A New-Generation Sensorless Vector Control Scheme for Induction Motor Drive

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Abstract—This paper presents some results of performance evaluation test via actual machines of a new hybrid vector control utilizing a new indirect orientation scheme and stable filter embedded direct orientation scheme for induction motors without speed or position sensor. It is shown through the test by 0.3(kW) and 3.7(kW) motors that the proposed sensorless vector control has the following high potentialities: 1) speed range is 0 to 600(rad/s) or more, 2) zero-speed command is accepted and settles the machines at a stable standstill with no vibration 3) it can make machines to track variable command of acceleration and deceleration ±6,000(rad/s^2), 4) it can make machines to drive directly load of at least 26 times larger inertia than that of the machine, 5) it can make machines to produce much larger torque than the rating in torque control mode even at standstill. The performance confirmed by the test is far away for previous schemes or sensorless drive apparatuses.

1. INTRODUCTION

Vector control is essential to high performance drive of induction motors that requires quick and precise torque and speed responses. In order to establish vector controlled states of the motor, position information of its interior flux to which orientation is taken by vector controller should be obtained first. The orientation scheme most widely used in today's industry is so-called slip frequency type one classified into indirect flux orientation schemes. Since it requires information of rotor speed for orientation, optical encoder as speed or position sensor is often mounted on rotor shaft.

However, there has been extensive industrial demand of sensorless vector control technique, which does not require speed or position sensor, for obtaining some benefit such as increasing of driving system reliability, elimination of wiring sensor cable, decreasing motor size in direction of shaft, decreasing a variety of cost related with the sensor etc. And main motor-drive companies in Japan have already produced sensorless vector control drive apparatus for induction motor in order to comply the demand. However they employ techniques of the first generation that cannot meet servo specification similar to that attained by vector control technique using encoder information[1]. The first generation sensorless vector control technologies have the following technical problems to overcome for servo control specification[1]:

1) Increase of servo tracking ability in speed control mode
2) Realization of stable zero speed control without vibration
3) Increase of speed dynamic range
4) Increase of driving ability for load with large inertia
5) Increase of torque producing ability at slow speed including standstill.

So far, a number of sensorless vector control schemes have been proposed for seeking practical performance as well as sensorless vector drive apparatuses. In addition to difference on oriented flux and orientation method, taking account of estimation methods for such speed, slip-frequency, flux, variation of reported schemes might diverge. However it still remains as a question what scheme will be able to meet best rigid servo control specification[1],[2].

Considering the performance achieved by a variety of previously reported schemes, it seems to be very hard to meet servo specification by a single scheme. From this view point, we have proposed a hybrid sensorless vector control scheme that can exploit preferable characteristics of both newly developed indirect scheme and stable filter embedded direct scheme[3]. We have also shown through extensive simulation that the hybrid vector control has possibility of high potential usefulness[3].

This paper shows typical results of performance evaluation test for the hybrid vector control via actual machines of 0.3(kW) and 3.7(kW). According to the evaluation test, its feature and performance common to both torque and speed controls can be summarized as in Table 1 and ones restricted to speed control, or torque control can be as in Table 2. 3 respectively. Test data shows that the performance of the newly developed vector control is much better than expected by simulation and that several performance such as tracking ability to variable speed command, torque producing ability in torque control mode at very low speed including standstill etc. are ten times better or more than those by main motor driving companies of Japan.

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Tab.1 Features common to torque and speed controls

