Current Detection Error Correction for 3-Phase AC Power Converters

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Abstract

For general 3-phase converters, current control is performed by using a current sensor installed in the AC current block. Depending on the current level sensor or parts installed in peripheral circuits, however, offset and gain unbalance errors may be generated at the time of current detection. In the case of motor control, a current ripple will be caused by the effect of the above errors and this ripple will result in a torque ripple in 1st and 2nd frequency components. This also becomes a factor causing vibration.

As a vibration suppression control approach, the company has been developing a periodic disturbance observer. Drawing on this engineering resource a new method for current detection error correction has been developed. This method compensates for current sensor detection errors in online mode. In addition, torque ripple of the 6th and 12th components attributable to motor structure can be suppressed at the same time by using the conventional method of torque ripple suppression control simultaneously.

1 Preface

For general 3-phase AC power converters like inverters, the AC current block is equipped with a current sensor and vector control is performed by feeding back the detected current value. Due to sensor characteristics in terms of linearity, hysteresis, temperature drift, noise, and also to accuracies of peripheral circuit components and detecting systems, there is a case where the current sensor may produce offset errors and gain unbalance errors in its detection value. By the effect of these errors, 3-phase currents will exhibit unbalanced waveforms that have different crest values and mean values in each phase.

For an example of motor control, the offset error in the 3-phase current causes torque ripples of the 1st component of electrical rotational frequency and the gain error results in those of the 2nd component. These errors finally lead to problems of vibration and noise. Since the sensor characteristics change over time, an online compensation method is needed by the market for high-accuracy correction.

For a vibration suppression control system, we have so far proposed the generalized periodic disturbance observer compensation method(1)~(3). In this method, a specific frequency component is regarded as an object to be suppressed, and despite its simple control circuit configuration, it has high suppression effect and stability. This paper introduces a current sensor error correction approach by using a periodic disturbance observer based on the fact that harmonic currents due to current sensor errors are caused by a frequency component of the specific order.

Since the offset error and the gain unbalance error are compensated in online mode, this system can cope with moment-to -moment errors. Further, for an example of a permanent magnet synchronous motor, this paper shows that torque ripples of the 6th and 12th components attributable to motor structure can be suppressed at the same time if a conventional technique of torque ripple suppression control is being used in combination with this current sensor error correction.

2 Torque Ripple Caused by Current Detection Errors(4)(5)

In this section, it explains a mechanism of torque ripple generation of the 1st and 2nd components of electrical rotational frequency considered to occur due to detection errors caused by the current sensor by using numerical expressions.

Output currents i_u, i_v, i_w of a 3-phase inverter are defined by Expression (1), where θ is motor's standard phase, ϕ is a phase difference from θ, and I is current amplitude.

$$\begin{pmatrix} i_u \\ i_v \\ i_w \end{pmatrix} = \begin{pmatrix} I\sin(\theta+\varphi) \\ I\sin\left(\theta+\varphi-\frac{2}{3}\pi\right) \\ I\sin\left(\theta+\varphi+\frac{2}{3}\pi\right) \end{pmatrix} \cdots\cdots\cdots\cdots\cdots (1)$$

Expression (2) defines 3-phase currents i_u^{sense}, i_v^{sense}, i_w^{sense} containing offset errors Δi_u, Δi_v, Δi_w and gain errors α, β, γ caused by sensor errors of the detected 3-phase current values.

$$\begin{pmatrix} i_u^{sense} \\ i_v^{sense} \\ i_w^{sense} \end{pmatrix} = \begin{pmatrix} i_u \\ i_v \\ i_w \end{pmatrix} + \begin{pmatrix} \Delta i_u \\ \Delta i_v \\ \Delta i_w \end{pmatrix} + \begin{pmatrix} (\alpha-1)\cdot i_u \\ (\beta-1)\cdot i_v \\ (\gamma-1)\cdot i_w \end{pmatrix} \cdots\cdots (2)$$

For Expressions (1) and (2), rotational coordinate transformation (*dq* transformation) is carried out in synchronization with motor phase θ so that Axis-*d* current i_d^{sense} and Axis-*q* current i_q^{sense} can be expressed by Equation (3) while offset and gain unbalance errors are caused, where values i_d and i_q are the detected Axis-*d* and Axis-*q* current values without no error generation.

