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확장영역 전기자동차 응용을 위한 유도전동기의 고효율 운전 특성

The High Efficiency Operating Characteristics of the Induction Motor for Extended Range Electric Vehicle Applications

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(Doo-young Ryu · Jin-geun Shon · Hee-jong Jeon · Uk-don Choi)

Abstract - In this paper, a high-performance control of the induction motor for electric car was implemented to escape dependence of the rare earth magnet. Proposed high-efficiency control algorithm is a Direct Rotor Field-Oriented Control method that is insensitive to the fluctuation of motor parameters. In the DRFOC method, we need to compensate fluctuation of stator transient inductance and magnetizing inductance caused by the magnetic saturation of induction motor in high-speed area. This paper proposes Back-EMF Observer based on stator current estimator of Luenberger style. Motor control system applied the Voltage Feedback Flux Weakening Control method for high-speed operation. The proposed algorithm was verified through tests by the power train of Extended Range Electric Vehicle consists of induction motor and differential gear.

Key Words : Back-EMF, Direct rotor field-oriented control(DFOC), Extended range electric vehicle, Induction motor

1. INTRODUCTON

A permanent magnet synchronous motor is extending its use in various industry field and electric car owing to its high efficiency and high rate of torque per unit volume. Recently the rare earth magnets monopoly gave rise to difficulties of demand and supply. And thus the induction motor is applied on propulsion system of electric car. The electric car motor drive system essentially requires the maximum torque control under the high speed area since the electric car is operated by rapid response and wide speed range. Constant output operation is necessary for the high-speed driving[1, 2].

In this case, Field Weakening Control is adequate for obtaining maximum torque under the limited current and voltage conditions. Since the Flux Weakening operation should have the accurate rotor magnet information of the motor parameters, the Field Weakening Control is required in order to endure the load change and motor constant fluctuation under the high speed condition. The industrial induction motor uses Indirect Rotor Flux Oriented Control (IRFOC) due to easy to implemented, however, the IRFOC is sensitive in rotor time constant fluctuation. As the rotor time constant is affected by the temperature and load conditions, it is difficult to estimate it secret value. This research applies Direct Rotor Flux Oriented Control(DRFOC), which estimates the rotor flux position, in order to complement the IRFOC weak point sand satisfy the electric car driving system performance[3, 4].

In particular, it suggested the Complex Vector PI Current Controller (CVPICC) and State filter based Back EMF Observer by means of the Synchronous Coordinate PI Current Controller for back electromotive force compensation. And Field Weakening Control of Voltage Feedback method was proposed instead of Feed Forward compensation Field Weakening Control for high-speed driving. Gopinath style is used as magnetic Flux Observer with current model in low-speed and voltage model in high-speed. Furthermore, this paper suggested the back electromotive force observer which is composed of Luenberger-style stator current estimator having State Filter characteristic.

The back electromotive force observer helps stable performance in high-speed and it has State Filter characteristic for eliminating the stator transient inductance and magnetization inductance fluctuation effect. This paper applied the suggested algorithm to induction motor (continuous 50[kw], maximum 100[kw]) of the power train for electric vehicle propulsion, Extended Range Electric Vehicle (EREV) driving Inverter

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(composed of continuous output 20[kw] GENSET) and verified its validity through simulations and EREV tests.

2. SYSTEM CONFIGURATION

Extended Range Electric Vehicle (EREV) System is composed of propulsion motor and reducer, propulsion motor controlling Inverter(Motor Control Unit; MCU), generating engine, generator with controlling appliances (Generator Control Unit; GCU) and battery. This research uses E segment size “GENESIS” for EREV that propulsion system drives the wheels by 3.909:1 differential gear and induction motor without reduction gear; 8 poles, rated speed 2,000[rpm], maximum 5,000[rpm] and continuous output 50[kw], maximum 100[kw]. EREV is added to the engine and generator as a means to extend the mileage of existing EV. Figure 1 shows system concept. Figure 2 is the system configuration of EREV.