Item	Features
Employed Mathematical Model	Model using parameters of minimum number, but no consideration of core loss factor
Orientation method	Hybrid of new indirect and stable filter embedded direct methods
Dependency on rotor parameter for orientation	Completely independent on rotor parameter
Dynamic range of interior signals Possibility of fixed arithmetic	Almost same as that of slip-frequency type vector control Probably possible
Utilization of voltage information	Using DC link voltage
Control period	about 130~170(μ s) for presented data
Current controller and bandwidth for linear control mode	Nonlinear PI controller 2,000(rad/s) for presented data
Range of angular frequency of generated power	0~600(rad/s) or more in sense of electrical frequency
Minimum of angular frequency of generated power	About 3(rad/s)
Maximum acceleration of angular frequency of generated power	About 6,000~10,000(rad/s²) under stable control of motor
Maximum of generated voltage	Theoretical maximum—dead time factor
Four quadrant operation	Possible
Variable speed operation	Stable control is observed even for variable speed of 6,000 (rad/s²) for tested machine
Instant re-start under free running and allowed speed range	Possible (within current limiter) 0~600(rad/s) or more for tested machine
Flux weakening	Not examined yet
Maximum load inertia	Examined up to 26 times of that of tested machine
Kind of applied motors	Not examined except for tested motor
Adaptive algorithm to identify motor parameters	Not installed yet

Tab.2 Features and performance of speed control

Item	Features
Speed estimation method	instant estimation method
Speed estimation of zero speed and stable control	Possible to estimate and control speed successively even including zero speed Quick drive and stop by 6,000 ~ 10,000(rad/s²) is successively allowed under stable control
Speed range	0~600(rad/s) or more without flux weakening
Precision of controlled speed Range of speed	Average error、about ± 3 (rad/s) 0~600(rad/s)
Maximum acceleration	About 6,000(rad/s²) Can change speed between 0~600 (rad/s) in 0.1 (s)
Speed ratio	infinity based on stable zero speed 150~250 based on minimum non-zero speed
Bandwidth of speed control	120(rad/s) under linear operation
Speed controller	Nonlinear PI controller
Dependency on rotor parameter	Dependent

Tab3 Features and performance of torque control

Item	Features
Requirement speed information	No information on speed is required
Speed range where torque is produced	0~600(rad/s) or more
Torque producing at standstill	No problem, it seems to be better than vector control using speed information
General properties	Similar to that of vector control using speed information
Function of speed limitation or traction Ranges of torque and speed	Implemented Allowed speed is 0~600(rad/s) or more Allowed torque is 0~300(%) of rating
Dependency on rotor parameter	Independent

2. THE HYBRID VECTOR CONTROL

In this section, we briefly summarize the hybrid vector control scheme that we originally developed using reference[3], [4].

Let θ denote the flux position of the rotor. What we need to realize vector control is its sinusoidal values such as $cos\theta$ and $sin\theta$, which is referred to as 2x1 position vector $[cos\theta \;\; sin\theta]^T$ in the following. According to the above manner, let $[cos\theta_1 \;\; sin\theta_1]^T$, $[cos\theta_2 \;\; sin\theta_2]^T$ be position vector estimate by scheme 1, 2 respectively. In the hybrid scheme, a single final estimate $[cos\theta_f \;\; sin\theta_f]^T$ is produced by combining two estimates as follows:

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

where F(s) is a weighting factor with low-pass characteristics of F(0)=1 and appropriate frequency band width. Note that $1-F(s)$ results in a high pass filter.

As scheme 1, new indirect orientation method that we originally developed is employed. It is as follows:

$$\hat{\phi}_{2nd} = \frac{R_{2n}}{s+W_2} i_{1d} \tag{2}$$

$$\hat{\phi}_{1d} = L_{1t} i_{1d} + \hat{\phi}_{2nd} \tag{3}$$

$$\omega = \frac{v_{1q} - (sL_{1t} + R_1) i_{1q}}{\hat{\phi}_{1d}} \tag{4}$$

where employed parameters and states are defined in conjunction with mathematical model of minimum number parameters[4], i.e.

$$M_n \equiv \left(\frac{M}{L_2}\right)M, \quad L_{1t} \equiv L_1 - M_n, \qquad W_2 \equiv \frac{R_2}{L_2}$$

$$R_{2n} \equiv M_n W_2 = \left(\frac{M}{L_2}\right)^2 R_2, \qquad \phi_{2n} \equiv \left(\frac{M}{L_2}\right)\phi_2$$

where right-hand sides of equations are conventionally defined parameters or states. Suffixes 1, 2 indicate stator, rotor association and suffixes d, q do direct, quadratic component of 2x1 vector in synchronous frame.

