High Performance Drives of Induction Motor with On-Line Tuning of Stator Transient Inductance in Field Weakening Region

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***Abstract*-Stator Transient inductance has much influence on rotor flux orientation. In this paper, a new simple on-line tuning scheme of inductances including stator transient inductance for rotor flux orientation control is proposed. Detuned effects caused by inductance variations are shown and simple on-line tuning scheme of them is proposed. Inductances are estimated and tuned by only stator flux and stator current. The proposed scheme is effective in wide speed region including the field weakening region. The proposed on-line tuning scheme is confirmed by the simulation and experiment results.**

NOMENCLATURE

Rs	:	Stator Resistance
Rr	:	Rotor Resistance
Lm	:	Magnetizing Inductance
Lls	:	Stator Leakage Inductance
Llr	:	Rotor Leakage Inductance
Ls	:	Stator Self Inductance
Lr	:	Rotor Self Inductance
$L\sigma$	:	Stator Transient Inductance
Tr		Rotor Time Constant

I. INTRODUCTION

Rotor flux orientation (RFO) control of induction motor has the merit of natural current decoupling between flux component and torque component. So the control scheme is simple and widely used. But it is sensitive to variations of parameter. So parameter variations must be considered for high performance drives.

Generally, the parameters of induction motor are varied with the change of operating condition [1]-[7]. So constant values of parameters, which are obtained from no load and locked rotor test, are not correct to real parameters except certain operating conditions. Rr and Rs are changed by temperature. In large size motor or the motor with deep bar, they are also changed by skin effect. Lm, Llr and Lls are changed by magnetic nonlinearity (as like saturation) and skin effect. These inductance variations are outstanding in field weakening region.

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Llr and $L\sigma$ are important for high performance drives[9]. In high speed region, voltage model is used for rotor flux estimation which is influenced by Rs, Llr and $L\sigma$. But, because Rs is varied slowly by temperature and voltage drop of Rs is very small in high speed region, the accuracy of rotor flux estimation is dominated by variations of Llr and $L\sigma$. Additionally, in recent studies on torque maximizing in field weakening region[10], the transition frequencies and current commands are determined by the functions of Llr and $L\sigma$. So these parameter variations must be considered for high performance drives, specially, in high speed region.

On-line estimation methods of $L\sigma$ have been studied [11][12]. Key ideas of these studies are high frequency signal injection. But conditions of the injected high frequency signal are different from real operating condition in aspect of frequency and amplitude. High frequency signals make stronger skin effects than real operating condition. Lower amplitude of high frequency signals makes difference caused by magnetic nonlinearity in leakage flux path. So the estimated values by those methods have some large error.

In this paper, new simple on-line tuning methods of Lm, Llr and $L\sigma$ are proposed. Stator current and estimated stator flux are used. Simulation and experiment results will show the usefulness of proposed scheme.

II. NEW SCHEME FOR ESTIMATION OF INDUCTANCES

The stator flux is estimated by the integration of back EMF, which is called as voltage model, as follow:

$$\lambda_s^s = \int (v_s^s - R_s i_s^s)dt \qquad (1)$$

Integration by pure integrator has the problems of drift and saturation. So the pure integrator is replaced by low pass filter (LPF).

$$\hat{\lambda}_s^s = \frac{1}{s+a}(v_s^s - R_s i_s^s) \qquad (2)$$

where '^' means estimated value.

Usually, Rs of (1) can be measured with accuracy and effect of its variation is negligible except very low speed range. So, by LPF of (2), the accuracy of estimated stator flux is determined. LPF of (2) makes errors of phase and magnitude. In this paper, compensation methods for the errors of LPF is used as like [13]

$$\hat{\lambda}_s^s = \frac{1}{s+a}(v_s^s - R_s i_s^s)\frac{\sqrt{\omega_e^2 + a^2}}{\omega_e}e^{-j\Phi} \qquad (3)$$
$$\Phi = 90^\circ - tan^{-1}\left(\frac{\omega_e}{a}\right)$$

The rotor flux can be given as

$$\hat{\lambda}_r^s = \frac{L_r}{L_m}\left(\hat{\lambda}_s^s - L_\sigma i_s^s\right) \qquad (4)$$