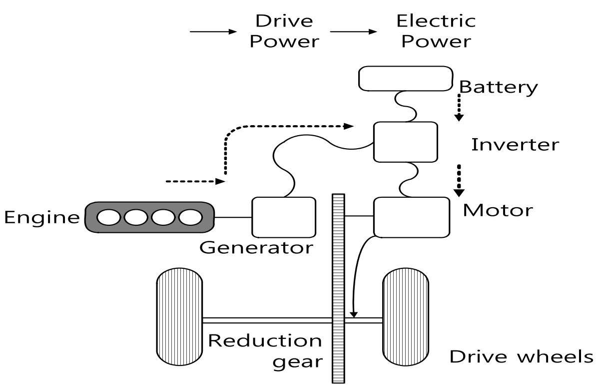

Fig. 1 System concept of EREV

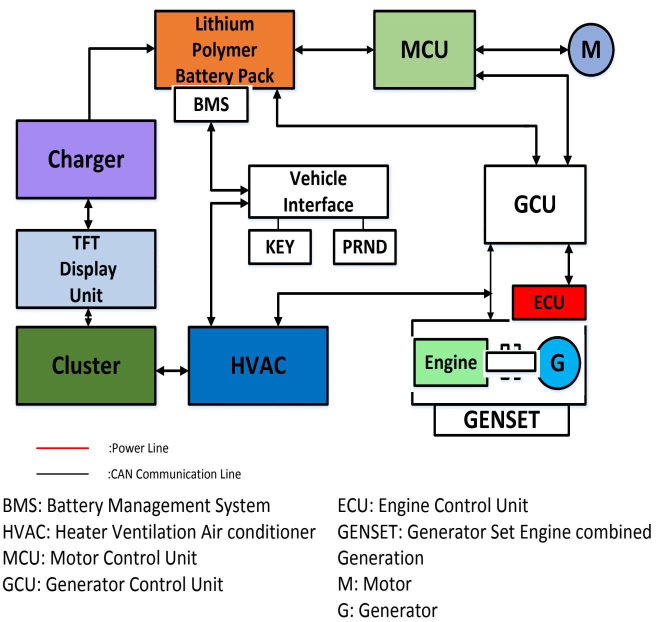

Fig. 2 System configuration of EREV

3. CONTROL ALGORITHM

3.1 Direct Rotor Flux Oriented Control

Flux Oriented Control is adequate for high performance control of induction motor. FOC is the method for the instantaneous torque control of induction motor. It separately controls the magnetic flux in motor and torque generating current according to the position of rotor magnetic flux such as controlling Direct Current motor. There are several significant preconditions to control the induction motor for electric vehicle such as estimation of parameters variable and measurement of magnetic flux position of motor. Direct Rotor Flux Oriented Control (DRFOC) directly estimates magnetic flux and finds the rotor magnetic flux position. DRFOC magnetic flux observer is constructed by Gopinath style. It uses motor current model in low-speed and voltage model in high-speed.

Since electric car motor frequently drives in high-speed, DRFOC uses stator resistance and transient leakage inductance under the high-speed mode. When the motor is overloaded, only leakage inductance affects the magnetic flux estimation, the advantage is robust to changes in the motor constants. Suggested Gopinath method magnetic Flux Observer can estimate accurate magnetic flux under the weak field area.

3.2 Flux Controller

When DRFOC performed perfectly, the rotator d axis of Synchronous Coordinates equation regarding magnetic flux is explained by the equation (1).

$$p\lambda^{e}_{dr} = r_r \frac{L_m}{L_r} i^{e}_{ds} - \frac{r_r}{L_r}\lambda^{e}_{dr} \qquad (1)$$

Rotating coordinate system stator d axis current can control rotor d axis magnetic flux as shown in equation (1), thus PI controller output is choose in stator d axis. Figure 3 shows applied composition of flux controller.