The synchronous angular frequency ω is integrated to produce rotor flux position θ, θ is converted into a 2x1 position vector and finally low frequency part of position vector $F(s)[cos\theta_1 \quad sin\theta_1]^T$ is obtained by filtering it.

High frequency part of position vector is produced by vector signal in stationary frame as follows:

$$(1-F(s))\begin{bmatrix} cos\theta_2 \\ sin\theta_2 \end{bmatrix} = \frac{(1-F(s))}{\phi_{2nd}s}\left[\mathbf{v}_1 - (sL_{1t} + R_1)\mathbf{i}_1\right] \qquad (5)$$

Note that the filter (1-F(s))/s no longer have high-pass characteristics, it generally have band-pass or low-pass characteristics, and that it is as stable as desired, and does require neither pure nor approximated integration at all. This features make our direct scheme with embedded filter distinguished from conventional direct ones that take pure or approximated integration and is almost under unstable condition.

In situation that speed of rotor has to be controlled rather than torque, speed controller must be implemented, which requires rotor speed. In the hybrid vector control scheme, electrical angular speed of rotor can be easily and instantaneously estimated in the following manner

$$\hat{\omega}_s = \frac{R_{2n}}{\hat{\phi}_{2nd}} i_{1q} \qquad (6)$$

$$\hat{\omega}_{2n} = \omega - \hat{\omega}_s \qquad (7)$$

where $\hat{\omega}_s, \hat{\omega}_{2n}$ are estimate of slip angular frequency and estimate of angular speed of rotor, respectively.

Note that in the hybrid vector control scheme such estimates yielded from indirect part as rotor flux, stator flux, slip angular frequency, electrical speed of rotor can be utilized over all dynamic range. i.e. their validity is not restricted to low frequency range.

In practical realization, some of measured variables in the hybrid vector control can be replaced by associated estimates such as command signals.

4. TEST OF PERFORMANCE EVALUATION

In order to evaluate basic performance of the new hybrid scheme, evaluation test have been carried out using motors of different power 0.3 and 3.7 (kW). We show some results of the test where main design parameters are selected such as

Tab. 4 Features of the tested motor

R_1	3.7(Ω)	rated current	2.26(A, rms)
L_1	0.21(H)	rated d-current	1.4(A)
L_{1t}	0.023(H)	rated q-current	3.6(A)
W_2	23(Ω/H)	rated voltage	120(V, rms)
pole pair	1	moment of inertia J_m	0.75x10^{-4} (kgm^2)
rated power	300(W)	rated speed	300(rad/s)
rated torque maximum torque	0.955(Nm) 2.86(Nm)	effective resolution of encoder	8,000(p/r)

Stable filter: $F(s) = \frac{50}{s+50}$

Bandwidth of speed control: $\omega_{sc} = 120(rad/s)$

A. Test by machine of 0.3(kW)

Evaluation test was carried out using the following equipment:

Tested motor: 0.3(kW) induction motor AD301M-4030 made by Meidencha Corporation (see Table 4 for detail)

Inverter etc.: Inverter units made by MyWay Labs Co.

Load machine: Synchronous motor of inertia J =19.6x10^{-4}(kgm^2) and rated speed 200(rad/s) made by Mitsubishi Electric Corporation

1) Servo-tracking characteristics for variable speed command of high acceleration

In order to evaluate servo-tacking and speed estimating capabilities, and effectiveness of attained bandwidth of speed control, we injected variable speed command of high acceleration to the tested motor with no load.

Fig.1 shows a example of results where range of variable speed command is 0~600(rad/s) and its acceleration is 5,000(rad/s^2). Although relatively large error occurs around 150(rad/s) in speed increasing mode, it exhibits incomparably excellent servo-tracking and settling performance as a sensorless vector control. Note that the performance is attained not only in speed increasing mode but also in speed decreasing mode including zero speed. As a reference, response by the vector control using encoder information of 8,000(p/r) is illustrated in Fig. 2. Both control systems are designed and realized in the same way and specification except for processing on flux orientation and rotor speed. Fig. 3 shows a example of response to zero-speed command, which is especially interesting for sensorless vector. All of voltage command(Vv=10(V)), controlled current(iv=1(A)), speed response(0(rad/s)) are very steady as seen. No vibration in system response occurred at least for two hours observation

