Paper

Frequency-Hybrid Vector Control with Monotonously-Increasing-Region Strategy for Sensorless Synchronous Motor Drive

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This paper proposes a newly developed frequency-hybrid(FH) vector control scheme with monotonously-increasing-region(MIR) strategy for sensorless cylindrical synchronous motor drive. It is confirmed through tests using a 750(W) motor that the proposed sensorless scheme has the following high potential: 1)it operates in both torque and speed controls, 2) it operates in both motoring and regenerating modes, 3) torque producing characteristics has good linearity over the rated torque range under constant speed, 4)for steady speed performance with correct flux orientation, its speed ratio based on rated speed is about 1/300 under motoring rated load and 1/200 under regenerating rated load, 5)for transient speed performance, its servo-tracking ability allows to track speed command of acceleration ±5,000(rad/s^2) under no-load.

Key words: hybrid, sensorless, vector control, synchronous motor, stability, MIR, FH

1. Introduction

Vector control is essential for high performance drive of synchronous motor that requires quick, precise or efficient torque and speed responses. In order to establish vector controlled states of the motor, position information on rotor flux(or magnet) to which orientation is taken by vector controller should be obtained first. For flux orientation an optical encoder as a magnet N-pole position sensor, which can be also used as a speed and position sensor, is often mounted on rotor shaft. However, there has been extensive industrial demand of sensorless vector control scheme, which does not require magnet position, rotor speed and position sensors, for obtaining some benefits such as elimination of wiring sensor cable, decreasing motor size in direction of shaft, increasing of driving system reliability, decreasing a variety of cost related with the sensor etc.

In order to meet the industrial demand, sensorless vector control technologies based on peculiar principles have been developed, but have some of the following fundamental problems to overcome [1]-[5]:

1) Operating in torque control mode as well as speed control mode.
2) Operating in regenerating mode as well as motoring mode.
3) Increase of allowed speed dynamic range, especially extension of allowed low speed. For example, attained speed ratio based on the rating is about 1/80 by papers, and 1/10 for commercially available drive apparatus.
4) Operating in variable speed control as well as steady one, and increase of quick servo-tracking ability.

This paper proposes a new frequency-hybrid(FH) vector control scheme as one of potential sensorless vector control ones for cylindrical permanent magnet synchronous motor drive[6], which was originally researched and developed for sensorless induction motor drive[7], [8]. This paper also proposes a monotonously-increasing region(MIR) strategy together with newly clarified principle, which is effective for increasing stability especially in low speed range[6]. The FH vector control with the MIR strategy can operate in both speed and torque control modes, and in both motoring and regenerating modes. It can exhibit such high performance that for steady response with correct flux orientation its speed ratio is about 1/300 in motoring mode and 1/200 in regenerating mode under rated load, for transient response its servo-tracking ability allows to track speed command of acceleration ±5,000(rad/s^2) under no-load.

2. Principle of FH orientation for vector control

2.1 FH orientation method

Denote the position of rotor flux vector evaluated in stationary frame by θ. What is required for realization of vector control is its sinusoidal values such as $\cos\theta$ and $\sin\theta$, which are referred to as 2x1 position vector $[\cos\theta \quad \sin\theta]^T$ in the following. According to the above manner, let $[\cos\theta_1 \quad \sin\theta_1]^T, [\cos\theta_2 \quad \sin\theta_2]^T$ be position vector estimate by orientation method 1, 2 respectively. In the FH orientation method, a single final estimate $[\cos\theta_f \quad \sin\theta_f]^T$ is produced by combining two estimates as follows:

$$\begin{bmatrix}\cos\theta_f \\ \sin\theta_f\end{bmatrix} = F(s)\begin{bmatrix}\cos\theta_1 \\ \sin\theta_1\end{bmatrix} + (1-F(s))\begin{bmatrix}\cos\theta_2 \\ \sin\theta_2\end{bmatrix} \quad (1)$$

where $F(s)$ is a frequency-weighting factor in form of Butterworth filter with low-pass characteristics of $F(0)=1$ and appropriate frequency band width. i.e.

$$F(s) = \frac{f_0}{s^n + f_{n-1}s^{n-1} + \cdots + f_1 s + f_0}. \quad (2)$$

Weighting factor $1-F(s)$ results in a high pass filter. The symbol s is used as a Laplace or differential operator d/dt as long as no expressing problem occurs.