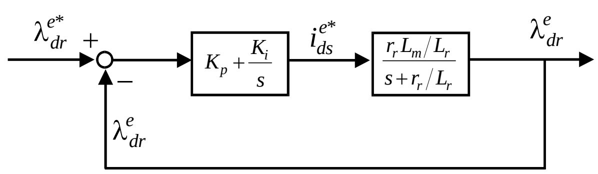

Fig. 3 Flux controller

3.3 Flux Weakening Control of Voltage Feedback Method

In case of Feed Forward Method flux weak driving, the driving stability is low owing to sensitive for parameters fluctuation. In order to overcome that weakness, this research realized Field Weakening Control of Voltage Feedback Method. It was the problem that Feed Forward Method field weakening driving mode turns up unnecessarily under the high speed light loading condition. Then, Field Weakening Control of Voltage Feedback Method solves the problem through the current controller output reflects both driving speed and loading condition. This is less sensitive from appliance parameters fluctuation than IFROC since it solely uses the current controller output. Figure 4 is block map of Field Weakening Control of Voltage Feedback Method.

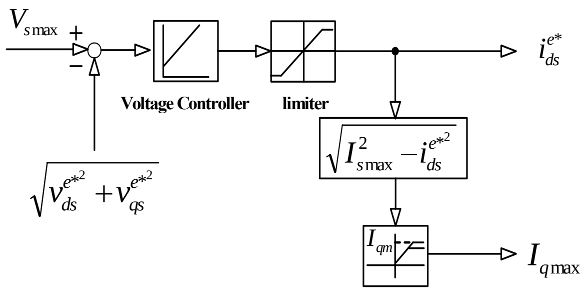

Fig. 4 Field Weakening Control of Voltage Feedback Method

The Voltage Feedback Flux Weakening Control method compared to the maximum available voltage and current voltage, Voltage Feedback Flux Weakening Control method is always using the maximum voltage in the field weakening control. Therefore, Voltage Feedback Flux Weakening Control is more efficient than Feed Forward Compensation method.

3.4 Parameter compensation with State Filter style Back EMF Observer

DRFOC and Flux Weakening Control method are insensitive to motor constant, however both stator transient inductance and magnetization inductance are affected by magnetic saturation in high speed. Fig 5 shows the Complex Vector based PI Current Controller. In order to complement those constant fluctuation effects, the Complex Vector method - back electromotive force estimator is required. The applied back electromotive force is Luenberger style. It is based on current estimator and has State-Filter characteristic. The voltage from motor current controller is expressed as follow.

$$\mathbf{v}^e_{dqs} = (sL_\sigma + R_s)\mathbf{i}^e_{dqs} + R_r\left(\frac{L_m}{L_r}\right)^2 \mathbf{i}^e_{dqs} + \mathbf{j}\omega_e L_\sigma \mathbf{i}^e_{dqs} - \frac{L_m}{L_r}\left(\frac{R_r}{L_r} - \mathbf{j}\omega_r\right)\boldsymbol{\lambda}^e_{dqr} \quad (2)$$

The difference between equation (2) and back electro-motive force observer output is equal to equation (3).

$$\mathbf{v}^e_{dqs} - \hat{\mathbf{v}}_{dq\_D} = \left(s\hat{L}_\sigma + \hat{R}_s\right)\hat{\mathbf{i}}^e_{dqs} \quad (3)$$

By solving simultaneous equations with equation (2) and (3), the back electromotive force estimation is found.