$$\begin{aligned} \begin{pmatrix} i_d^{sense} \\ i_q^{sense} \end{pmatrix} &= \begin{pmatrix} i_d \\ i_q \end{pmatrix} \\ &+ \frac{1}{\sqrt{6}} \begin{pmatrix} (2\Delta i_u - \Delta i_v - \Delta i_w) & \sqrt{3}(\Delta i_v - \Delta i_w) \\ \sqrt{3}(\Delta i_v - \Delta i_w) & -(2\Delta i_u - \Delta i_v - \Delta i_w) \end{pmatrix} \cdot \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} \\ &+ \frac{I}{2\sqrt{6}} \begin{pmatrix} \sqrt{3}(\beta-\gamma) & (2\alpha-\beta-\gamma) \\ (2\alpha-\beta-\gamma) & -\sqrt{3}(\beta-\gamma) \end{pmatrix} \cdot \begin{pmatrix} \cos(2\theta+\phi) \\ \sin(2\theta+\phi) \end{pmatrix} \\ &+ \frac{I}{\sqrt{6}} \begin{pmatrix} 0 & -3+(\alpha+\beta+\gamma) \\ 3-(\alpha+\beta+\gamma) & 0 \end{pmatrix} \cdot \begin{pmatrix} \cos\phi \\ \sin\phi \end{pmatrix} \quad \cdots (3) \end{aligned}$$

From Expression (3), it is recognized that the offset error falls on vibration of the 1st components in Axis-*d* and Axis-*q* currents and the gain unbalance error is a cause of vibration of the 2nd component and DC component.

Now Expression (3) is transformed into Expression (4) in such a manner that the 1st vibrational components (second term) of Axis-*d* and Axis-*q* currents in Expression (3) are replaced with id1f and i_{q1f}, 2nd vibrational components (third term) with i_{d2f} and i_{q2f}, and constant terms (fourth term) with C_d and C_q. When the replaced values are substituted for a general torque formula given by Expression (5) in order to express influence upon output torque, Expression (6) is obtainable. In this case, L_d and L_q are assumed to be inductance on Axis *d* and Axis *q*, Ψ is an armature interlinkage flux, and p is the number of polar pairs. The first term in the second line of Expression (6) denotes an ideal torque, the second term is for the torque error of DC component, the third term is vibration of the 1st component, the fourth term is the vibration of the 2nd component, and the fifth term is a complex vibration component caused by the 1st and 2nd vibration. Actually, however, higher harmonic torque ripples are also generated because the harmonic components are contained in inductance and armature interlinkage flux.

Given above, it is observed that the current detection error results in the generation of torque ripple composed mainly of the 1st and 2nd components of electrical rotational frequency and that it also affects the steady-state torque error.

$$\begin{pmatrix} i'_d \\ i'_q \end{pmatrix} = \begin{pmatrix} i_d \\ i_q \end{pmatrix} + \begin{pmatrix} i_{d1f} \\ i_{q1f} \end{pmatrix} + \begin{pmatrix} i_{d2f} \\ i_{q2f} \end{pmatrix} + \begin{pmatrix} C_d \\ C_q \end{pmatrix} \cdots\cdots\cdots (4)$$

$$\begin{aligned} &T = p i_q (\Psi + \Delta L i_d) \\ &\Delta L = L_d - L_q \end{aligned} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

$$\begin{aligned} T &= p i'_q (\Psi + \Delta L i'_d) \\ &= p i_q (\Psi + \Delta L i_d) \\ &\quad + p(\Psi C_q + \Delta L (C_q i_d + C_d i_q + C_d C_q)) \\ &\quad + p(\Delta L (i_q + C_q)\cdot i_{d1f} + (\Psi + \Delta L\cdot(i_d + C_d))\cdot i_{q1f}) \\ &\quad + p(\Delta L (i_q + C_q)\cdot i_{d2f} + (\Psi + \Delta L\cdot(i_d + C_d))\cdot i_{q2f}) \\ &\quad + p(\Delta L i_{d1f} i_{q1f} + (\Delta L i_{d1f} i_{q2f} + \Delta L i_{d2f} i_{q1f}) + \Delta L i_{d2f} i_{q2f}) \cdots (6) \end{aligned}$$

3 Current Detection Error Correction Approach

As explained in the previous section, periodic vibration is generated in torque and currents due to the effect of current detection errors. As a control approach for the suppression of periodic vibration, the company developed the generalized periodic disturbance observer system (1)~(3) and this system is applied to current detection error correction. First, a concept of generalized periodic disturbance observer is introduced, and then a method of application to current detection error correction is described.