2.2 Indirect orientation method

Circuit equation of cylindrical synchronous motors in the synchronous rotating frame, which is synchronized with rotor flux vector, can be described as

$$v = R\,i + \begin{bmatrix} s & -\omega \\ \omega & s \end{bmatrix}\left[L i + \begin{bmatrix} \Phi \\ 0 \end{bmatrix}\right] \tag{3}$$

where v , i are 2x1 stator voltage, current vectors respectively, and R, L, Φ are stator resistance, inductance and back emf coefficient respectively. Such a relatively new orientation approach for synchronous motors is taken in this paper that synchronizing angular frequency ω is generated first and is integrated to produce an estimate of rotor flux position θ, succeedingly the estimate is converted into a 2x1 position vector. This class of orientation method is referred to as indirect one in this paper. The indirect method is very popular for induction motor drive[7], [8], but seems to be rarely used for synchronous motor drive[4], [6].

As a candidate of the indirect method for generating synchronous angular frequency ω, the following can result directly from (3):

$$\omega = \frac{v_q - (sL+R)\,i_q}{\Phi + L i_d} \tag{4}$$

where the suffixes d, q indicate direct, quadratic components of 2x1 vectors in the synchronous frame.

As the low-frequency position vector $[\cos\theta_1 \quad \sin\theta_1]^T$ in the FH orientation method, estimate by the indirect method is employed.

Note that estimate of rotor speed $\hat{\omega}_m$ can be determined simply by dividing the synchronous angular frequency ω by the number of pole pairs N_p, i.e.

$$\hat{\omega}_m = \frac{\omega}{N_p}. \tag{5}$$

2.3 Direct orientation method

Circuit equation of cylindrical synchronous motors in the stationary frame can be described as

$$v = R\,i + s\left[L i + \Phi \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix}\right]. \tag{6}$$

Rearranging (6) with respect to position vector and multiplying it by the high pass filter *1-F(s)* yields

$$(1-F(s))\begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} = \frac{(1-F(s))}{\Phi s}\left[v - (sL+R)i\right]. \tag{7}$$

It should be noted that the filter *(1-F(s))/s* in right-hand side of (7) is reduced to and realized as

$$\frac{1-F(s)}{s} = \frac{s^{n-1} + f_{n-1}s^{n-2} + \cdots + f_1}{s^n + f_{n-1}s^{n-1} + \cdots + f_1 s + f_0}, \tag{8}$$

that it no longer has high-pass characteristics, it generally has band-pass or low-pass characteristics, and that it is as stable as desired, and does require neither pure nor approximated integration at all. These features make the proposed direct method with embedded-filter in (8) distinguished from conventional direct ones that take pure or approximated integration and are almost under unstable condition.

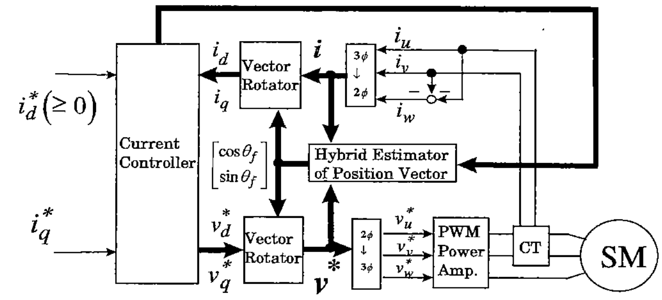

Fig. 1. An example of system configuration using the hybrid estimator.

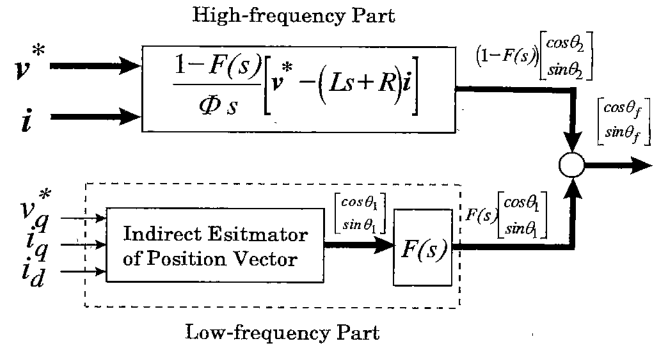

Fig. 2. A configuration of hybrid-estimator of position vector.