$$\hat{\mathbf{v}}_{dq\_D} = \left[\frac{s^2 b_o + sK_o + K_{io}}{s^3\hat{L}_\sigma + s^2(b_o + R_s) + sK_o + K_{io}}\right] \times \left[(s\Delta L_\sigma + \Delta R_s)\hat{\mathbf{i}}^e_{dqs} + R_r\left(\frac{L_m}{L_r}\right)^2 \mathbf{i}^e_{dqs} + \mathbf{j}\omega_e L_\sigma \mathbf{i}^e_{dqs} - \frac{L_m}{L_r}\left(\frac{R_r}{L_r} - \mathbf{j}\omega_r\right)\boldsymbol{\lambda}^e_{dqr}\right] \quad (4)$$

$$\cong \begin{cases} -\omega_e L_\sigma i^e_{qs} \\ \omega_e L_s i^e_{ds} \end{cases}$$

Where, $\Delta L_\sigma = L_\sigma - \hat{L}_\sigma$, $\Delta R_s = R_s - \hat{R}_s$,back EMF as well as L_σ and L_s can be estimated. The proposed State Filter style Back EMF Observer is showed in Figure 5.

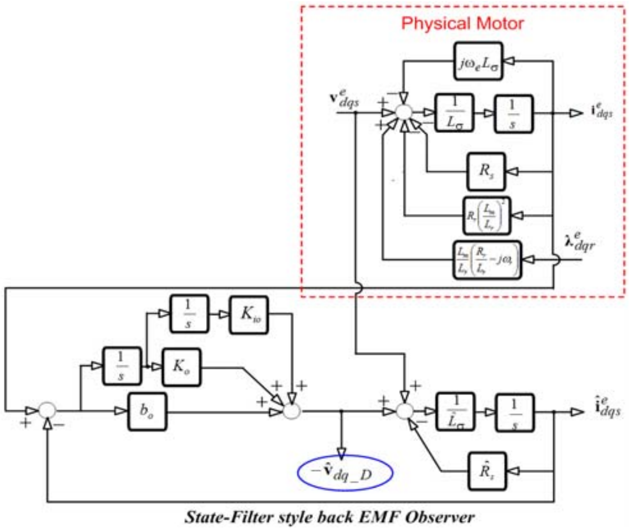

Fig. 5 State Filter style Back EMF Observer

3.5 Complex Vector PI current Controller

The accurate inductance value is necessary to eliminate mutual current interference component in the existing Synchronous Coordinates PI Current Controller. The inductance value error cannot remove the mutual interference component and declines the current control performance. Exceptionally, the error is 0 in the normal state. The integrator, which the current controller has, bears mutual current interference component from inductance error. In order to overcome the structural fault of Synchronous Coordinates PI Current Controller, Complex Vector based PI Controller was proposed. The Complex Vector PI Current Controller irrespectively the speed of pole, always pole-zero cancellation is occurred. Therefore it is suitable for high-speed driving. In addition, R-L error is solved by separately inserting the damping resistance which improves the controlling performance.

