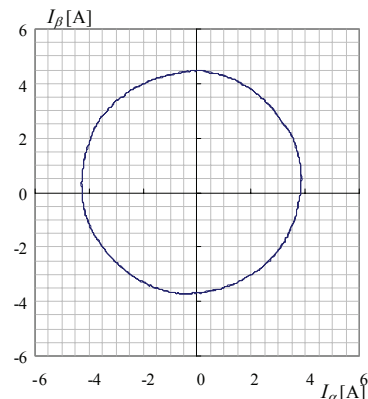
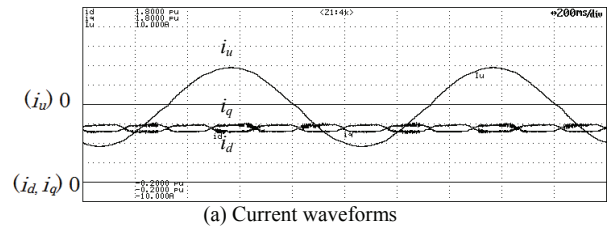
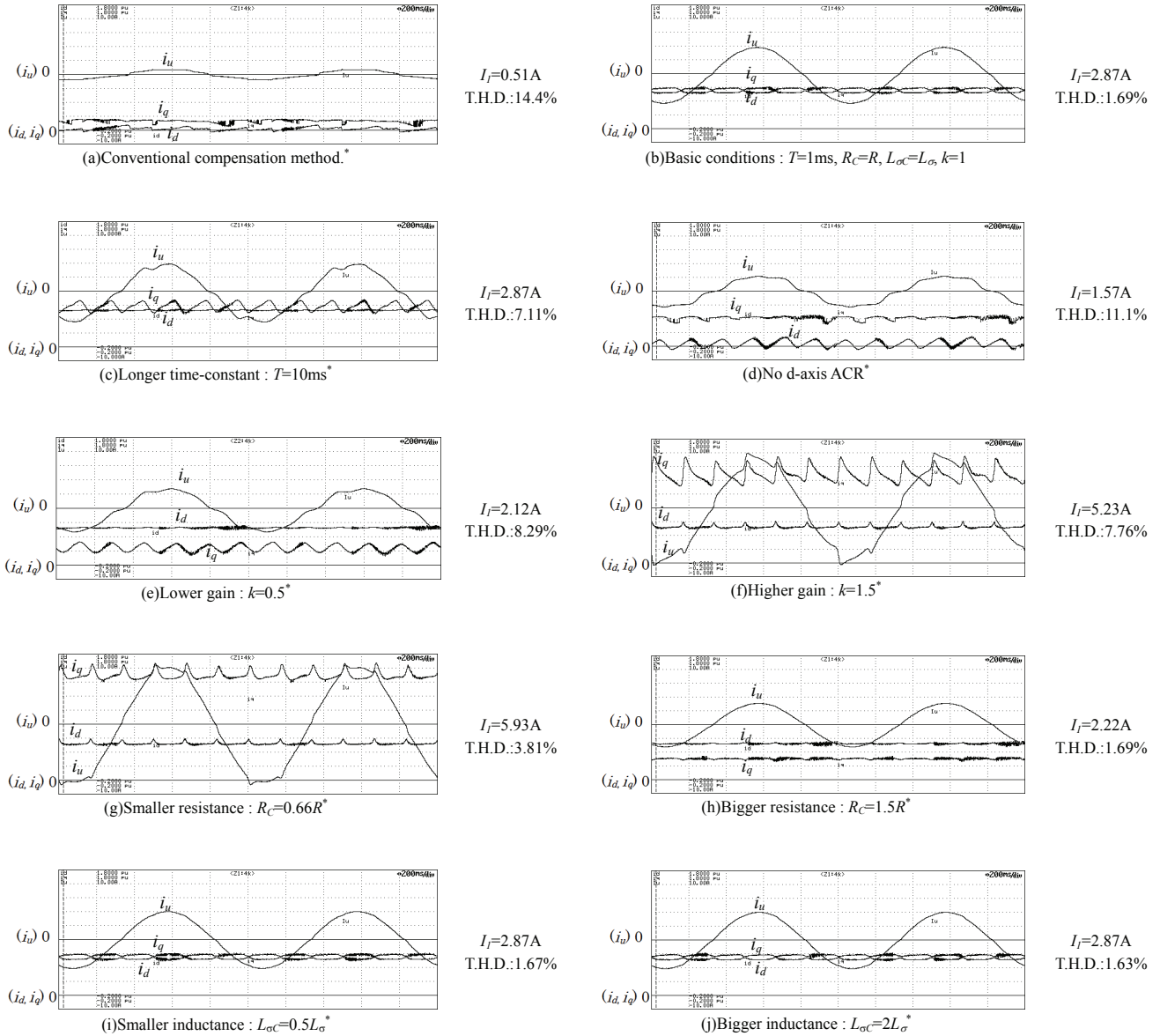


