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Efficiency Optimization Control of Driving System for Urban Electric Bus Based on Loss Model

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Abstract: In order to improve the efficiency of the driving system of the urban electric buses, the three-phase asynchronous motor loss model was established, the relational expression of the optimal flux, parameter, angler speed and the torque of motor was deduced based on the loss model on the basis of orientation vector control and simulations based on the optimal efficiency model which were about the loss model of the motor of the urban electric bus were carried out in MATLAB/Simulink and the motor efficiency with non-optimum is 62.95%, while the optimized efficiency is 84.23% based on the loss model optimization; finally, to verify the practicability of the method, the simulation experiment with real vehicle was carried out and the mean efficiency of the motor was improved from 59.93 to 82.45%. The results showed that the rapider control response and global optimal efficiency could be achieved by this method compared with normal vector control method.

Key words: Electric city bus, efficiency optimization, loss model

INTRODUCTION

The insufficient endurance of the electric vehicle is the main obstacle restricting the development of the electric vehicle industry, there is important significance to improve the endurance of the electric vehicle for the limited on-board energy. And the energy efficiency would be improved impressively especially when the urban electric buses working at low speed, frequent braking condition.

The efficiency optical method of the induction motor vector control based on loss model of the motor (LMC for short) has the advantages of rapid dynamic response and global optimal efficiency (Rowan and Lipo, 1983; Kusko and Galler, 1983; Kim *et al*., 1984; Lorenz and Yang, 1992) which received extensive attention for calculating directly to obtain optimal flux. The steady state equivalent circuit of the d-q axis motor and the solution optimal flux equation based on scalar control and vector control were obtained by Kioskeridis and Margaris (1996) and Garcia *et al*. (1994). The torque response and tracking performance were improved by Naxin Cui and others based on this model. The optimal efficiency was achieved by Youjie Lin based on the loss model through the distribution of the active power, reactive power of the induction motor. Taking rotor iron loss into account, the thesis (Cui *et al*., 2005; Lin *et al*., 2010; Xu and Shao, 2010) established the loss model of the induction motor, deduced the efficiency optimization control condition of the of vector control of induction motor in the steady state by the use Lagrange algorithm. But this method depends on accurate motor loss model, while to establish accurate model is still being explored without suitable solution. The JXK6121BEV urban electric bus was selected as the research object, in the rotary coordinate, the motor loss model was established considering the copper loss and iron loss and the effectiveness and model practicability of the efficiency optimization control to the loss was verified by the simulation results on the condition of certain torque, angular velocity and real vehicle working state.

BUILD THE LOSS MODEL OF THE MOTOR

To establish the accurate loss model is the presupposition to obtain the global optimal efficiency based on the efficiency optimization control to the loss model. The controllable loss during operation included iron loss and copper loss, equal to about 80%-90% of the total loss. Only the controllable loss was took into consideration in the thesis to optimize the driving system of the urban electric bus.

The iron loss P_{fe} included hysteresis loss and eddy current loss which was related with the structural parament of the iron core, voltage frequency and flux density and directly affected the efficiency of the driving system.

$$
\begin{aligned}
P_{Fe} &= P_{Fes} + P_{Fer} = (P_{hs} + P_{es}) + (P_{hr} + P_{er}) \\
&= (k_h\omega_1 + k_e\omega_1^2)\Phi_m^2 + (k_h\omega_s + k_e\omega_s^2) \\
&\approx \frac{\omega_1^2\Phi_m^2}{1/k_e} + \frac{\omega_s^2\Phi_m^2}{1/k_e} \\
&= \frac{\omega_1^2\Phi_m^2}{R_{Fes}} + \frac{\omega_1^2\Phi_m^2}{R_{Fes}/s^2}
\end{aligned} \tag{1}
$$

Where, P_{fes}: Stator iron loss, P_{fer}: Rotor iron loss, P_{hs}: Stator hysteresis loss; P_{hr}: Rotor hysteresis loss; P_{es}: Stator eddy current loss; P_{er}: Rotor eddy current loss, k_h: Hysteresis loss coefficient, k_e: Eddy current loss coefficient, w_1: Stator voltage frequency; w: Rotor rotate frequence; Φ_m: Air gap flux

When the frequency was not very low, eddy current loss was far greater than the hysteresis loss, so there was tiny error ignore the error caused by the hysteresis loss. $W_1\Phi_m$ equaled to the voltage of the air gap, the stator iron loss resistance $R_{Fes} = 1/k_e$ was a constant, the rotor iron loss resistance was $R_{fer} = R_{fes}/s^2$, the total iron loss resistance was:

$$
R_{Fe} = \frac{R_{Fes} \times R_{Fer}}{R_{Fes} + R_{Fer}} = \frac{R_{Fes}}{1+s^2} \tag{2}
$$

When the motor is on the state of low or empty load, s is approximated to 0 and the equivalent resistance of the iron loss was $R_{Fe} \approx R_{Fes}$, the coefficient could be obtain in the power frequency empty load experiment.

