AN EFFICIENCY OPTIMIZED OPERATION OF INDUCTION MOTOR DRIVE SYSTEMS FOR ELCTRIC VEHICLES

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ABSTRACT-The induction motor of the electric vehicles is controlled based on the vector control method to obtain good torque control characteristics. In the conventional vector control system, the field exciting current should be kept on a constant value to keep a stable flux level.

This method has a liability that core loss becomes increasing at the light load region. To solve this liability, the efficiency maximizing control method of the vector controlled induction motor is n proposed in thid paper. We developed light weight water cooled 60kW induction motor drive system which adopts our method and fabricated a conversion electric car for actual vehicle test We demonstrate the usefulness of drive system by comparing its driving mode with conventional field oriented system and an efficiency maximizing controlled induction motor.

1. INTRODUCTION

In recent years, the use of AC Induction motor has become mainstream for driving Electric Vehicles. The induction motor for electric vehicle should be satisfy volume, weight, velocity, efficiency, reliability, cost and robustness.

The induction motor is a high efficiency machine when operating close to its rated power point. However, in an EV system, the motor is frequently working in the entire possible operation region in the torque-speed plane. Therefore, in the case of driving at light load torque region, the proportion of core loss becomes increasing. To solve this problem, the developed efficiency maximizing control method is required.

The switching losses of the IGBT are a main part of the inverter losses in opertion. We adopted the overmodulatin strategy for induction motors. This allows less inverter pulses at high speed and more peak power capability at high speed region. In this paper, a comparision of power consumtion value is presented for the highway driving mode and city driving mode. We confirmed the validity of the efficiency maximized control in an EV through simulation and vehicle test.

2. CONFIGURATIONS OF DRIVE SYSTEM

The drive system is comprises of sevral components like motor, controller(inverter, dc/dc converter, on-board charger) and differential gear uint.

2.1 Characteristics of the motor

We designed 60kW induction motor for a compact passanger vehicles. In order to reduce iron loss, laminations of the stator and rotor are made with thin silicon steel plate, the frame and endbells are made by aluminum casting to reduce weight.

The forced liquid cooling system is adapted to effective cooling. The power density of the motor is more then 1.0[kW/kg]. The motor specifications are shown in Table 1. Photo.1 is overview of induction motor for EV.

Table 1. Motor Specifications

Motor specifications		
Maximum power	[kW]	60
Efficiency	[%]	93
Maximum torque	[Nm]	140
Rating voltage	[V]	195
Number of poles	[pole]	4
Base speed	[rpm]	3,600
Maximum speed	[rpm]	10,000
Primary resistance	[mΩ]	20.77
Secondary resistance	[mΩ]	10.37
Core loss resistance	[mΩ]	81.03
Magnetizing inductance	[mH]	3.468
Leakage inductance	[μH]	97.03
Weight	[kg]	57

Photo.1 Overview of the induction motor for Electric Vehicle

2.2 Control method of the inverter

The specifications of controller are shown in Table 2. The electric vehicle drive system is required high efficiency, accurate torque control and high reliability. In this paper, direct field oriented control method is adopted using the closed loop flux observer to obtain exact flux information for stability of controller and advanced performance. In this method, flux of the induction motor can be illustrate voltage model using the stator voltage equation and current model using the current model of rotor respectively. These model can be change depending on the motor speed. These model is consist with PI controller. In the low speed region, current model flux observer is applied and in the high speed region, voltage model flux observer is applied. In this case, the selection of the gain of the PI controller and sampling time *Ts* are very important. The system bandwidth and change over frequency of current model and voltage model is decided by constant k1, k2 of PI controller. In the direct field oriented control system, flux magnitude λ_r, q axis flux λ^s_{qr}, d axis flux λ^s_{dr}, flux position θ_e is obtained by the closed loop flux observer. The flux magnitude λ_r and flux position θ_e is expressed with,

$$\lambda_r=\sqrt{\lambda_{qr}^{s2}+\lambda_{dr}^{s2}} \qquad (1)$$

$$\theta_e=\tan^{-1}\left(\frac{\lambda^s_{qr}}{\lambda^s_{dr}}\right) \qquad (2)$$

respectively.

