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Efficiency Optimization Control of Driving Motor for Electric City Bus Based on GRNN

Wang Ye-Qin and Yang Yan
Faculty of Electronic and Electrical Engineering, Huaiyin Institute of Technology,
Huaian, Jiangsu, 223003, China

Abstract: In order to improve the operation efficiency of drive system for electric city Bus, a hybrid method for motor efficiency optimization control is proposed, the loss model is used to determine the optimal flux search range and the influence of parameters variation on optimization control precision is reduced through identification of motor's parameters on line. Motor speed, torque , mutual inductance and rotor resistance were taken as the input of generalized regression neural network,and the optimal flux can be searched by the generalized regression neural network; Contrast experiment between the hybrid method and the conventional vector control is carried out under the given speed and torque, the simulation results show that efficiency increase 23.77% in light load and low speed areas (1003 r/min/200 N.m). Finally eficiency of real car operating mode is test in 100 kW test platform of power train, the efficiency of drive motor increase by an average of 24.99% in hybrid control method. This approach provides an effective way for the improvement of energy utilization in electric city bus.

Key words: Electric city bus, driving motor ,efficiency optimization,GRNN

INTRODUCTION

The endurance mileage deficiency of EV is still the main obstacle which restricts the development of electric vehicle industry, so it is significant to improve the operation energy efficiency of electric vehicle in the case of limited vehicle energy.

Three-phase induction motor is one of the most useful driving motor, the domestic and foreign scholars have done plenty of researches on the efficiency optimization. The efficiency optimization method based on loss model (Loss Model Controller, LMC for short) is used to gain the optimal flux by computing, which can get fast response and gain a global optimization flux, but the control accuracy is easily effected by the parameters variety (Kim *et al*., 1984; Xu and Shao, 2010; Pei *et al*., 2012).

Search method (SC for short) is independent of mathematic model, by determining the searching range and step size, rotor flux is searched online to minimize the total input power, so as to realize efficiency optimization and solve the contradiction between searching speed and torque ripple in low frequency (Vaez *et al*., 1999).

The traditional SC method has a great limitation in the aspect of rapidity and accuracy because of the disadvantages of fixed step size. Recently, intelligent controls are introduced into efficiency optimization of motor, such as adaptation (Miao *et al*., 2009), fuzzy control (Zhang *et al*., 2007), neural network (Pryymak *et al*., 2002) and so on and intelligent searching method is put forward. Introduction of the intelligent control can reduce the searching time to a certain extent and accelerate the speed of convergence, but it can't solve the problem of flux and torque ripple in efficiency optimization completely.

Scholars proposed a hybrid method for efficiency optimization control with the combination of LMC and SC, Firstly, it calculate the approximate optimal value of flux using LMC and then SC is used to seek the most optimum value online, the hybrid method patch the deficiency of the two methods, which develop its advantages and avoid disadvantages (Liu *et al*., 2005; Yu *et al*., 2012).

This study take type JXK6121BEVelectric city bus as study objects, establish the loss model of induction motor, on this basis, torque and speed is collected to calculate the initial value of optimal flux according to the actual conditions and the search scope is defined. Then generalized regression neural network controller is used to search the optimal flux in a certain search scope and the searching result will be more accurate through identification the parameter of driving motor.

Corresponding Author: Wang Ye-Qin, Faculty of Electronic and Electrical Engineering, Huaiyin Institute of Technology, Huaian, Jiangsu, 223003, China

ESTABLISH THE LOSS MODEL OF THREE-PHASE INDUCTION MOTOR

Controllable losses including iron loss and copper loss account for about 80-90% of the total loss during motor operation. Only the controllable losses are considered in this study, which are used to solve the efficiency optimization of the electric city bus driving system. Based on the rotor field oriented vector control principle of three-phase induction motor, Kirchhoff's law and the principle of electromagnetic induction, the loss model of motor in rotor field oriented vector control can be described as follows (Xu and Shao, 2010; Pei *et al*., 2012):

$$P_{loss} = P_{Fe} + P_{cu} = (k_1 + k_2\omega^2)\psi_r^2 + k_3\frac{T_e^2}{\psi_r^2} \tag{1}$$

where, n_p-Rated speed of induction motor; p-number of pole pairs; T_e-Electromagnetic Torque; among which:

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

The efficiency of induction motor can be expressed as follows:

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

The optimal flux ψ_r^{opt} can be obtained by evaluating the derivative of rotor flux ψ_r to Eq. 2:

$$\psi_r^{opt} = \sqrt[4]{\frac{k_3}{k_1 + k_2\omega_r^2}}\sqrt{T_e} \tag{3}$$

PARAMETER IDENTIFICATION OF MOTOR

This study presents a method to identify the parameters of rotor resistance and inductance coefficient based on the reactive power theory and the theory of model reference adaptive and the problem of decline in efficiency control accuracy of the driving system can be solved which are caused by the motor parameters deviate from the ratings.