3.1 Generalized Periodic Disturbance Observer Compensation Method (1)~(3)

Fig. 1 shows a control block diagram of a generalized periodic disturbance observer relating to

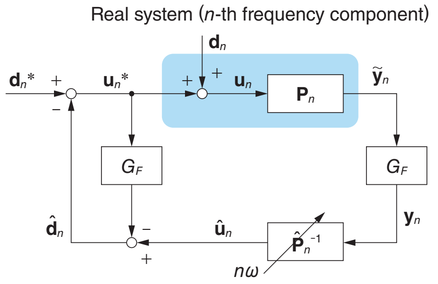


Fig. 1 **Control Block Diagram of Generalized Periodic Disturbance Observer**

The basic configuration is shown for the periodic disturbance observer generalized in complex vector expression.

the n-th frequency component. The vector notation for each signal in the diagram denotes the complex vector $\mathbf{X} = X_A + jX_B$.

Symbol G_F is a Low Pass Filter (LPF) that is effective to both real and imaginary parts after rotational coordinate transformation. It is used for frequency component extraction. The real system $\mathbf{P}_n$ possesses system's overall frequency transfer characteristics from the input value $\mathbf{u}_n$ including the characteristics of the actuator and sensor to the output detection value $\mathbf{y}_n$. In any system, therefore, an objective model for control can be generalized with a simple complex vector.

The basic operation is the same as that of an approach for a conventional disturbance observer. Value $\mathbf{u}_n$ is determined by presuming the real system's input from the inverse system $\hat{\mathbf{P}}_n^{-1}$ based on n-th frequency component $\mathbf{y}_n$ detected through the LPF. Since periodic disturbance $\mathbf{d}_n$ is included in the real system input, Value $\mathbf{d}_n$ is presumed by subtracting the current command value $\mathbf{u}_n^*$ from $\hat{\mathbf{u}}_n$ through G_F. When $\hat{\mathbf{d}}_n$ is subtracted from periodic disturbance command value $\mathbf{d}_n^*$ (0 for suppression), it becomes possible to cancel periodic disturbance.

Although the generalized periodic disturbance observer comes in a simple configuration, it features high robustness against modeling error⁽³⁾ and vibration of specific frequency component can be effectively suppressed. Therefore, we adopted this method for the 1st and 2nd vibration suppression control in connection with current detection errors and as an approach for current detection error correction.

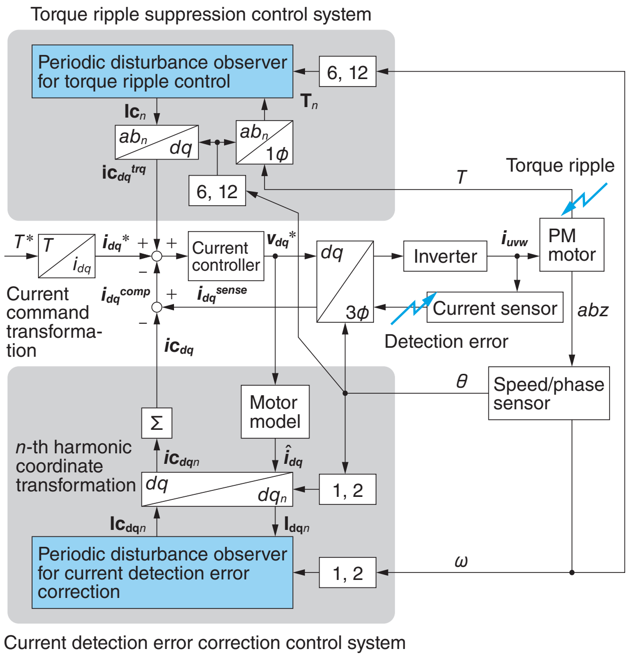


Fig. 2 **Torque Ripple Suppression Control System and Current Detection Error Correction**

The upper part shows the torque ripple suppression control system and the lower part shows the current detection error correction control system.

3.2 Application to Current Detection Error Correction⁽⁴⁾⁽⁵⁾

A control system configuration diagram is shown in the lower part of **Fig. 2** as a current detection error correction control system. The generalized periodic disturbance observer shown in above **3.1** is applied to current detection error correction control. The upper part shows the torque ripple suppression control system to be discussed later. The center part of the diagram shows a generic vector control system where Axis dq current command $\boldsymbol{i}_{dq}^*$ is generated from torque command T^* in order to perform feedback control so that the current detection value can follow up the command value with the aid of a current controller. Axis dq voltage command $\boldsymbol{v}_{dq}^*$ obtained as a current controller output is turned into a 3-phase voltage command through dq inverse transformation. This command is given to the inverter in order to drive the permanent magnet synchronous motor (PM motor).