It could be obtained from the rotor magnetic field oriented vector control that the direction of the m axis was the direction of the rotor flux, that was:

$$
\psi_{rd} = \psi_{rm} = \psi_r \tag{3}
$$

$$
\psi_{rq} = \psi_{rt} = 0 \tag{4}
$$

where, ψ_{rd}: Flux component of rotor in d axis, ψ_{rq}: Flux component of rotor in q axis, ψm: Flux component of rotor in m axis, ψ_{rt}: Flux component of rotor in t axis.

Ignoring the leakage inductance of the rotor magnetic field oriented vector control, $\psi_{st} = \psi_{rt} = 0$ and that equaled to internal short circuit of the cage type asynchronous rotor, the voltage component of the rotor in m axis and t axis was $u_{rm} = u_{rt} = 0$, the equivalent electrical circuit of the motor considering the loss could be obtained as Fig. 1 showed.

Lm: Mutual inductance coefficient, $L_{\sigma s}$,$L_{\sigma r}$: Leakage inductance coefficient of the rotor and stator, Rs: Equivalent resistance of the stator, R'_r: Equivalent resistance of the rotor covered to the stator side, i_{sm}, i_{rm}: Current in the m axis of the stator and rotor, i_{st}, i_{rt}: Current in the t axis of the stator and rotor, u_{sm}, u_{rm}: Voltage in the m axis and t axis of the stator.

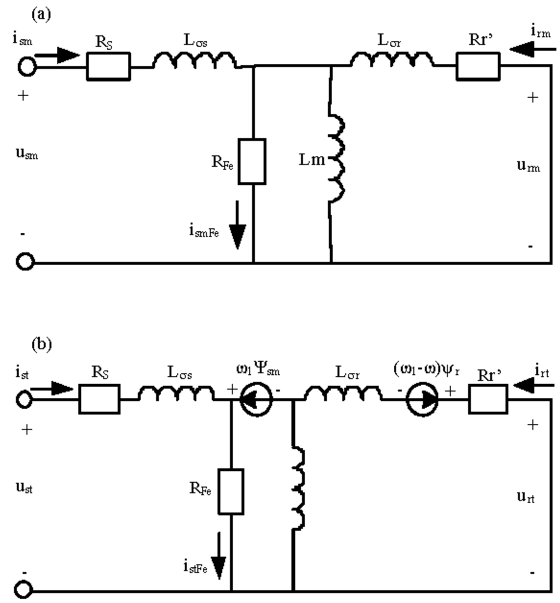

Fig. 1(a-b): Equivalent circuit of induction motor in m, t axis considering loss (a) Equivalent circuit on the m axis and (b) Equivalent circuit on the t axis

Thus the mathematical loss model under the rotor magnetic field oriented vector control of the asynchronous motor could be deduced that:

$$
P_{loss} = (k_1 + k_2\omega^2)\psi_r^2 + k_3\frac{T_e^2}{\psi_r^2} \tag{5}
$$

$$
k_1 = \frac{R_s}{L_m^2},\ k_2 = \frac{1}{R_r + R_{Fe}},\ k_3 = \frac{L_r^2}{n_P^2 L_m^2}(R_s + \frac{R_r R_{Fe}}{R_r + R_{Fe}})
$$

EFFICIENCY OPTIMIZATION CONTROL SIMULATION MODEL

The Eq. 5 showed that, under the given condition, that was the condition of constant rotor angular frequency and constant torque, without considering the change of the motor parameters in working process, among the controllable losses of the asynchronous motor, only the rotor flux ψ_r was controllable, so that the losses in the motor could be minimize by controlling the rotor flux ψ_r.