In synchronous frame (superscript 'e'), flux equations of induction motor are given as

$$\lambda_{ds}^e = L_s i_{ds}^e + L_m i_{dr}^e \qquad (5)$$

$$\lambda_{qs}^e = L_s i_{qs}^e + L_m i_{qr}^e \qquad (6)$$

$$\lambda_{dr}^e = L_m i_{ds}^e + L_r i_{dr}^e \qquad (7)$$

$$\lambda_{qr}^e = L_m i_{qs}^e + L_r i_{qr}^e \qquad (8)$$

When rotor flux orientation is achieved, $\lambda_{qr}^e = 0$ and, in steady state, $i_{dr}^e = 0$. So (5) and (6) is reduced as

$$\lambda_{ds}^e = L_s i_{ds}^e \qquad (9)$$

$$\lambda_{qs}^e = L_\sigma i_{qs}^e \qquad (10)$$

Through (3), (9), and (10), instantaneous values of $L\sigma$ and Ls with variations can be estimated as following

$$\hat{L}_s = \frac{\hat{\lambda}_{ds}^e}{i_{ds}^e} \qquad (11)$$

$$\hat{L}_\sigma = \frac{\hat{\lambda}_{qs}^e}{i_{qs}^e} \qquad (12)$$

It has been reported that Lls is hardly varied except very low range of magnetizing current because the stator slots of induction motor are open structure and the paths of stator leakage flux include airgap. So variation of Lls is neglected in normal magnetizing current level [7].

Therefore, the variation of Ls is caused mainly by the variation of Lm.

$$\Delta L_s = \Delta L_m + \Delta L_{ls} \approx \Delta L_m \qquad (13)$$

$$\hat{L}_m = \hat{L}_s - L_{ls} \qquad (14)$$

Also, Lls can be identified and initialized by (14) if Lm is accurately known. But (9), (11), (13) and (14) can be used only in steady state.

$L\sigma$ is hardly changed by the variation of Lm. $L\sigma$ is changed less than 3% when Lm is changed about 50%. But $L\sigma$ is proportional to Llr. $L\sigma$ is described by three parameters Lm, Lls, Llr as like (15). As before mentioned, Lls can be considered as constant. So in the (15), $L\sigma$ is changed by the variation of Llr.

$$L_\sigma = (L_m + L_{ls}) - \frac{L_m^2}{(L_m + L_{lr})} \qquad (15)$$

Therefore, Llr is estimated by $L\sigma$ as following

$$\hat{L}_{lr} = \frac{\hat{L}_m^2}{(\hat{L}_s - \hat{L}_\sigma)} - \hat{L}_m \qquad (16)$$

III. IMPLEMENYATION OF PROPOSED SCHEME

A. *Initialization of Parameters*

RFO must be promised before implementation of proposed scheme. For the achieving RFO, accurate parameter initialization is needed. Rs, Lm and Tr must be initialized for proposed scheme.

Lm is not changed if flux reference is not changed. So, if flux reference in constant torque region is determined, Lm is also determined and the value obtained by off-line methods can be used for initialization without additional initialization scheme. The value of Lm doesn't make much influence on in indirect RFO if Tr is accurately initialized and voltage model is used for rotor flux estimation. But accurate value of it is needed for estimating and initializing Lls. Lm can be measured independently by methods of [1].

Accurate value of Rs is needed for accurate flux estimation with voltage model. Rs of small size motors, which usually have large value of it, can be measured directly at the terminal of motors. In large size motors, resistance of power devices and dead time effect must be considered. Rs can be initialized more accurately by the method of [14].

Rs is estimated by (17). V_{ds}^e means voltage distortion due to dead time. V_{ds1}^{e*}, V_{ds2}^{e*} mean voltage command of D axis in steady state.

$$R_s = \frac{V_{ds1}^{e*} - V_{ds2}^{e*}}{I_{ds1}^e - I_{ds2}^e} \qquad (17)$$

Tr is the most important parameter for achieving indirect RFO because it is used in slip calculation. It can be initialized easily by observation of the output of speed controller when speed reaches to its command value. Fig. 1 shows the output of speed controller. Tr_con means the value that is used in controller

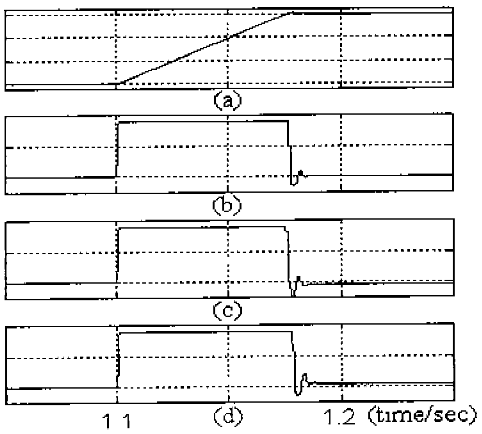

Fig. 1. Initialization of *Tr* (a) Speed, (b) I_{qs}^{e} at *Tr_con* =*Tr*, (c) I_{qs}^{e} at *Tr_con* <*Tr*, (d) I_{qs}^{e} at *Tr_con* >*Tr*.