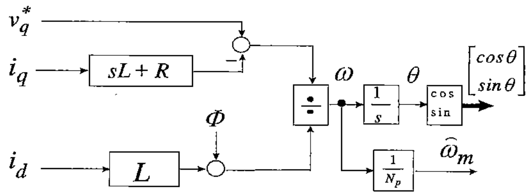

Fig. 3. A configuration of indirect estimator of position vector.

For the high-frequency part in the FH method, i.e. the second term in (1), the stable-filter-embedded direct method in (7) together with (8) is employed.

Fig. 1 depicts a configuration of vector control system based on the FH orientation method, which is realized as a hybrid estimator of position vector. As illustrated, configuration of remaining parts except for the estimator is the same as a typical vector control system using a position sensor. This configuration is useful for performance comparison of the two systems. Figs. 2, 3 depict configurations of the hybrid and indirect estimators respectively by (1), (4), (5), (7), (8) where stator voltage command is used instead of measured stator voltage for simple realization.

3. MIR strategy for stability

Denote an electrical angle from rotor flux vector ϕ_m to stator current vector i by $\theta_{\phi i}$ as in Fig. 4. Torque τ produced by interaction of the rotor flux and the stator current can be described as[9]

$$\begin{aligned}\tau &= N_p \|\phi_m\| \|i\| \sin\theta_{\phi i} \\ &= N_p \Phi \|i\| \sin\theta_{\phi i}\end{aligned} \tag{9}$$

Torque characteristics depending on the angle in (9) is depicted as in Fig. 5. It is clearly observed that torque producing region can be divided into two peculiar regions such as monotonously-increasing region(MIR) and monotonously-decreasing region.

It is quite reasonable under stable vector control using flux position sensor to control the absolute angle to be equal to or larger than $\tau/2$ (rad), since for constant torque generation, optimum angle minimizing copper loss locates at the critical point and optimum angle maximizing power factor locates in the monotonously-decreasing region[9], [10]. It should be noted that this optimum strategy is meaningful under assurance of stable torque generation only.

Generally speaking, disturbance torque acts on the motor rotor so as to spread the angle $\theta_{\phi i}$ wider. Suppose a situation that stator current vector in a sensorless vector control system is controlled to be located in the monotonously-decreasing region, and disturbance torque instantly increases. Since the sensorless vector control system cannot necessarily detect increasing disturbance as instantly as it occurs, torque balance between the rotor and the disturbance will be lost immediately after instant increasing of the disturbance because of monotonously decreasing characteristics. Consequently the sensorless vector control system loses control for stable torque generation.

However, if current vector is controlled to be located in the MIR, disturbance which spreads the angle wider causes increase of rotor torque as instantly as its increase because of monotonously-increasing characteristics itself. Then stable torque generation can be automatically kept even for instant increase of disturbance. This paper calls the newly proposed strategy for stability that controls the stator current vector to be located in the MIR as MIR strategy. It is very powerful especially in very low speed range.

For cylindrical synchronous motor, the MIR strategy can be realized by controlling the magnetizing component of the current vector to be positive.

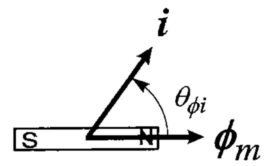

Fig. 4. Positional relation between stator current and rotor flux vectors.

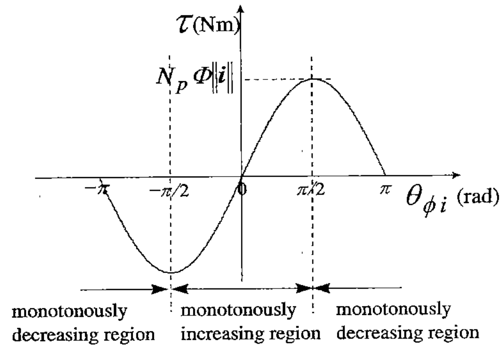

Fig. 5. Torque characteristics to relative angle between rotor flux and stator current vectors for cylindrical synchronous motor.