Ignore the mechanical loss and stray loss of the asynchronous motor, the efficiency of the induction motor can be expressed as:

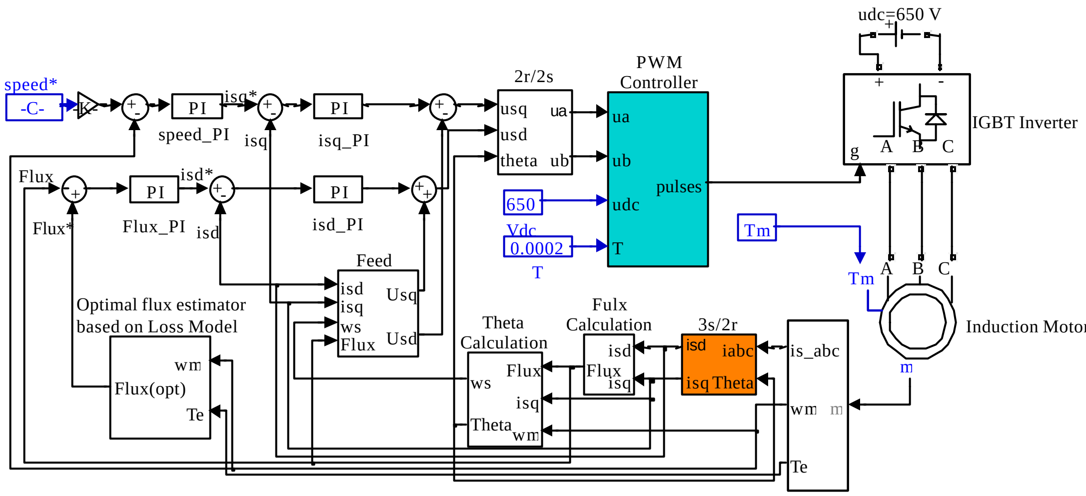

Fig. 2: Efficiency optimization simulation model of the city bus driver based on loss model

$$\eta_m = \frac{P_{out}}{P_{loss}+P_{out}} = \frac{\omega T_e}{(k_1+k_2\omega^2)\psi_r^2 + k_3\frac{T_e^2}{\psi_r^2} + \omega T_e} \quad (6)$$

It can be seen form Eq. 6 that the efficiency η_m was a convex function of the rotor flux ψ_r, that was in certain working condition, there was an optimal ψ_r^{opt} to get maximum efficiency η_{max}. To seek the Eq. 6, after the derivation of the rotor flux ψ_r, the optimal flux could be obtained:

$$\psi_r^{opt} = \sqrt[4]{\frac{k_3}{k_1+k_2\omega_r^2}}\sqrt{T_e} \quad (7)$$

On the condition of the loss model and the rotor flux oriented vector control to the asynchronous motor, the optical efficiency simulation model of the urban electrical bus based the loss model was established as shown in Fig. 2. The inputs were rotor angular frequency and the electromagnetic torque of the motor and the outputs was optimal flux value, after being comparison with the actual flux value, the result would be sent to the flux controller to obtain optimum efficiency of the electric urban bus driving motor.

RESEARCH OF SIMULATION EXPERMENT

The motor parameters inputted in the simulation model: the stator resistance was 0.017 ohm, the rotor resistance was 0.021 ohm, the mutual inductance was 13.62 mH, the rotor inductance was 3.261mH, the pole pair number was 2, the iron loss resistance was 93.5 ohms.

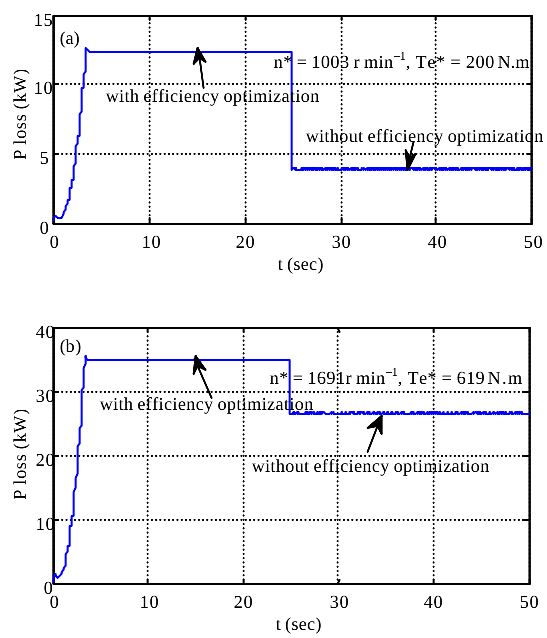

Fig. 3(a-b): Loss of motor before and after efficiency optimization (a) Power loss under 1003 r min^{-1} 200 N.m and (b) Power loss under 1691 r min^{-1} 619 N.m

In given angler speed, torque, stable load condition, the motor loss power of the urban electric bus was showed in Fig. 3. The comparison of the motor loss model without optimization in the condition of 1003 rpm/200 N.m and 1691 rpm/619 N.m was showed in Fig. 3. The non-optimum efficiency in this article refereed to