B. On-Line Tuning of Inductances with Proposed Methods

With accurately initialized parameters for RFO, on-line tuning of inductances is performed. Direct use of (11), (12), (14) and (15) has some problem as like stability due to noise and interference of current controller. So, in this paper, PI type controllers are used.

Fig. 2 shows the block diagram of on-line tuning of inductances. Estimated $\hat{L}_{\sigma}$ and $\hat{L}_{s}$ are compared respectively with L_{σ_con} and L_{s_con} which are currently used in the field-oriented controller. Through PI controllers, L_{m_con}, L_{lr_con} are tuned and after that L_{s_con}, L_{σ_con} are updated. But, dark part of Fig. 2 is performed only in steady state of flux.

C. Overall Control Flow

At first indirect vector control of RFO is executed with accurately initialized parameters. After that, all inductances are identified by proposed scheme. And then, rotor flux is estimated by voltage model. Before the transition to field weakening region, indirect scheme is changed to direct

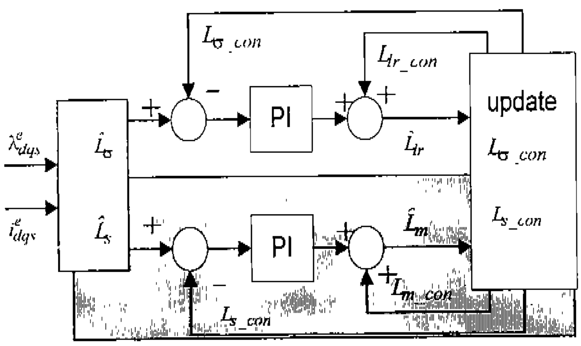

Fig. 2. Block diagram of on-line tuning of inductances.

by scheme with estimated rotor flux voltage model at *Wch*. Fig. 3 shows the control flow of RFO with proposed methods.

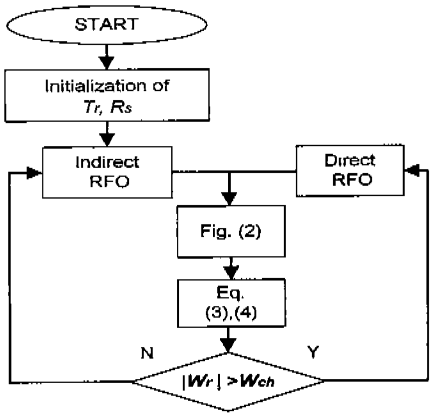

Fig. 3. Flowchart of RFO control with proposed on-line tuning scheme.

Ⅳ. Simulation And Results

A computer simulation was performed of the rotor flux-oriented system shown in Fig. 4 to evaluate the performance of the proposed tuning scheme using the software package of MATLAB/SIMULINK.

The parameters of induction motor which is used in this simulation and experiment are shown in Table Ⅰ.

Fig. 5 shows on-line tuning at 2.4 sec with proposed methods when speed command is 900 rpm with load torque of 7 Nm, considered that the controller has 1.5 times of real *Llr* and *Lσ*. After the system is tuned at 2.4 sec, RFO has been achieved. Fig. 5(a) shows that L_{σ_con}, which is used in controller, has been converged to the real value of motor. Fig. 5(b)shows that load torque has been exactly estimated.

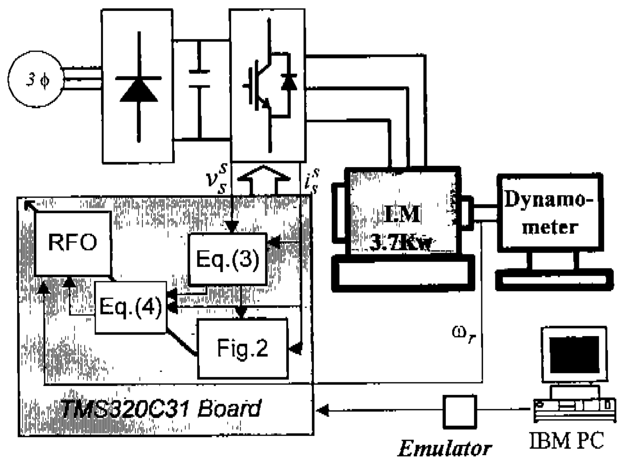

Fig. 4. Overall system for experiments.