Parameter identification of inductance coefficient: There tow expression form of the reactive power theory as follows (Noguchi *et al*., 1997):

$$q = u_{s\beta} i_{s\alpha} - u_{s\alpha} i_{s\beta} \tag{4}$$

$$q = (i_{s\alpha}\frac{d\psi_{r\beta}}{dt} - i_{s\beta}\frac{d\psi_{r\alpha}}{dt}) + L_m(i_{s\alpha}\frac{di_{r\beta}}{dt} - i_{s\beta}\frac{di_{r\alpha}}{dt}) \tag{5}$$

Equation 4 can be used to calculate the accurately instantaneous reactive power, Eq. 5 associate with the coefficient of inductance which is needed to identify and the result get from Eq. 5 is the estimated value of instantaneous reactive power. According to the model reference adaptive control theory, take the Eq. 4 as the reference model and the Eq. 5 as the as the adjustable model, among which estimated value $\hat{L}_m$ is used to instead of the coefficient of inductance L_m:

$$\hat{q} = (i_{s\alpha}\frac{d\psi_{r\beta}}{dt} - i_{s\beta}\frac{d\psi_{r\alpha}}{dt}) + \hat{L}_m(i_{s\alpha}\frac{di_{r\beta}}{dt} - i_{s\beta}\frac{di_{r\alpha}}{dt}) \tag{6}$$

Identification the parameter of rotor resistance: By substitution of the back EMF[14] of induction motor into Eq. 4, the two forms of instantaneous reactive power can be described as Eq. 7 and 8:

$$q = (i_{s\alpha} u_{s\beta} - i_{s\beta} u_{s\alpha}) - \sigma L_s(i_{s\alpha}\frac{di_{s\beta}}{dt} - i_{s\beta}\frac{di_{s\alpha}}{dt}) \tag{7}$$

$$q = \frac{L_m}{L_r}[(\psi_{r\alpha} i_{s\alpha} + \psi_{r\beta} i_{s\beta})\omega_r + \frac{R_r}{L_r}(\psi_{s\alpha} i_{s\beta} - \psi_{r\beta} i_{s\alpha}) \tag{8}$$

The rotor resistance variation is difficult to measure accurately in the running process of the motor, that is, the two parameters are estimate rather than actual value in Eq. 8, then the estimate value rotor flux $\hat{\psi}_r$ and rotor resistance $\hat{R}_r$ are used to instead of the actual value ψ_r and R_T. Because the rotor field oriented vector control strategy is adopt, transform it into the rotor field oriented synchronous coordinate, then Eq. 8 can be expressed as follows:

$$q = \frac{L_m}{L_r}\hat{\psi}_r i_{sd}\omega_r + \frac{\hat{R}_r}{L_r}\hat{\psi}_r i_{sq} \tag{9}$$

According to the model reference adaptive control theory, PI controller is taken as the adaptive controller to identify the parameter of motor:

$$\hat{L}_m = (K_p + \frac{K_i}{s})(q - \hat{q}) \tag{10}$$

$$\hat{R}_r = (K_p + \frac{K_i}{s})(q - \hat{q}) \tag{11}$$

GENERALIZED REGRESSION NEURAL NETWORK MODELING

Generalized Regression Neural Network (GRNN) is a kind of radial basis function neural network. The GRNN includes the input layer, model layer, the summation layer and the output layer.

The neurons number of input layer is equal to the dimension of eigenvector of input sample; Each neuron model layer correspond to different samples, the number of neuron is equal to the learning sample number n in input layer, the transfer function of model layer neuron is described as follows:

$$P_i = \exp(\frac{(X-X_i)^T(X-X_i)}{2\sigma^2}), i = 1,2, ..., n \qquad (12)$$

where, X-Input variables; Xi-learning sample corresponding to neuron I, σ-smoothing parameter.

Calculation the summation of output layer neurons according to Eq. 13:

$$\sum_{i=1}^{n} Y_i \exp(-\frac{(X-X_i)^T(X-X_i)}{2\sigma^2}) \qquad (13)$$

If Yi = 1 in Eq. 13, that is the sum is calculated for all outputs of neurons in mode layer, the connection weights between neurons and the pattern layer is 1, the corresponding transfer function is:

$$S_{Nj} = \sum_{i=1}^{n} y_{ij} P_i, i = 1, 2, ..., 1 \qquad (14)$$

Otherwise, the sum is calculated for all pattern layer neurons, the connection weight between the pattern layer i neurons and summation layer neuron j is the elements Y_{ij} in output samples and the corresponding transfer function is:

$$S_{Nj} = \sum_{i=1}^{n} y_{ij} P_i, j = 1, 2, ..., 1 \qquad (15)$$

where, l-The number of output layer neurons.

Divides the output of neurons in summation layer:

$$y_i = S_{Nj} / S_D, j = 1, 2, ..., 1 \qquad (16)$$

From the transfer function, we can seen that, for the GRNN model, once learning sample is determined, then the connection weights between the neurons and the network structure is determined. In the training process, the transfer function of each unit model layer is adjusted to obtain the best regression estimation results by changing the smoothing parameter, rather than changing the adjusting the connection weights between neurons (Ying *et al*., 2011).