The 3-phase motor currents $\boldsymbol{i}_{uvw}$ are detected by the current sensor and Axis dq current detection value after dq transformation is assumed to be $\boldsymbol{i}_{dq}^{sense}$. If this $\boldsymbol{i}_{dq}^{sense}$ value contains a detection error, the 1st and 2nd component vibration is generated in the dq transform value $\boldsymbol{i}_{dq}$ of 3-phase currents $\boldsymbol{i}_{uvw}$ actually carried, as suggested by Expression (3). This is due to a fact that the current controller uses a current value that contains a detection error by the feedback control. As a result of the current controller functioning to compensate for the said detection error, a vibration-related component is generated in the Axis *dq* voltage command $\boldsymbol{v}_{dq}^*$ that is an output from the current controller. Resulting from a voltage command that contains vibration, imbalance appears in actual 3-phase motor currents $\boldsymbol{i}_{uvw}$. In this case, the current detection value $\boldsymbol{i}_{dq}^{sense}$ is wrongly observed due to a detection error. It incorrectly appears as "there is no generation of vibration." As a result, the vibration remains to stay in actual 3-phase motor currents $\boldsymbol{i}_{uvw}$ and torque ripple as defined by Expression (6) are generated.

As a result, an actual Axis *dq* current is presumed from the voltage command $\boldsymbol{v}_{dq}^*$ that contains a vibration component so that the generalized periodic disturbance observer can compensate for the current vibration of the 1st and 2nd components due to current detection errors. In the first place, the voltage command $\boldsymbol{v}_{dq}^*$ is substituted for the PM motor model of Expression (7) to determine the Axis *dq* current presumption value $\hat{\boldsymbol{i}}_{dq}$, where $R =$ armature resistance and $\omega =$ angular frequency. Since the generalized periodic disturbance observer has a high robustness, it is unnecessary to provide for any numerically strict motor model.

$$\hat{\boldsymbol{i}}_{dq}=\begin{pmatrix}\hat{i}_d\\ \hat{i}_q\end{pmatrix}=\begin{pmatrix}\dfrac{1}{R+sL_d}\cdot(v_d^*+\omega\hat{i}_qL_q)\\[2ex] \dfrac{1}{R+sL_q}\cdot(v_q^*-\omega\hat{i}_dL_d-\omega\Psi)\end{pmatrix}\cdots(7)$$

According to Expression (8), harmonic coordinate transformation is made for Value $\hat{\boldsymbol{i}}_{dq}$ and a frequency component is extracted in order to determine the *n*-th current vibration value $\mathbf{I}_{dqn}$, where $\mathcal{L}$ is a Laplacian operator.

$$\mathbf{I}_{dqn}=G_F\cdot\mathcal{L}\left[\begin{pmatrix}\cos n\theta & \sin n\theta\\ -\sin n\theta & \cos n\theta\end{pmatrix}\cdot\begin{pmatrix}\hat{i}_d\\ \hat{i}_q\end{pmatrix}\right]\cdots\cdots(8)$$

An input of Value $\mathbf{I}_{dqn}$ is then entered in the generalized periodic disturbance observer to obtain the *n*-th compensation current $\mathbf{Ic}_{dqn}$. Expression (9) below shows coordinate transformation from $\mathbf{Ic}_{dqn}$ into *n*-th current compensation value $\boldsymbol{ic}_{dqn}$ in the coordinate transformation system.

$$\boldsymbol{ic}_{dqn}=\begin{pmatrix}\cos n\theta & -\sin n\theta\\ \sin n\theta & \cos n\theta\end{pmatrix}\cdot\mathbf{Ic}_{dqn}\cdots\cdots\cdots\cdots(9)$$

According to Expression (3), the offset error and the gain error are subject to the generation of the 1st and 2nd harmonic currents. Therefore, the objective order for suppression is assumed to be $n = 1$ and 2, and generalized periodic disturbance observer of the respective orders are arranged in parallel configuration. Values $\boldsymbol{ic}_{dqn}$ of each order are summed up to define a final current detection error correction value $\boldsymbol{ic}_{dq}$. As a result, the current detection value $\boldsymbol{i}_{dq}^{comp}$ is obtained, where the detection error contained in $\boldsymbol{i}_{dq}^{sense}$ is corrected. After all, it is possible to obtain a current value without any detection error while torque ripple caused by detection error are suppressed.