Fig. 5(c) shows the estimated $\hat{\lambda}^e_{dr}$ has converged to reference value and $\hat{\lambda}^e_{qr}$ has been converged to zero.

Fig. 6 shows the performance of proposed scheme and sensitivity for mismatched L_{lr} and L_σ in field weakening region. In Fig. 6, rotor flux is weakened according to the reciprocal proportion of rotor speed. Speed command is changed from 1500 rpm to 2800 rpm with the load torque of 11.3 Nm. Each ***a*** shows the results when controller has the error of +50% of L_{lr} and each *c*, -50% of L_{lr}. Each ***b*** has correct value of L_{lr}. In the case of ***a***, flux is higher than that of ***b***. So, excessive back EMF is induced. So current control of torque component can be failed as shown in Fig. 6. In the case of ***c***, flux is lower than that of ***b*** and available torque is considerably deceased.

Fig. 7 show simulation results of maximum torque control strategy in field weakening region proposed by [14]. In this control strategy, transition frequency into field weakening region I (W_{base}) and that into field weakening region II (W_1) is determined by the function of L_{lr} and L_σ. Also, current commands in each region, are determined by the functions of L_{lr} and L_σ. The conditions of ***a***, ***b*** and ***c*** are equal to Fig. 6. Fig. 7 is divided at 1.2(*sec*) for changing the scale. Transition frequencies and current commands are given in [14].

Desirable results are in ***b***. W_{base} and W_1 of ***a*** are smaller than those of ***b***. W_{base} and W_1 of *c* are larger than those of ***b***. So, between W_{base} and W_1 of ***b***, ***b*** and ***c*** are in field weakening region I and developed torque are similar. But, after reaching at W_1, ***a*** and ***b*** are in field weakening region II and have similar developed torque. In other words, when controller has larger values of L_{lr} and L_σ than those of real motor, the performance in field weakening region I is more degraded. When controller has smaller values of L_{lr} and L_σ the performance in field weakening region II is more degraded. So accurate estimation and tuning of L_{lr} and L_σ are needed.

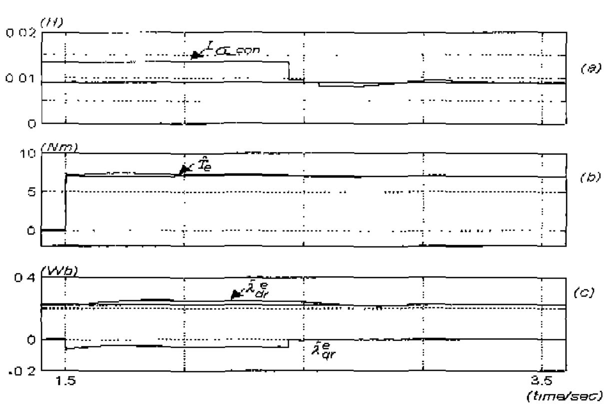

Fig. 5. On-line tuning in constant torque region.

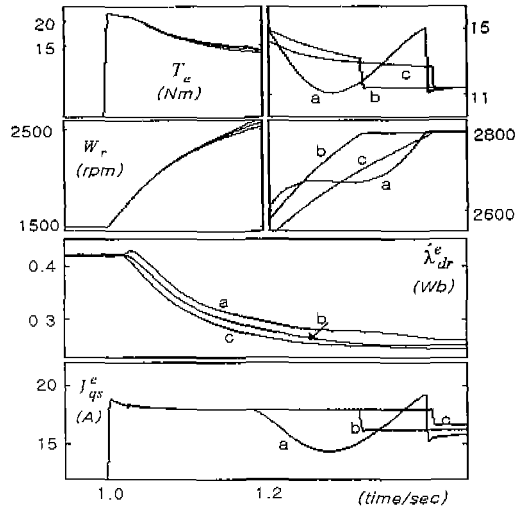

Fig. 6. RFO with flux weakening by reciprocal proportion of Wr.