2) Steady characteristics for large inertia load

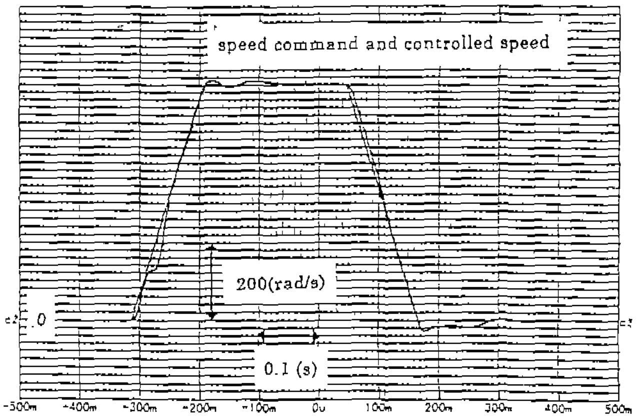

Fig. 1 Response of 2 poles 0.3(kW) induction motor to command of acceleration 5,000(rad/s²)

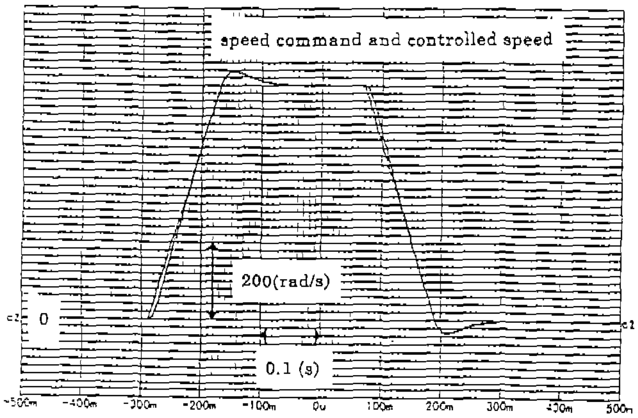

Fig.2 Reference response of 2 poles 0.3(kW) induction motor by standard vector control using 8.000 (p/r) encoder information