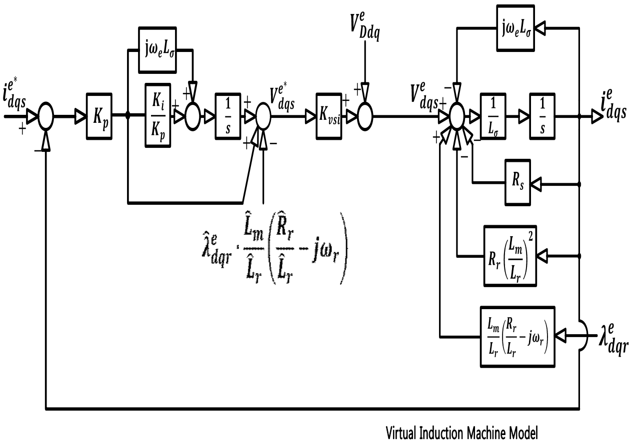

Fig. 6 Block diagram of Complex Vector PI Current Controller of implemented IM

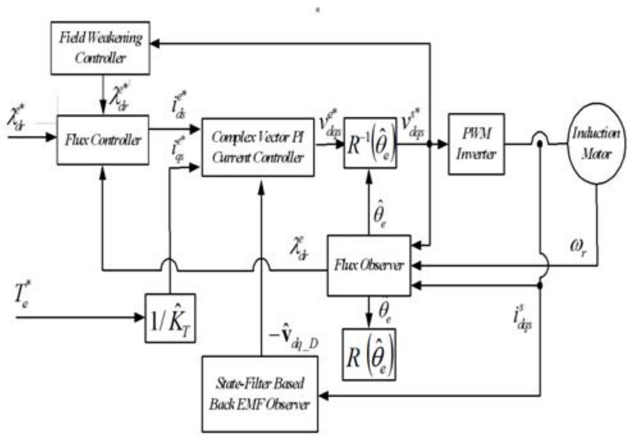

Fig. 7 Entire control block diagram of the proposed algorithm

4. SIMULATION

The characteristics of the torque variation due to the parameter errors of IRFOC and DRFOC are shown in Figure 8 and Figure 9.

Figure 8 is simulation result of the rate of torque changing due to the IRFOC parameter errors such as rotor resistance, mutual inductance, and transient inductance Lsigma. Simulation result of the rate of torque changing due to the DRFOC parameter errors are shows in Figure 9.

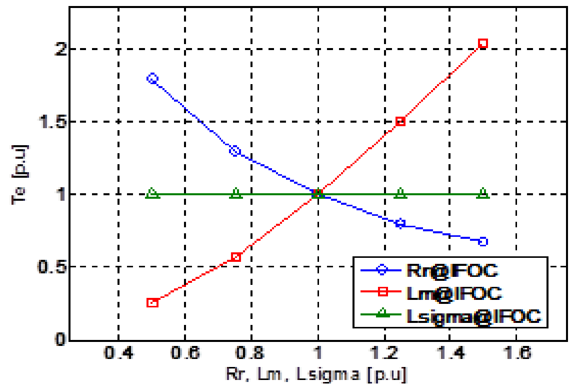

Fig. 8 Simulation results of the rate of torque changing due to the IRFOC parameter errors

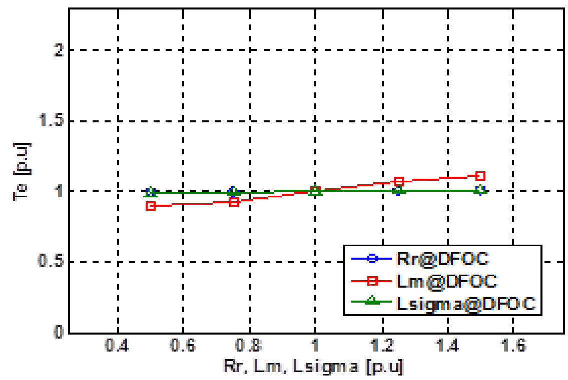

Fig. 9 Simulation results of the rate of torque changing due to the DRFOC parameter errors

As shown in Figure 8, IRFOC is very sensitive to the variation of the rotor resistant and mutual inductance. On the other hands, DRFOC can be found insensitive to the variation of the parameters. As shown in Figure 9, Torque fluctuation due to changes in the parameters of the DRFOC is accurate within 5[%].

The simulation results of DRFOC are shown in Figure 10 and Figure 11. In case of ± 25[%] fluctuation

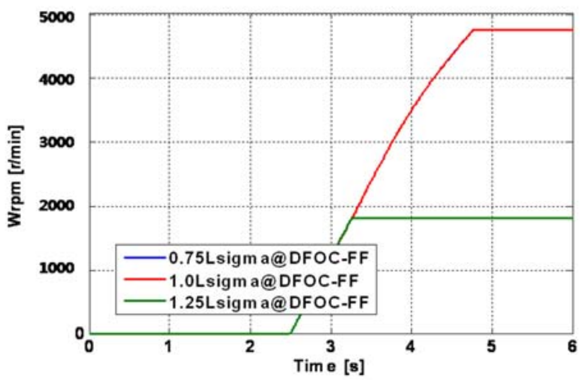

Fig. 10 The response characteristics of maximum speed of feed forward flux weakening control method according to the change of Lsigma