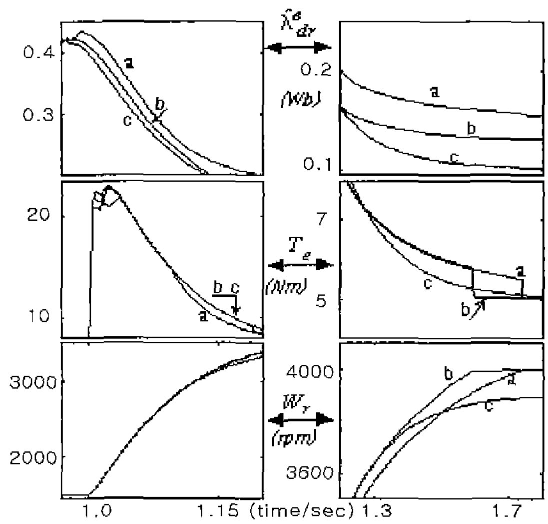

Fig. 7. Maximum torque control strategy in field weakening region (simulation)

V. EXPERIMENT AND RESULT

In order to verify the proposed tuning scheme, the overall system shown in Fig. 4 has been implemented. The input voltage of IGBT inverter is V_{dc}=330V. The switching frequency is 4 kHz. The current control period is T_c=125 μs. The speed and the flux control period are T_s=1.25 ms respectively. The tuning period of inductances is T_s=1.25 ms. The stator currents are detected through Hall-type sensors. The stator currents are sampled and held at every sampling instant, then A/D converted with 2 μs conversion time. The induction motor used in these experiment, is 3.7 Kw three phase induction motor with parameters of Table. I. This induction motor has open stator slot and closed rotor slot of single cage.

Fig. 8 shows that L_σ tuned well by proposed tuning scheme with the speed of 900 rpm and load torque of 5 Nm. In this experiment, L_{σ_con} is initialized to the value of 1.5 times of real value. $\lambda^{e}{}_{dr}{}^{*}$ is 0.225 Wb with 5 A of I^{e}_{ds} and 0.045 mH of Lm. $\hat{\lambda}^{e}{}_{dr}$ is slightly lower than the value in detuned condition and is converged to $\lambda^{e}{}_{dr}{}^{*}$ correctly after tuning. After tuning, field orientation is achieved, and $\hat{\lambda}^{e}{}_{qr}$ is converged to zero.

Fig. 9 shows the experiment results with the proposed scheme when ω_r^* is changed form 1500 rpm to 2800 rpm with base speed ($Wbase$) of 1600 rpm and load torque of 11.3 Nm. Control algorithm of flux weakening as to reciprocal proportion of rotor speed is used. This load torque is the maximum at the speed 2800 rpm. So speed cannot be increased more than 2800 rpm with the load torque of 11.3 Nm. $\hat{\lambda}^{e}{}_{qr}$ remains nearly zero by the tuning of inductances. It shows that the proposed scheme improves the performance of vector control in field weakening region.

Fig. 10 shows the variations of inductances at the same condition of Fig. 9. $\hat{L}_\sigma$ and L_{σ_con} are tuned well and decreased about 2 mH as speed is increased. Llr_con is also decreased about 2 mH. The decreases of them are assumed that it is caused by skin effect [7].

Fig. 11 shows the experiment results without proposed scheme with the same condition of Fig. 9. Developed torque is decreased by detuned effect. So increasing of speed is stopped at 2630 rpm. $\hat{\lambda}^{e}{}_{qr}$ is increased negatively. It shows that parameter variation and detuned effect is more severe in field weakening region.

Ⅵ. CONCULUSION

In this paper, simple on-line tuning methods of inductances of induction motor was proposed. $L\sigma$ and Ls were estimated from stator current and stator flux which the real operation condition. And then, Lm and Llr were tuned. Simple PI type controllers were used for implementation of on-line tuning.

For the proposed scheme, accurate initialization methods of Rs, Lm and Tr were reviewed.

Detuned effects caused by the variation of Llr are analyzed in two flux weakening control strategies

Simulation and experiment results showed that proposed methods were excellent in constant torque region and field weakening region.

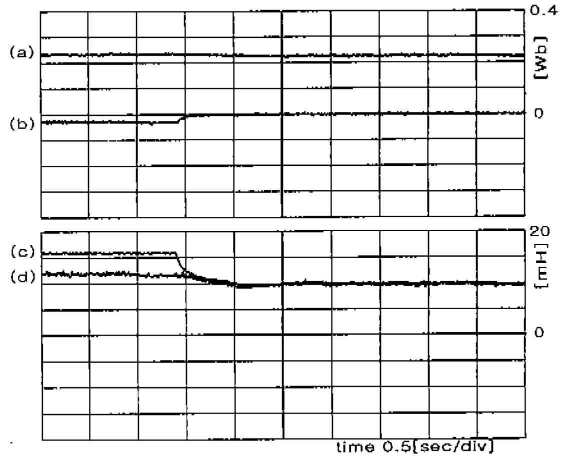

Fig. 8. On-line tuning in constant torque region.