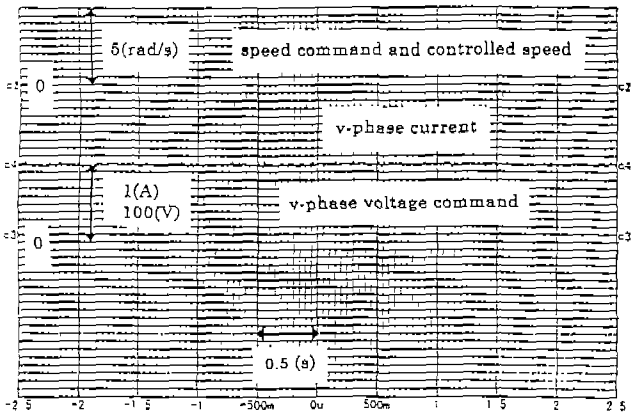

Fig.3 Response of 2 poles 0.3(kW) induction motor to command of zero speed

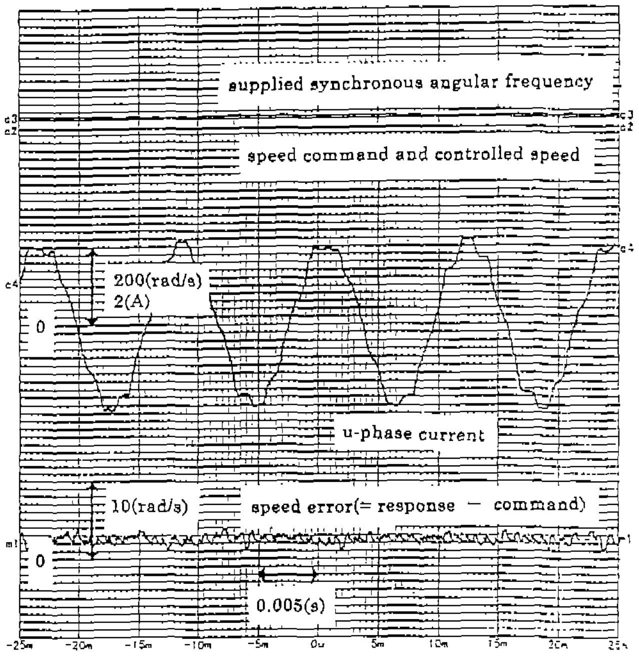

Fig. 4 Steady response of 2 poles 0.3(kW) induction motor to command of 500(rad/s) where load inertia ratio to the tested motor is about 26.

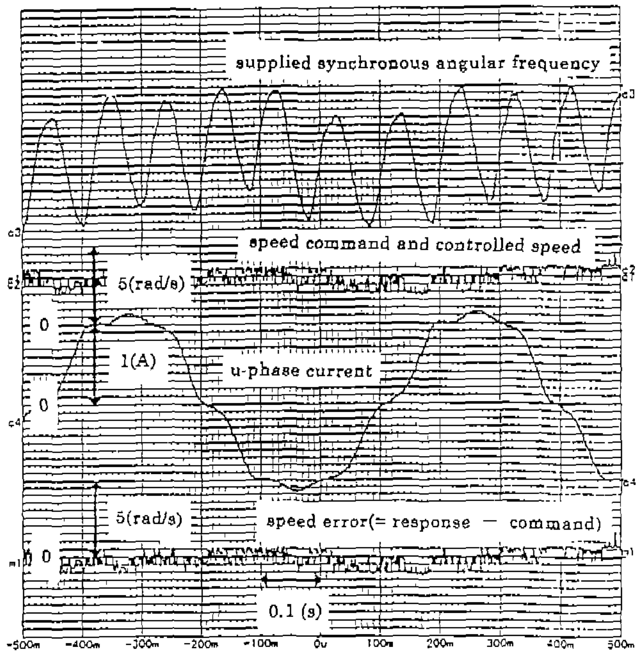

Fig.5 Steady response of 2 poles 0.3(kW) induction motor to command of 3(rad/s) where load inertia ratio to the tested motor is about 26

In order to evaluate large inertia accommodation, we connected load with the tested motor, where inertia of the load is 26 time bigger than that of tested motor, and injected constant speed command.

Fig. 4 shows the response to speed command of 500(rad/s) where we had to take load speed rating of 200(rad/s) into consideration. Plotted data indicates, from top, generated angular frequency of power, speed command and controlled speed as its response(measured by encoder of tested motor), u-phase current, speed error(controlled speed – speed command) respectively. It is observed that motor speed is well controlled within average error of about 2.5 (rad/s). As understood from the slip angular frequency, the load has friction of big enough for the tested motor as well.

Fig. 5 shows the response to the speed command of low speed 3(rad/s), which is 1/167 of the command for Fig. 6. Each data indicates the same meaning as in Fig. 6 although scaling of each axis is different. As observed, generated angular frequency of supplied power oscillates with amplitude of 3(rad/s), which is 1/200 of maximum speed. This oscillation of small amplitude can be seen over all speed range. It seems to be inevitable error for our sensorless vector control system using no additional sensor such as voltmeter.

B. Test by machine of 3.7(kW)

In order to examine motor power dependency of the hybrid vector control scheme, similar evaluation test was carried out using 3.7(kW) induction motor MVKC115A made by Fuji Electric Co.(see Table 5 for detail)

1) Servo-tracking characteristics for variable speed command of high acceleration

For evaluating servo-tacking and speed estimating capabilities, and effectiveness of attained bandwidth of speed control, we injected variable speed command of high acceleration to the tested motor with no load. Fig.6 shows a example of results where range of variable speed command is 0~150(rad/s) and its acceleration is 5,000(rad/s^2) which corresponds to 10,000(rad/s^2) in sense of electrical angular frequency. It exhibits incomparably excellent servo-tracking and settling performance as a sensorless vector control system similarly to the 0.3(kW) motor. As reference, response by the vector control system using encoder information of 8,192(p/r) is illustrated in Fig. 7. Fig. 8 shows a example of response to zero-speed command, All of voltage command, controlled current, speed response are very steady just like the case of the 0.3(kW) motor.