Table 2. Controller specifications

Controller specifications		
Inverter peak output [1min]	[kva]	90
Output frequency	[Hz]	400
On-board Charger	[kW]	6.6
Input voltage [dc]	[V]	250-405
DC/DC Converter	[kva]	1.35
Weight	[kg]	30

The blockdiagram of closed loop flux observer is shown in Fig.1. Photo.2 is overview of the controller

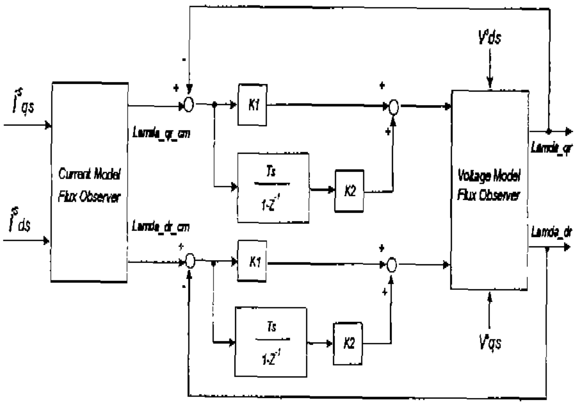

Fig.1 Blockdiagram of Closed Loop Flux Observer

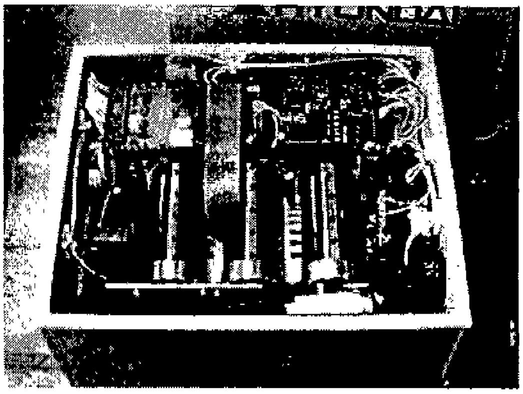

Photo.2 Overview of the controller

3. EFFICIENCY OPTIMIZING CONTROL OF THE INDUCTION MOTOR

3.1 An efficiency optimizing Condition

In the conventional vector control, the motor input current is controlled by torque component and exiting component current separatly, the exiting current is controlled to be approximately constant from 0 speed to rating speed except constant output power operation.

Therefore in this operation area, the percentage of core loss in the total loss increases at light loads. This is caused by a problem of the efficiency decrease.

An efficiency optimized control is very important to extend the travelling distance per charge, in the induction motor for electric vehicle. The Fig.2 is T-type equivalant circuit of vector controlled induction motor. From this equivalant circuit, constants are below.

$$L\sigma=\frac{(L1L2-M^2)}{L2} \qquad (3)$$

$$Rc=\alpha\frac{(\omega M)^2}{Rn}\cdot R2'=\alpha^2R_2\cdot M'=\alpha M\cdot \quad \alpha=\frac{M}{L^2}$$

$$Rn'=\alpha Rn$$

Here, $L1$, $L2$:primary, secondary self inductance, $R1$, $R2$:primary, secondary resistance, M:mutual inductance, Rn:core loss resistance, ω:power angular frequency, p:number of pole pair

In the Fig.2, Io' is the exiting current and I_t is torque current. Primary current I_1 is expressed as shown in equation (4).

$$I_1=\sqrt{(I_t+I_c)^2+I_{o'}^2} \qquad (4)$$

Where, I_c is the core loss current and T is the torque.

$$I_c=\omega M'\frac{I'_o}{Rc}=Rn\frac{I'_o}{\omega M} \qquad (5)$$

$$T=3pM'I'_oI_t \qquad (6)$$

Total loss of the induction motor is expressed as below.

W_{total}=stator copper loss+rotor copper loss +stator & rotor iron loss+mechanical loss.