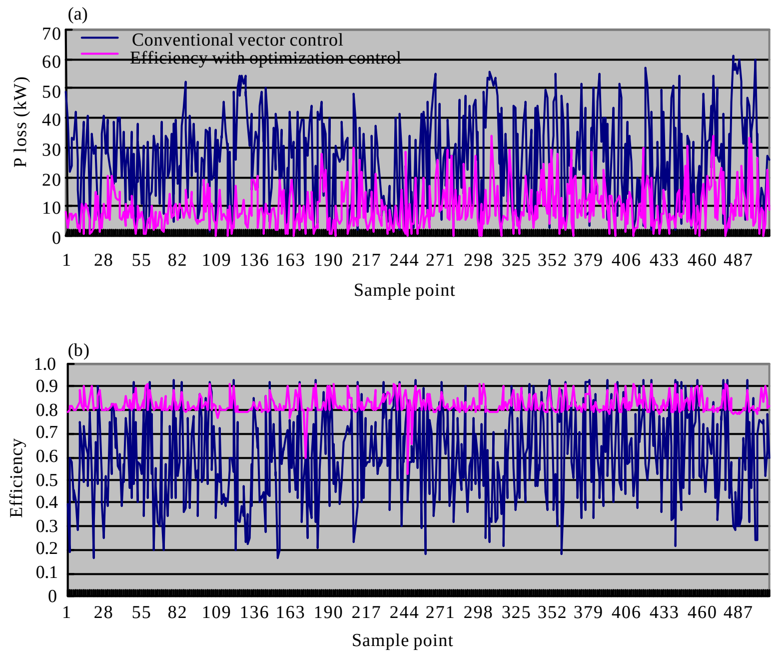

Fig. 4(a-b): Contrast experimental of the two efficiency optimization method in actual operation of the bus (a) Loss power and (b) Motor efficiency

the driving system controlled by rated flux with conventional vector control method.

To compare the losses, the thesis artificially controlled startup time of the optimal efficiency, while in the practical application, the efficiency optimization control would be start immediately as the system to stable condition. Fig. 3a showed that the conventional vector control loss power 12.36 kW and loss model efficiency optimization control power loss 3.93 kW, the corresponding motor efficiency increased from 62.95 to 84.23%. Figure 3b conventional vector control power loss was 34.88 kW and with the loss model efficiency optimization control the power loss was 26.65 kW which mean that the corresponding motor efficiency increased from 75.86 to 80.44%. The dynamic characteristics of the method could rapid track a given speed/torque with tiny pulsation.

The actual working condition point of the urban electric bus was collected, the optimal efficiency control simulation with actual vehicle working condition was carried out and the motor efficiency and power loss curve were showed in Fig. 4. The average loss of actual vehicle working condition point with conventional vector control was 26.25 kW and the average efficiency was 59.93%; while with the optimal efficiency control based on the loss model the average loss was 9.25 kW and the average efficiency was 82.45%, the result showed that the loss model-based efficiency optimal control could improve the overall efficiency of the electric urban bus driving system, save energy and prolong the endurance of the vehicle with once charging.

CONCLUSION

In order to improve the energy efficiency of the urban electric bus whose energy was limited, based on the rotor magnetic field oriented vector control principle, considering iron loss and copper loss in m-t axis equivalent circuit the motor loss model was derived and optimal flux was obtained. Based on the loss model of the electric urban bus driving motor the simulation model was achieved with MATLAB/Simulink and the simulation experiment was carried out, the conclusions were got as follows:

- On the conditions of rotational speed of 1003 r^{-1} min^{-1} $torque^{-1}$ of 200N.m, speed of 1691 r^{-1} min^{-1} $torque^{-1}$ of 619 N.m, compared with the conventional vector control, the optimal efficiency control based on loss model, the loss power reduced 8.43 and 8.23 kW, respectively and the efficiency increased 21.28 and 4.58%, respectively
- The experimental results showed that the loss model was effective to improve the efficiency of the system in stable working condition, but in the two given conditions the efficiency improved degree had larger difference and the reason was that in the condition of speed of 1691 r^{-1} min^{-1} $torque^{-1}$ of 619 N.m, the

working condition point was near the motor rated working point and the motor was in the efficient working condition, so there was a little room for improvement, while in the condition of the speed of 1003 r^{-1} min^{-1} $torque^{-1}$ of 200 N.m the motor was in low-speed, low-load working condition and the efficiency of the motor could be increased largely

- Most of the urban electric buses in the city worked in the low load condition, the thesis collected real vehicle working conditions data to carried out simulation experiments, using real vehicle working conditions point with the optimal efficiency control based on the loss model of efficiency the average loss reduced 17 kW and the average efficiency improved 22.52%. The optimal efficiency control method could improve the overall working efficiency of the electric urban bus driving system which was of certain practicality

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