2) Steady characteristics

We examined steady response of non-zero speed. But for 3.7(kW) motor, we could not prepare large inertia simply due to some inconvenience.

Fig. 9 shows the response to speed command of 150(rad/s) Plotted data indicates from top, generated angular frequency of power, speed command and controlled speed as its response(measured by encoder of tested motor), speed error(controlled speed – speed command), u-phase current, respectively. It is observed that motor speed is well controlled within about ± 1(rad/s) error, and average error is almost zero.

Tab.5 Features of the tested motor

R_1	0.3(Ω)	rated current	19(A, rms)
L_1	0.0321(H)	rated d-current	18(A)
L_{1t}	0.0018(H) estimated	rated q-current	27.5(A)
W_2	38(Ω/H) estimated	rated voltage	180(V, rms)
pole pair	2	moment of inertia J_m	0.0163(kgm^2)
rated power	3.7(kW)	rated speed	150(rad/s)
rated torque	24.7(Nm)	effective resolution of encoder	8,192(p/r)

Fig. 10 shows the response to the speed command of very low speed 1.5(rad/s), which is 1/100 of the command for Fig. 9. Each data indicates the same meaning as in Fig. 9 although scaling of each axis is different. It is interesting to note that generated angular frequency of supplied power oscillates with amplitude of 3(rad/s) which is almost the same as in 0.3(kW) motor shown in Figs . 4 and 5.

5. CONCLUDING REMARKS

In this paper we show the some results of performance evaluation test for the newly developed hybrid vector control scheme for induction motors without position or speed sensor. It is confirmed to some extent through the test that the new sensorless scheme have potentiality of servo-performance, which is far away for previous schemes and sensorless drive apparatus.

We plan to pursue additional test using a large motor of 30(kW) class and also to install adaptive identification algorithm identifying adaptively stator and rotor resistances under driving. We expect these tasks increase the degree of completion of the scheme

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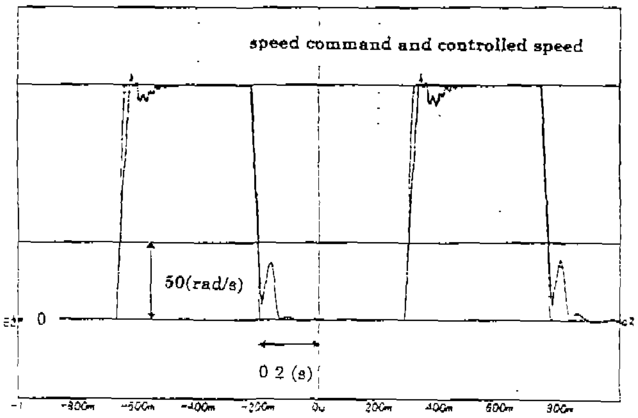

Fig. 6 Response of 4 poles 3.7(kW) induction motor to command of acceleration 5,000(rad/s^2)

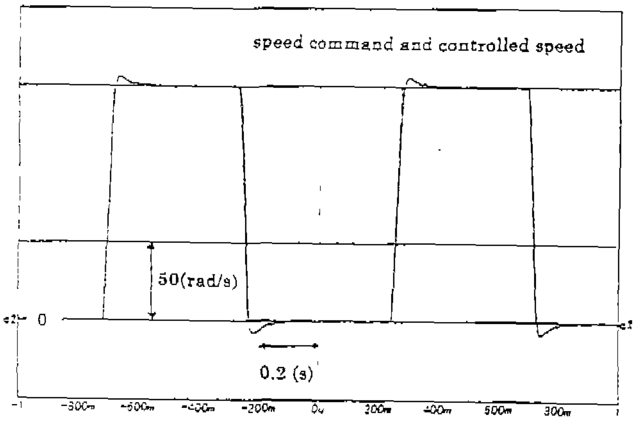

Fig.7 Reference response of 4 poles 3.7(kW) induction motor by standard vector control using 8,192 (p/r) encoder information