3.3 Combined Use with Torque Ripple Suppression Control

In addition to current detection errors explained above, torque ripple can be generated due to uniformity in motor's electromagnetic structure. Here in this section, we explain the combined use of the torque ripple suppression control system (see the references (1) and (2)) and the method of current detection error correction control introduced in the previous section. The upper part of **Fig. 2** shows a torque ripple suppression control system. The torque readout value *T* is used as an input and the torque ripple is suppressed with the use of a generalized periodic disturbance observer. In the test in this paper below, motor-borne torque ripple suppression was set at the objective orders of $n = 6$-th and 12-th and current detection error correction and torque ripple control were carried out at the same time. In other words, the 1st and 2nd components of torque ripples were compensated for by current detection error correction control and 6-th and 12-th components were compensated for by the torque ripple suppression control system.

4 Test Result

In order to confirm the adequacy of the control system introduced in Chapter **3**, the PM motor testing equipment in a control configuration in **Fig. 2** was used for the verification on the three patterns below. In regard to the detection error of an actual current sensor, however, there were moment-to-moment variations in dispersion. For this testing, consequently, current sensor detection errors specified in **Table 1** were intentionally applied to make the effect confirmation easier.

① Motor-borne torque ripple suppression control only
② Current sensor detection error correction only
③ Simultaneous compensation by ① and ②

Fig. 3 shows a test result in the case of torque ripple suppression control only. In this figure, the shaft torque waveforms are shown at the upper stage, the result of frequency component analysis is shown at the middle stage, and 3-phase current waveforms are shown at the lower stage. The respective diagrams on the left show the waveforms before application of torque ripple suppression control and those on the right are those after application. Before application in particular, the 1st, 2nd, 6-th, and 12-th torque ripples were generated. Regarding 3-phase current waveforms, 3-phase unbalance was caused by current sensor detection errors. After application of control, however, 6-th and 12-th torque ripples were well suppressed, but the unbalance remained to stay in the 1st and 2nd torque ripples and current waveforms due to current detection errors.

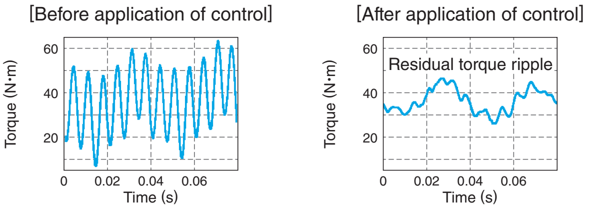
Fig. 4 shows a test result in the case of current sensor error correction only. In this case, 3-phase unbalance in current waveforms and offset errors can be compensated for by reducing 1st and 2nd torque ripples. However, motor-borne 6-th and 12-th torque ripples still remained.

Lastly, **Fig. 5** shows the result of testing where both control systems are applied. All of the 1st, 2nd, 6-th, and 12-th torque ripples, the object for suppression, were suppressed and unbalance in 3-phase current waveforms and offset errors could be eliminated.

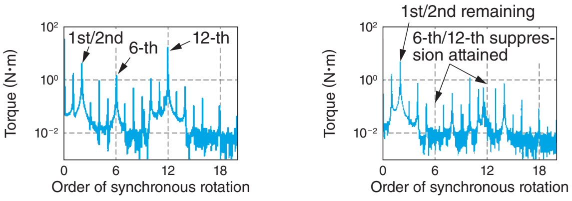
Table 1 **Detection Error Setup for Current Sensor**

For correction effect verification, detection errors are set up for current detection values in each phase.

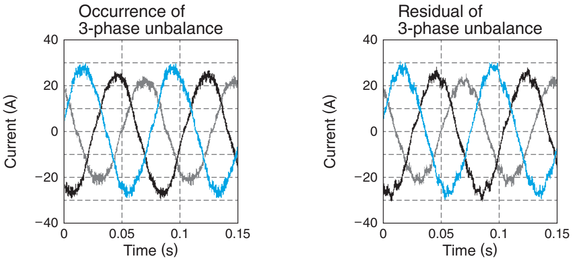
Error setup	Phase U	Phase V	Phase W
Offset error (A)	+1.36	−1.36	−0.54
Gain error (%)	+10	−20	+20