4. Evaluation tests

4.1 Configuration of experiment system

In order to evaluate basic performance of the new FH vector control scheme with the MIR strategy, evaluation tests have been carried out using the equipment illustrated in Fig.6. Test motor is a 750(W) cylindrical synchronous motor (FXEM5750-D) made by Oriental Motor Co. Ltd. (refer to Table 1 for detail). Load machine is a vector-controlled synchronous motor(HA-SH102, MR-H100A) of inertia J =19.6x10^{-4}(kgm^2) and rated speed 209(rad/s) made by Mitsubishi Electric Corporation. Torque sensor system is the one(TPN-2KMAB, DPM-700B) made by Kyowa Electric Instruments Co. Ltd.

Note that the load machine have ten times larger inertia than the test motor. This kind of load machine is also useful for examination of large inertia accommodation ability of the test motor. And note that a minimum number of current and voltage sensors are used in the performance evaluation tests. i.e. only two AC current sensors and a single DC link voltage sensor are utilized to realize the FH vector control scheme with the MIR strategy for sensorless drive.

The low-pass filter $F(s)$ as main design parameter for the FH vector control scheme is selected such as

$$F(s) = \frac{35}{s+35}.$$

The MIR strategy is realized by injecting simply constant d-current command such as

$$i_d^* = 2.0(A)$$

which is about 25% of the rated q-current. The control scheme is realized using a single DSP with control period (in other word, computing-time) of 200(micro second). PWM frequency for inverter is 5(kHz).

Remark 1: Design of the low-pass filter $F(s)$ is important for keeping flux orientation by the FH vector control scheme. It is found experimentally that the order of the low-pass filter will be 3rd enough, and that useful cut-off frequency of $F(s)$ will range from 20 to 60 (rad/s). Characteristics of FH orientation method applied to the synchronous motor is not the same as that to induction motor. Although the indirect orientation method operates appropriately even at over 100(rad/s) for induction motor[8], but not for the synchronous motor.

4.2 Test of torque control

Evaluation test for torque control was carried out in such a way that first of all rotor of the test motor is controlled to be a specific speed by the load machine, then torque command is injected to control system for the test motor.

Fig. 7 shows results in motoring mode, which are arranged

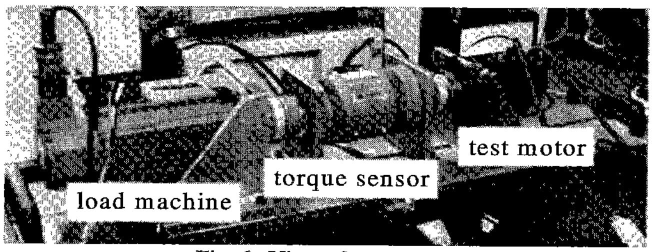

Fig. 6. View of test system.

Table1. Characteristics of test motor (FXEM5750-D).

R	0.596(Ω) (nominal 0.375(Ω))	rated speed	314(rad/s)
L	0.0053(H)	rated current	4.5(A, rms)
Φ	0.084(V s/rad)	rated q-current	7.8(A)
N_p	4	rated voltage	110(V, rms)
rated power	750(W)	moment of inertia J_m	0.000135 (kgm^2)
rated torque	about 2.4(Nm)	effective resolution of encoder	8,000(p/r)

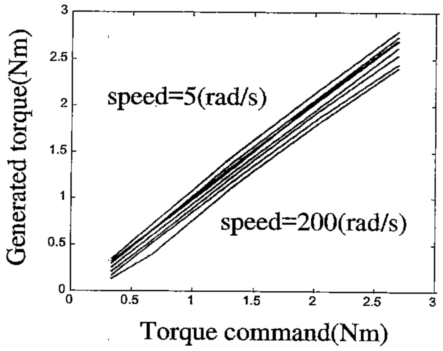

Fig. 7. Linearity characteristics of torque response in motoring mode.