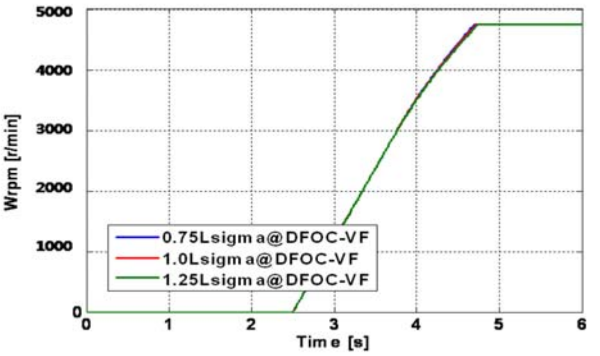

Fig. 11 The response characteristics of maximum speed of voltage feedback flux weakening control method according to the change of Lsigma

of the transient inductance, the motor speed did not reach up to the top speed like indicated in Figure 10. On the other hand, when the Voltage Feedback Flux Weakening Control method is applied as shown in Figure 11 the motor speed was reached up to the top speed. Figure 10 indicates results of the Feed Forward Flux Weakening Control method. Figure 11 is results of Voltage Feedback Flux Weakening Control method.

5. TEST RESULTS

5.1 Environment of Test

Figure 12 is induction motor for EREV. Figure 13 shows the speed of the motor torque output characteristics. 238[Nm] continuous torque and the maximum torque of 477[Nm], and the rated speed of 2,000[rpm] and a maximum speed of 5,000[rpm] and the maximum line-to-line voltage is 175[V]. Figure 14, the scene is to test the performance of the motor using a dynamometer. Figure 13 shows the component placement EREV.

Figure 15 shows arrangement of the electrified parts of the EREV. The propulsion system is the rear-wheel-drive. The main battery is placed in the trunk, and the GENSET, MCU, etc. were placed engine room.

Fig. 12 Photos of the Induction motor for EREV

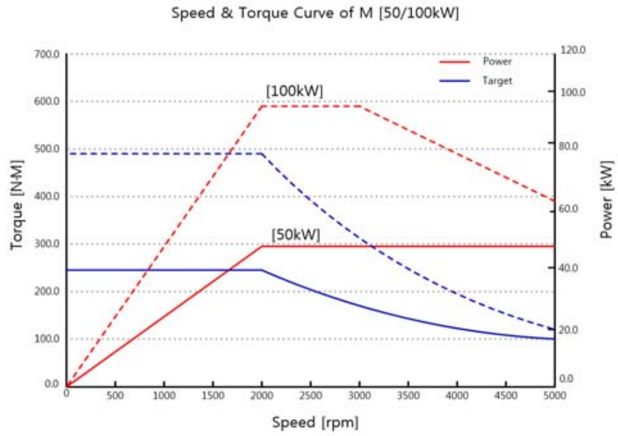

Fig. 13 Speed-torque curve and output power of the motor for EREV

Fig. 14 A scene of the motor performance test

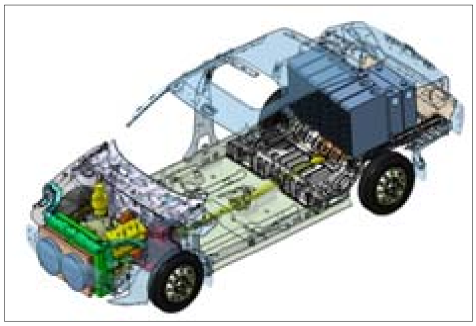

Fig. 15 An arrangement of the electrified components of EREV

5.2 Testing Results

The measurement results torque fluctuation due to parameter errors was consistent with the simulation results. Figure 16 is showing testing scene of EREV at the chassis dynamometer. Figure 17 is the graph, which measures the torque fluctuation rate of parameter error in IRFOC, has similar result with simulation result. When the rotator resistance and transition inductance Lsigma change, the torque fluctuate heavily. On the contrast, DRFOC has rare torque fluctuation in accordance with the parameter errors. As shows in Figure 18, the rate of