(a) $\hat{\lambda}^{e}{}_{dr}$, (b) $\hat{\lambda}^{e}{}_{qr}$, (c) $\hat{L}_\sigma$, (d) L_{σ_con}.

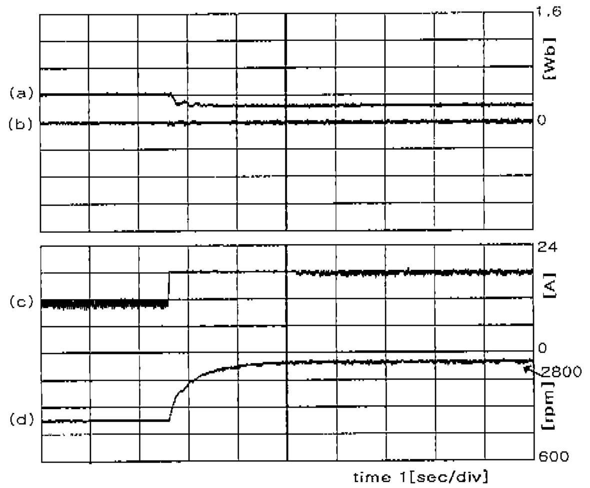

Fig. 9. On-line tuning in filed weakening region (a) $\hat{\lambda}^{e}{}_{dr}$, (b) $\hat{\lambda}^{e}{}_{qr}$ (C) i^{e}_{qs}, (d) ω_r [600 rpm/div]

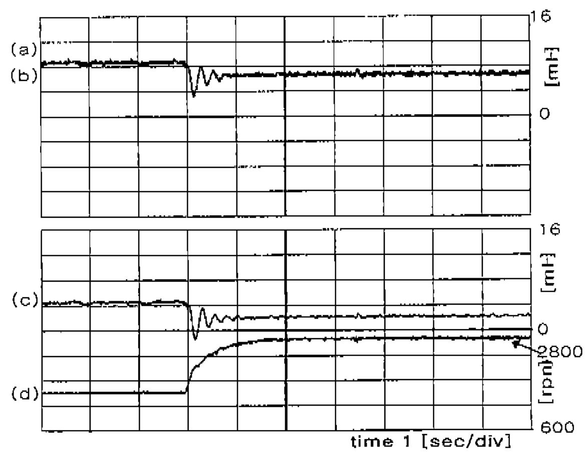

Fig. 10. Parameter variations at the same condition of Fig.11.

(a) L_{σ_con}, (b) $\hat{L}_\sigma$, (C) $\hat{L}_{lr}$, (d) ω_r [600 rpm/div]

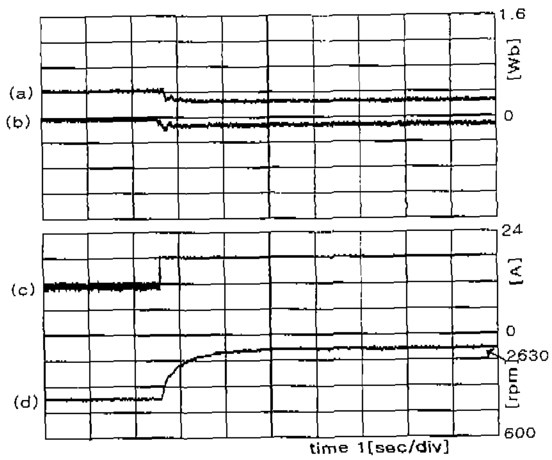

Fig. 11. Detuned effect in field weakening region at the same condition of Fig. 9. (a) $\hat{\lambda}^e_{dr}$, (b) $\hat{\lambda}^e_{qr}$, (C) i^e_{qs}, (d) ω_r [600rpm/div]

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Table.1 Parameters.

Induction Motor 3.7 [kW]				
Rs [ohm]	1.26		Lls [H]	0.0047
Rr [ohm]	0.27		Llr [H]	0.0051
Lm [H]	0.05		Pole	4