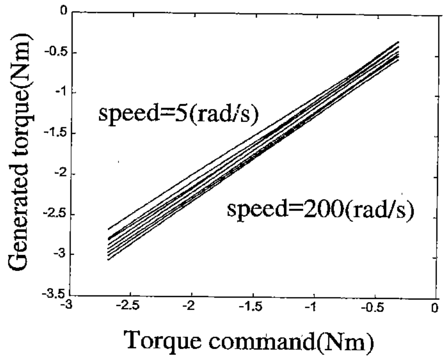

Fig. 8. Linearity characteristics of torque response in regenerating mode.

as linearity characteristics to command at several speeds. Each line is associated, from top to bottom, with response at speeds of 5, 10, 20, 40, 80, 120, 160, 200(rad/s) respectively. Note that allowed minimum and maximum speeds are restricted by the load machine.

Fig. 8 is other results but in regenerating mode. Each line is associated from top with response at speeds of 5,10, 20, 40, 80, 120, 160, 200(rad/s) respectively.

As clearly observed, in both modes of motoring and regenerating, good linearity is attained at each constant speed. However, the responses in both modes show speed dependency. In motoring mode, generated torque decreases as speed increases. On the other hand, in regenerating mode, generated torque increases as speed increases.

This opposite phenomena result mainly from the same cause, computing-time(control period) of 200(micro second) for generating voltage command. Strictly speaking, position of the rotating rotor flux vector at estimated or measured instant cannot be the same as the one when the following voltage command is injected because of the computing-time. The relative positional difference becomes large as rotor speed increases. The rotating flux vector forces the angle from the flux vector to the stator current vector, which is depicted in Fig. 4, to be smaller in motoring mode, but to be larger in regenerating mode. Since the MIR strategy is realized in a simplified manner for this evaluation test where positive constant d-current command is injected over all speed range, it is possible to produce more torque than the rating even under the constant rated q-current.

The similar phenomena occur in speed control as well as torque control. Refer to Figs. 9 to 11 in the following for actual wavelike data showing clearly the phase-varying phenomena in motoring mode, and Figs. 12 to 14 in regenerating mode.

It should be noted that the speed-dependent torque characteristics is due to computing-time, but not to FH vector control scheme itself. Similar phenomena can be observed for standard vector control using a position sensor.

4.3 Test of speed control

A. Steady characteristics in motoring mode

In order to evaluate steady performance of speed control under the rated motoring load, various constant speed commands are injected to the test motor. In order to show clearly the performance, let us directly depict non-processed wavelike responses at crucial speeds of 200, 10, 1(rad/s) below instead of processed data. Mechanical speed of 10(rad/s) corresponds to electrical speed of 40(rad/s) in this case, and cutoff frequency of the low-pass filter *F(s)* is designed to be 35(rad/s).

1) Response for speed 200(rad/s)

Fig. 9 shows a response to speed command of 200(rad/s)(2/3 of the rating). Allowed maximum speed in this test is restricted by the rating 209(rad/s) of the load machine. Plotted data indicates, from top, cosine values of true and estimated positions of rotor flux vector(center of rotor magnet position), U-phase current, and controlled speed error to command. The actual flux vector position is directly measured by an encoder of effective 8000(p/r) mounted on rotor of the test motor. The steps on the wavelike responses result from discrete-time control with period of 200(micro second). It is observed that position of the flux vector is identified very well and motor speed is controlled within average error of about 1(rad/s). The sensorless scheme shows similar response to the standard vector control using actual flux position information except for the small speed error.

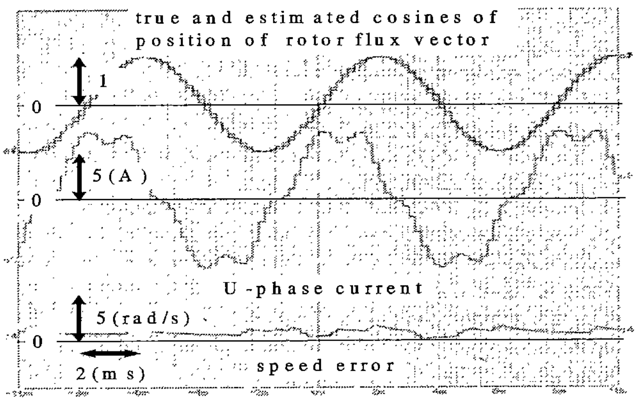

Fig.9. Steady speed control response by the FH vector control with MIR strategy to command of 200(rad/s) under rated motoring load.