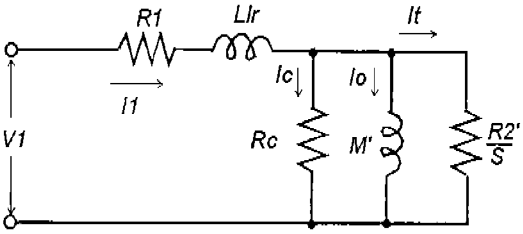

Fig.2 T-type equivalant circuit of vector controlled IM

The ratio of the torque current and the exiting current for efficiency maximizing control is as follows

$$\beta=\frac{I_t}{I_o} \qquad (7)$$

The induction motor loss can be expressed as a function of β.

$$Wtotal=(R1+R2)\frac{T}{pM'}\beta+(R1+Rn')\frac{T}{(pM'\beta)}+2\frac{Rn}{(\omega M)}\frac{R1T}{(pM')}+Wm \qquad (8)$$

To maximize the motor efficiency at any load condition, the loss at the opertion status should be minimized. By solving for a through $\frac{dWtotal}{d\beta}=0$, the conditions for optimizing the efficiency can be obtained and expressed with equation (9)

$$\beta=\sqrt{\frac{(R1+Rn')}{(R1+R2')}} \qquad (9)$$

Therefore the opimal value of the exiting current can be obtained with expression(10)

$$Io'^{*} = \sqrt{\frac{T^{*}}{3pM'\beta}} \qquad (10)$$

The Fig.3 is blockdiagram of efficiency maximizing control system. In this figure, $I^{*}ds$ is as same as $I_o'^{*}$of the equation (10).

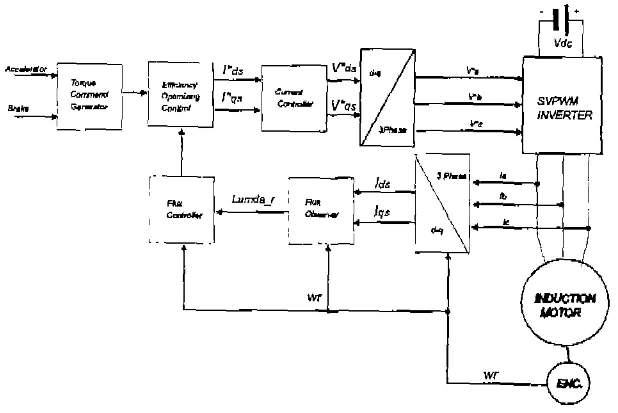

Fig.3 Blockdiagram of efficiency maximizing control system

3.2 Comparison of drive system characteristics

The control characterisitics of induction motor drive system is compared with vector control method and efficiency optimized control by computer simulation.

The Fig.4 is simulation result of the voltage and current characteristics of the vector controlled induction motor. The Fig.4 is illustrate from the top, full load current, full load voltage, no-load voltage, no-load current respectively. The Fig.5 is simulation result of the voltage and current characteristics of efficiency maximizing controlled induction motor.