(a) Shaft torque response



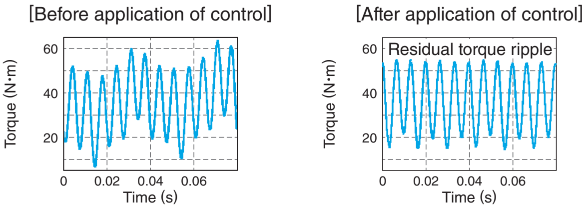
(b) Result of shaft torque FFT analysis



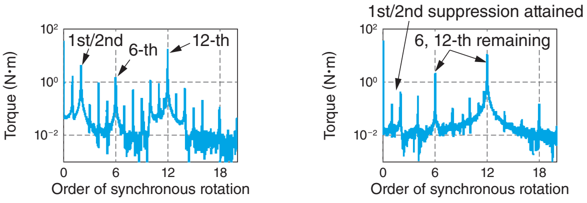
(c) 3-phase current waveforms

Fig. 3 **Test Result ① (Torque Ripple Suppression Only)**

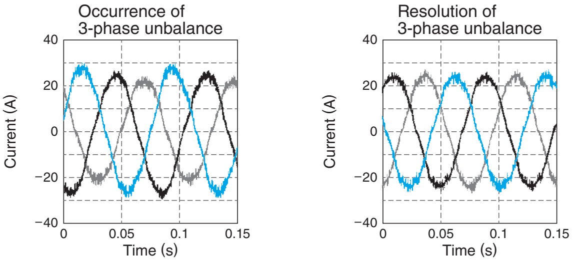
Torque time response (upper stage), torque frequency analysis (middle stage), and 3-phase current waveforms (lower stage) are shown. The left side shows the result of testing without torque ripple suppression control and the right side shows the result with control. We could suppress motor-borne 6-th and 12-th torque ripples, but the 1st and 2nd components caused by current detection errors remained to stay.



(a) Shaft torque response



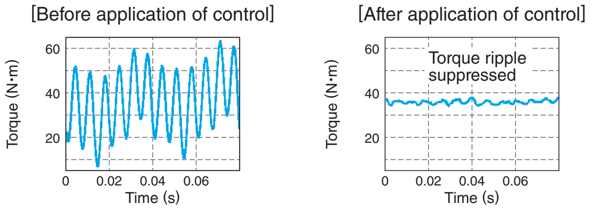
(b) Result of shaft torque FFT analysis



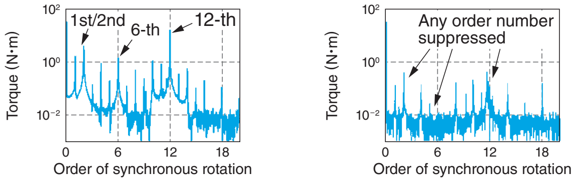
(c) 3-phase current waveforms

Fig. 4 **Test Result ② (Current Sensor Error Correction Only)**

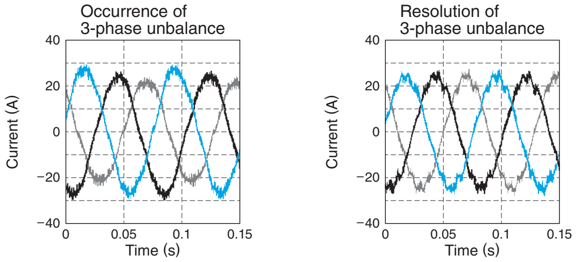
Torque time response (upper stage), torque frequency analysis (middle stage), and 3-phase current waveforms (lower stage) are shown. The left side shows the result of testing without torque ripple suppression control and the right side shows the result with control. We could suppress the 1st and 2nd components caused by current detection errors, but motor-borne 6-th and 12-th torque ripples remained.



(a) Shaft torque response



(b) Result of shaft torque FFT analysis



(c) 3-phase current waveforms

Fig. 5 **Test Result ③ (Combined Use of Torque Ripple Suppression Control and Current Sensor Error Correction)**

Torque time response (upper stage), torque frequency analysis (middle stage), and 3-phase current waveforms (lower stage) are shown. The left side shows the result of testing without torque ripple suppression control and the right side shows the result with control. We could suppress both the 1st and 2nd components caused by current detection errors and also motor-borne 6-th and 12-th torque ripples.

As mentioned above, from the test results, we could confirm that more effective suppression of torque ripples is possible when we combine and use an approach of motor-borne torque ripple suppression control and that of current detection error correction.

5 Postscript

This paper introduced the method of current detection error correction by using generalized periodic disturbance observer. Since current detection errors are corrected in online mode, we could improve accuracy for current control. In addition, when the torque ripple attributable to motor structure is suppressed at the same time, we could improve the torque ripple suppression performance.

Going forward, we will continue to work on advancing performance of our system equipment by actively using control technologies.

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