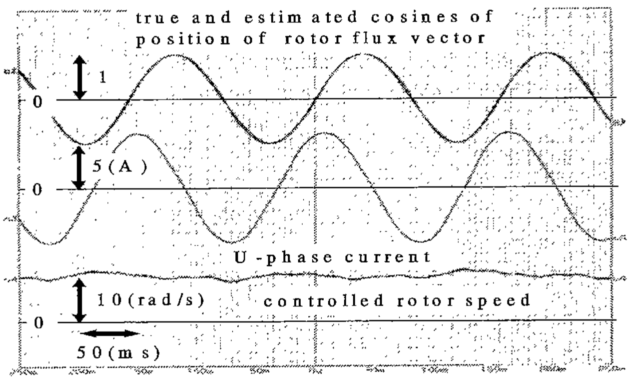

Fig.10. Steady speed control response by the FH vector control with MIR strategy to command of 10(rad/s) under rated motoring load.

As explained for torque control, the phenomena happen that actual phase difference between true cosine of rotor flux vector position and U-phase current becomes smaller due to computing-time than designed.

2) Response for speed 10(rad/s)

Fig. 10 shows a response to speed command of 10(rad/s) (1/30 of the rating). Plotted data indicates the same meanings as in Fig. 9 except for the bottom wavelike data which is speed response itself. It is observed that position of the flux vector is well identified, and that actual flux position and controlled current have good shapes. As inferred form these, the sensorless vector control can achieve quite similar response to the standard vector control with the sensor. For magnitude of speed errors whose averages are zero, the sensorless vector control is slightly better than the standard vector control using an encoder of effective 8,000(p/r).

3) Response for speed 1 (rad/s)

Fig. 11(a) shows a response to very low speed command of 1(rad/s) (1/300 of the rating) Plotted data indicates the same meanings as in Fig. 10. Among two cosine values of true and estimated positions of rotor flux vector, smooth one is estimate. It is observed that flux orientation is still successful even at the very low speed, and that average speed error is zero.

Fig. 11(b) is a reference response by the standard vector control using an encoder of effective 8,000(p/r). It is observed that cosine value of position of rotor flux vector by

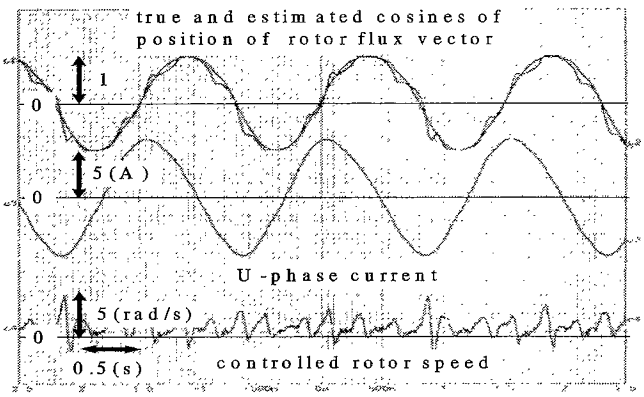

Fig. 11.(a) Steady speed control response by the FH vector control with MIR strategy to command of 1(rad/s) under rated motoring load.

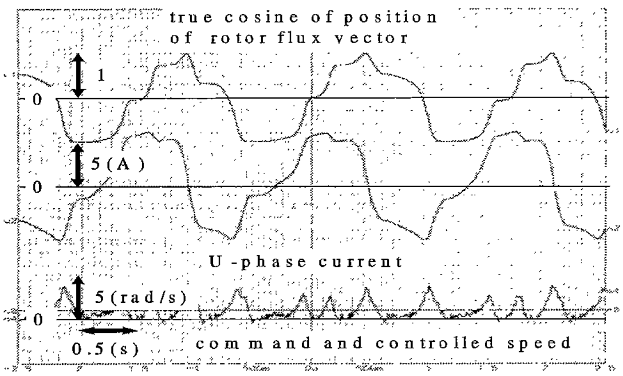

Fig.11.(b) Steady speed control response by vector control using encoder of effective 8,000(p/r) to command of 1(rad/s) under rated motoring load.

the standard vector control is no longer smooth. As seen, for a certain low speed range, it is possible for the FH vector control to exhibit relatively better performance than the sensor-used vector control.