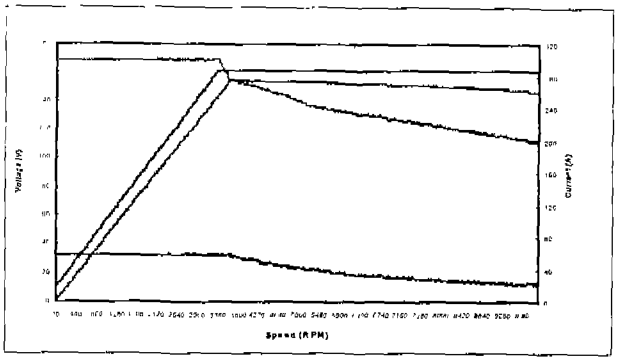

Fig.4 Vector controlled induction motor

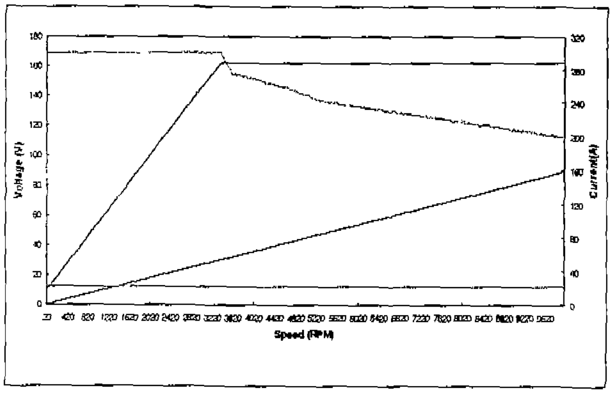

Fig.5 Efficiency maximizing controlled induction motor

The Fig.5 is illustrate from the top, full load voltage, full load current, no-load voltage, no-load current respectively. As shown in Fig.5, no load current is extremely low compared with Fig.4. This means that the core loss decreases due to a drop in the exiting current during light load using efficiency maximizing control. In this simulation result, voltage value is phase voltage.

4. SIMULATION OF ELECTRIC VEHICLE PERFORMANCE

The travelling distance per charge of the electric vehicle can be simulated with the below equations.

Generally, the drag is calculated with the following equation(11).

$$Fd = Frol + Fair + Facc \qquad (11)$$

Where, the rolling resistance $Frol$ is calcurated with,

$$Frol = \mu \times mt \times g \qquad (12)$$

Where, mt:Vehicle weight[kg], μ:Rolling friction resistance, The aerodynamic drag is expressed with,

$$Fair = \rho \times Cd \times S \times \frac{V^2}{2} \tag{13}$$

ρ:Air density, Cd:Coefficient of air resistance, S:Total surface projected area [m^2], v:Velocoty[m/sec], The acceleration resistance is expressed with,

$$Facc = (mt + mr)a \tag{14}$$

mr:Rotary inertial weight[kg],
a:Acceleration[m/sec^2],

The equation (15) is the slop resistance when vehicle drive on a slop.

$$Fg = mt \times g \times \sin\theta \tag{15}$$

g:Gravitation acceleration[m/sec^2],
θ:Angle[rad]

The power required for motor during travel is calcurated with equation (16).

$$Pm = Fd \times \frac{V}{\eta t} \tag{16}$$

ηt:Gear efficiency

The vehicle specifications are shown in Table 3.

Table 3. Electric Vehicle Specifications

Vehicle specifications		
Curb weight with batteries	[kg]	1,708
Forward projected area	[m^2]	1.645
Rolling resistance coefficient		0.011
Aerodynamic drag coefficient		9.0^{e-6}
Tire radius	[m]	0.29
Reduction gear efficiency	[%]	87
Reduction gear ratio	[rpm]	8:1
NiMH Battery specifications		
Nominal voltage	[V]	324
Rated capacity	[kWh]	28
Weight	[kg]	560
Battery internal resistance	[mΩ]	0.9

5. EVALUATION OF ELECTRIC VEHICLE THROUGH THE TEST

From Fig.6 to Fig.9 is test results according to the driving mode. The Fig. 6 and Fig. 7 are shown speed, motor input voltage, torque, and output power in the high way driving mode with the vector control method and the efficiency optimizing vector control method repectively. The Fig. 8 and Fig.9 are shown city driving mode.