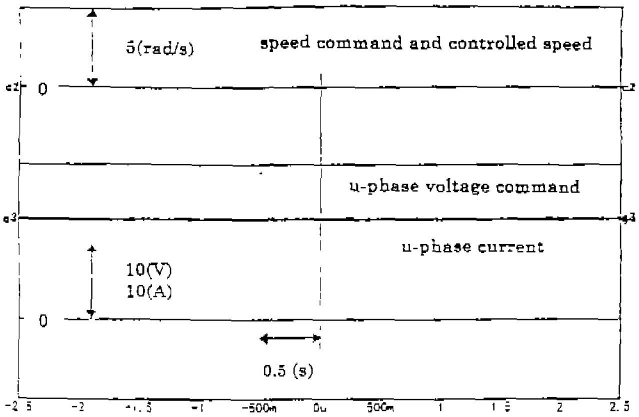

Fig.8 Response of 4 poles 3.7(kW) induction motor to command of zero speed

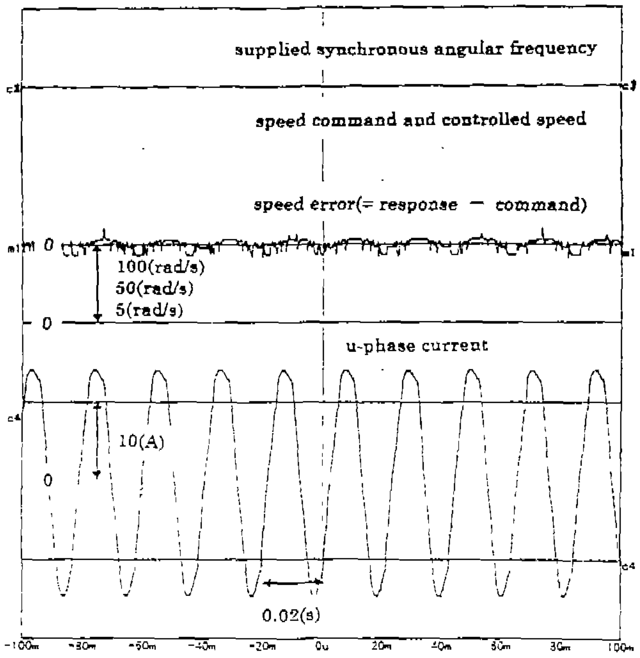

Fig. 9 Steady response of 4 poles 3.7(kW) induction motor with no load to command of 150(rad/s)

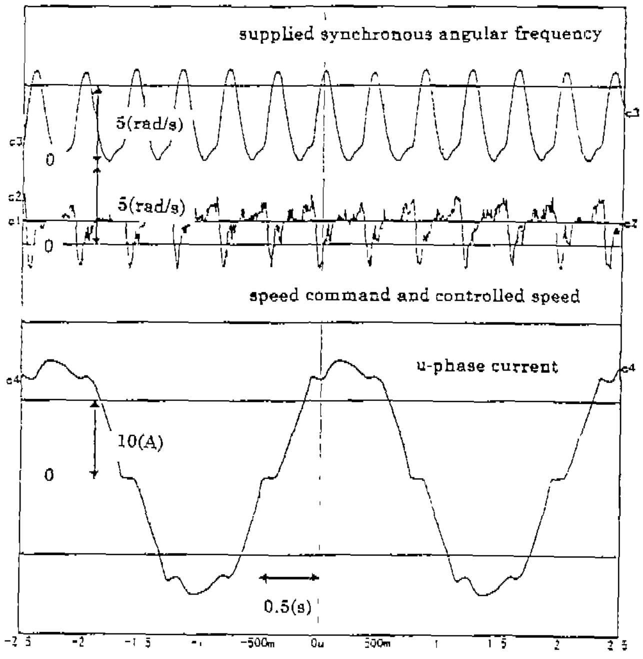

Fig.10 Steady response of 4 poles 3.7(kW) induction motor with no load to command of 1.5(rad/s).