The difference between two responses would be caused mainly by the existence of direct feedback of position vector of rotor flux or not. i.e. For the sensor-used vector control, measured position vector, which can be considered as output to the position vector inputted to the vector-rotators, is directly fed back as the input for next control. The feedback seems to enhance the cog-like rotating at very low speed. On the other hand, the FH vector control generates a position vector for the vector-rotators using current and voltage information only, and does not have such direct feedback.

B. Steady characteristics in regenerating mode

Let us show non-processed wavelike responses of speed control under regenerating rated load at crucial speeds of 200, 10, 1.5(rad/s) below.

1) Response for speed 200(rad/s)

Fig. 12 shows a response to speed command of 200(rad/s). Plotted data indicates the same meanings as in Fig. 9 in motoring mode.

As explained for torque control, the phenomena happen that phase difference between true cosine of rotor flux vector position and U-phase current becomes larger due to computing-time than designed. Resulting phase difference is almost $-\pi/2$(rad).

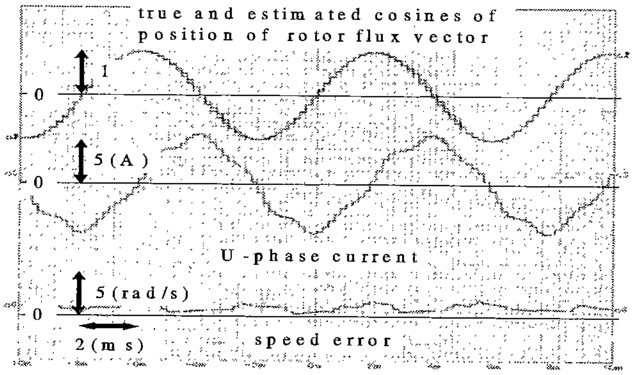

Fig.12. Steady speed control response by the FH vector control with MIR strategy to command of 200(rad/s) under rated regenerating load.

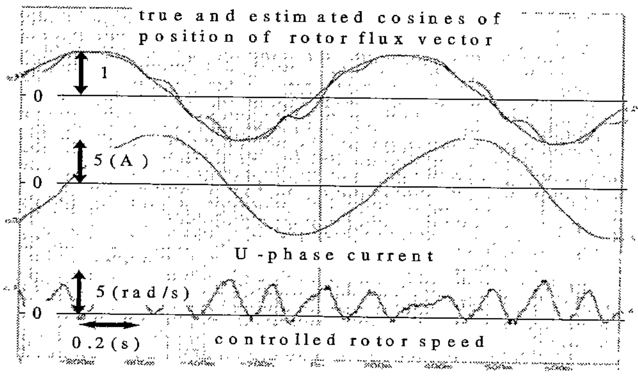

Fig. 14.(a) Steady speed control response by the FH vector control with MIR strategy to command of 1.5(rad/s) under rated regenerating load.

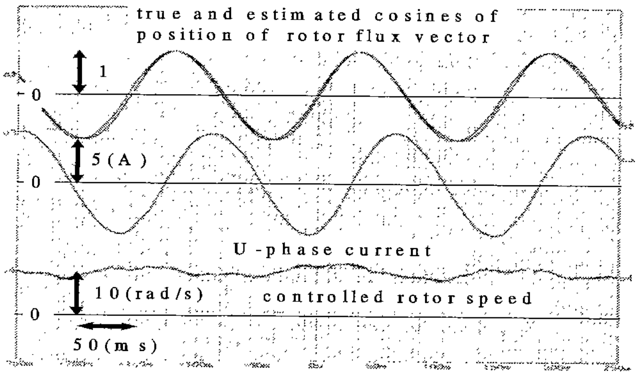

Fig.13. Steady speed control response by the FH vector control with MIR strategy to command of 10(rad/s) under rated regenerating load.