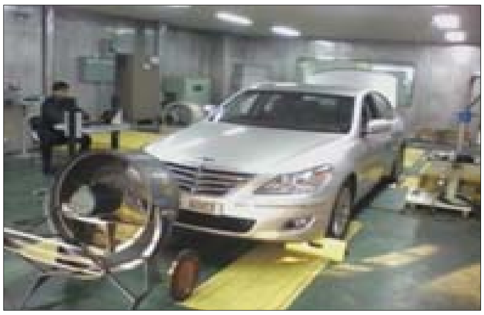

Fig. 16 Testing scene of EREV at the chassis dynamometer

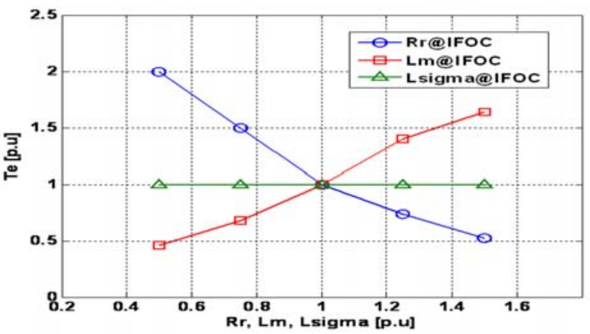

Fig. 17 Test results of the rate of torque changing due to the IRFOC parameter errors

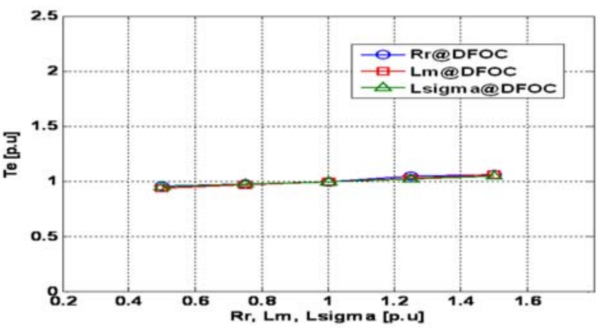

Fig. 18 Test results of the rate of torque changing due to the DRFOC parameter errors

torque variation was less than 5[%]. DRFOC is verified that it strongly endures from the parameter error.

In order to verify the validity of the suggested algorithm, EREV acceleration test was performed at the proving ground. As a result, the acceleration time takes 12.4 sec from 0km/h to 100km/h. Proposed algorithm was consistent with the calculated results.

6. CONCLUSION

This paper applied Direct Rotor Flux Oriented Control method to the power train of Extended Range Electric Vehicle in order to obtain stable operating characteristics under the whole electric car speed area. In the Gopinath style Flux Observer, the current model was used in low-speed mode while the voltage model was conducted in high-speed. This research applies Voltage Feedback Field Weakening Control which insensitive to parameter variations and reflects the speed and load conditions, in order to complement the Feed Forward Field Weakening Control weak points and satisfy the electric vehicle driving system performance. Particularly Complex Vector style Back EMF Observer was used in order to compensate for the stator transient inductance and the magnetizing inductance fluctuation due to magnetic saturation in the high-speed area. It proposes Back-EMF Observer based stator current estimator of Luenberger style having State Filter characteristic. The proposed algorithm was verified through test by Extended Range Electric Vehicle propulsion system consist of induction motor without reduction gear. Acceleration test result of EREV showed a stable behavior for all speed area. The result of parameter estimation in the field weakening region showed a stable control performance. Proposed algorithm coincided with simulation results.

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