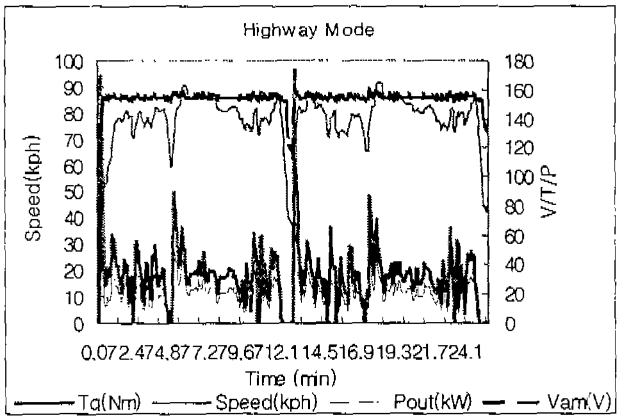

Fig.6 Vector control of highway driving mode

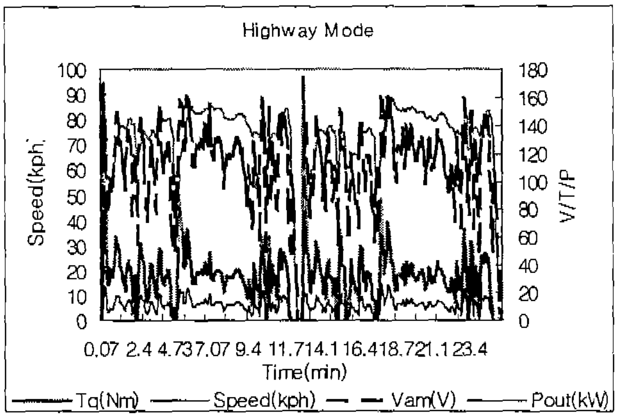

Fig.7 An efficency control of highway mode

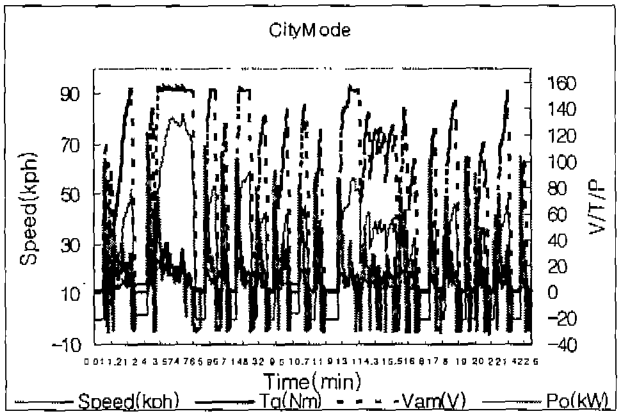

Fig.8 Vector control of city driving mode

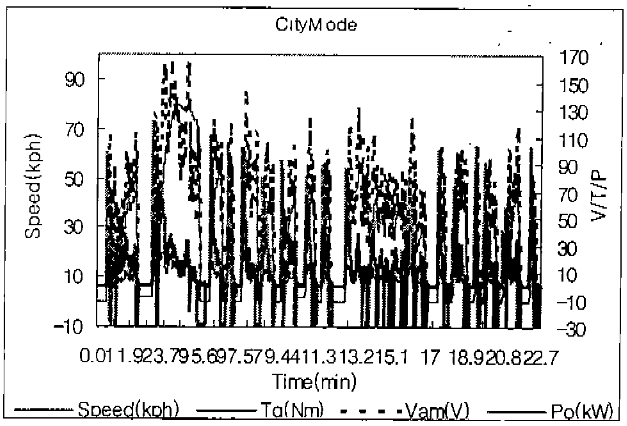

Fig.9 An efficiency control of city driving mode

The test results of the energy consumtion during vector control and efficency maximizing control are shown in Table 4.

Table 4. Test results of actual vehicle

Method Drivig mode	Vector control	Efficiency maximizing control
Consumed power in the highway mode	10.85kW	9.25kW
Consumed power in the city mode	3.958kW	3.29kW

6.CONCLUSION

In this paper, the conversion electric veicle "ACCENT-EV" is fabricated for the practical application of designed motor drive system. We confirmed the validity of the proposed efficiency optimized control in an EV through simulation and actual vehicle test. The 4 quadrant operation control method is carried out and we compared with highway driving mode and city driving mode. The test results are as follow.

1)According to actual driving test, the maximum speed is shown 120 km/h and acceleration time from 0 to 100 km/h is shown 20sec.

2)In the highway driving mode, power consumsion of the proposed method is about 17% less than conventional vector control method.

3)In the city driving mode, power consumsion of the proposed method is about 20% less than conventional vector control method.

From these results, we can conclude that the proposed method is useful for an EV application.

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