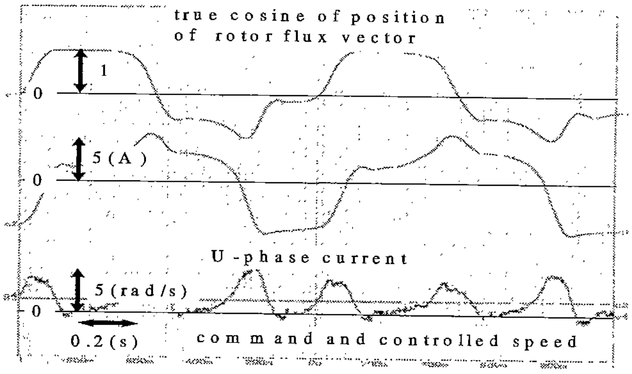

Fig14.(b) Steady speed control response by vector control using encoder of effective 8,000(p/r) to command of 1.5(rad/s) under rated regenerating load.

2) *Response for speed 10(rad/s)*

Fig. 13 shows a response to speed command of 10(rad/s). Plotted data indicates the same meanings as in Fig. 10 in motoring mode.

3) *Response for speed 1.5 (rad/s)*

Fig. 14(a) shows a response to very low speed command of 1.5(rad/s) (1/200 of the rating). Plotted data indicates the same meanings as in Fig. 11(a) in motoring mode. Fig. 14(b) is a reference response by the standard vector control using an encoder of 8,000(p/r).

C. Servo-tracking characteristics

In order to evaluate servo-tacking capabilities and attained bandwidth of speed control, variable speed command with high acceleration is injected to the tested motor with no-load and its response is examined. Fig.15 shows an example of results where the band width is designed to be 160(rad/s), range of variable speed command is 2~200(rad/s) and its acceleration is $\pm$ 5,000(rad/s^2). A decreasing vibration right after zero speed crossing is caused by speed estimation error at very low speed including zero. As seen, the proposed sensorless vector control system exhibits incomparably excellent servo-tracking performance as a sensorless system. Note that the performance is attained not only in speed-increasing mode but also in speed-decreasing mode.

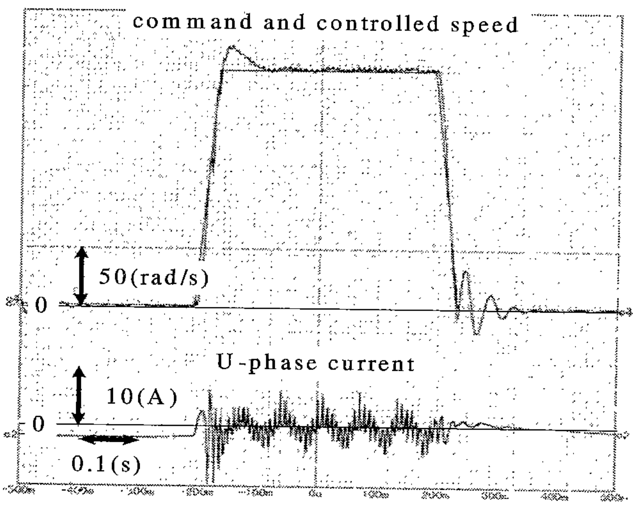

Fig.15. Speed tacking response to command with acceleration of $\pm$ 5,000(rad/s^2) between 2 and 2,000(rad/s).

5. Concluding remarks

This paper proposed the newly developed FH vector control scheme with the MIR strategy for sensorless cylindrical synchronous motor drive and identified its usefulness through the performance evaluation tests. The test results show the proposed scheme could be classified into a group of the most useful sensorless vector control schemes[1]-[6].

It will be worthy of noting that the FH vector control scheme with the MIR strategy will be applied to salient-pole permanent magnet synchronous motor as well. i.e. The FH orientation method will be also applied to salient-pole synchronous motor but with simple modification of the direct orientation method in order to handle pole-saliency[9]. The MIR strategy can be directly applied to and useful for sensorless salient-pole synchronous motor drives. Torque characteristics of the salient-pole motor with respect to angle between flux and current of stator is no longer sinusoidal, but is divided into such two regions as MIR and monotonously decreasing region similarly to the cylindrical motor[9].

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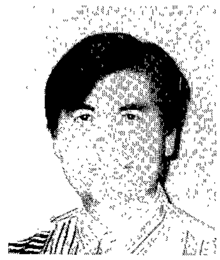

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