Fig.9 Proposed compensation method. (Output frequency 1Hz, no load, 750W induction motor)

important in the sensor-less vector control due to use the voltage command for the speed estimation. The disturbance observer is not complicated, and does not require the high accuracy for the motor parameter. The proposed system is suitable for the general-purpose inverter.



*Where (a) and (c) to (j), no parameter information means that parameters are same to (a).

All waveforms have a same time division 200ms/div, i_u has a current division 2A/div and i_d, i_q has a current division 0.2pu/div.

Fig. 10. Comparison variations of parameter mismatch from the ideal condition.

REFERENCES

- [1] T. Sukegawa, K. Kamiyama, K. Mizuno, T. Matsui, and T. Okuyama, "Fully digital vector-controlled PWM VSI fed ac drives with an inverter dead-time compensation strategy," *IEEE Transaction on Industry. Application.*, vol. 27, no. 3, pp. 552–559, May/June. 1991.
- [2] S.-G. Jeong and M.-H. Park, "The analysis and compensation of deadtime effects in PWM inverters," *IEEE Transaction on Industry. Electronics.*, vol. 38, no. 2, pp. 108–114, Apr. 1991.
- [3] J.-W. Choi and S.-K. Sul, "Inverter output voltage synthesis using novel dead time compensation," *IEEE Transaction on Power Electronics*, vol. 11, no. 2, pp. 221–227, Mar. 1996.
- [4] A. Muñoz-Garcia and T. A. Lipo, "On-line dead-time compensation technique for open-loop PWM-VSI drive," *IEEE Transaction on Power Electronics*, vol. 14, no. 4, pp. 683–689, Jul. 1999.
- [5] A. Muñoz-Garcia, T. A. Lipo, and D. W. Novotny, "A new induction motor V/f control method capable of high performance regulation at low speeds," *IEEE Trans. Ind. Applicat.*, vol. 34, pp. 813–821, July/Aug. 1998.
- [6] H. Zhao, Q. M. J. Wu, and A. Kawamura, "An accurate approach of nonlinearity compensation for VSI inverter output voltage," *IEEE Transaction on Power Electronics.*, vol. 19, no. 4, pp. 1029–1035, Jul. 2004.
- [7] A. Cichowski, J. Nieznanski, "Self-Tuning Dead-Time Compensation Method for Voltage-Source Inverters" *IEEE Power Electronics Letters*, vol. 3, no. 2, June 2005
- [8] J. Holtz and J. Quan, "Sensorless vector control of induction motors at very low speed using a nonlinear inverter model and parameter identification," *IEEE Trans. Ind. Applicat.*, vol. 38, no. 4, pp. 1087–1095, Jul./Aug. 2002.
- [9] H.-S. Kim, H.-T. Moon, and M.-J. Youn, "On-line dead-time compensation method using disturbance observer," *IEEE Transaction on Power. Electronics.* vol. 18, no. 6, pp. 1136–1345, Nov. 2003.
- [10] N. Urasaki, T. Senjyu, K. Uezato, T. Funabashi, "An Adaptive Dead-Time Compensation Strategy for Voltage Source Inverter Fed Motor Drives" *IEEE Transactions on Power Electronics*, vol. 20, No. 5, Sep. 2005