EXPERIMENTAL AND SIMULATION STUDY

The efficiency optimization scheme of drive motor for electric city bus based on the hybrid method is shown in Fig. 1. In the condition of the start-up and break, in order to ensure the dynamic performance of drive system, Taking the rated flux as given flux ensure that the drive motor can quickly reach the given speed and torque in the rotor field oriented vector control system; when the driving system reaches a steady state, the loss model is used to obtain the optimal flux in advance and make it as the initial value of searching and based on the loss model equation, abundant data are produced, which are used to train the neural network and optimize the estimation of rotor flux, the optimal flux is searched out from the neural network controller and so as to realize the optimal efficiency control of the electric city bus driving system. In order to verify the control effect of efficiency optimization system, the simulation model was established in MATLAB/Simulink and a simulation study are carried out.

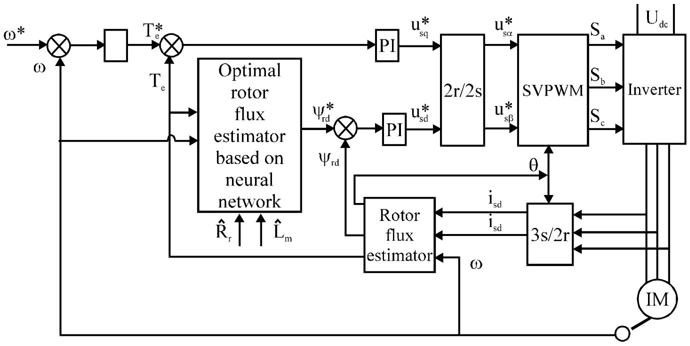

Fig. 1: The efficiency optimization scheme of drive motor for electric city bus based on the hybrid method

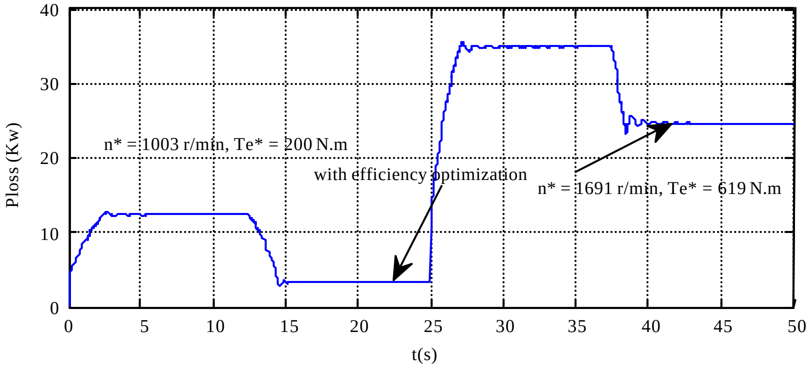

Fig. 2: Loss of motor under efficiency optimization control when speed and torque breaks

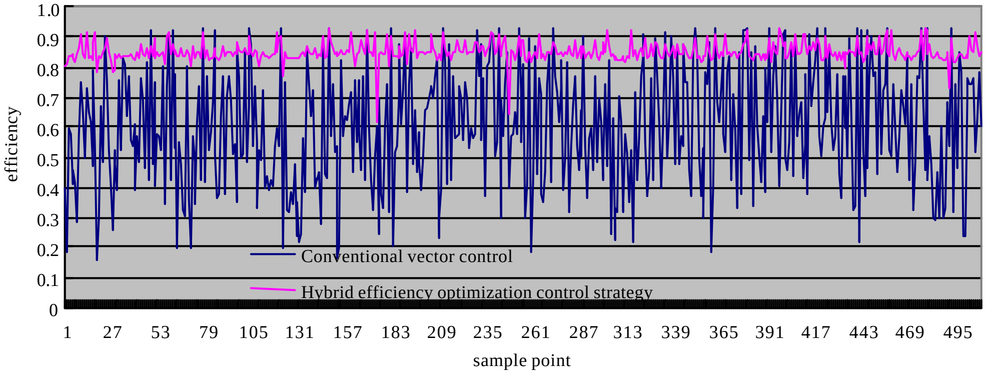

Fig. 3: Contrast experimental of the two efficiency optimization method in actual operation

In the running process of the system, take the rotor resistance and mutual inductance which are gained by searching online as the auxiliary input parameters of flux optimal estimator based on neural network, this method can solve the drop of the estimator precision caused by the variation of motor parameters in the method based on the loss model.

In order to illustrate the process of hybrid method for efficiency optimization, the simulation experiment for the abrupt speed and torque change was carried out, the simulation result is shown in Fig. 2.

As Fig. 2 shows that rated flux is used as the given flux in vector control system to ensure the fast tracking the given speed and torque, in the moment of start-up and at 13 seconds, efficiency optimizing control based on the hybrid method was used to the vector system, the loss was reduced to 3.22 kW, after a brief decline, the corresponding efficiency of motor was 86.72%, which was increased by 23.77% than that before efficiency optimizing and the loss was reduced by 9.14 kW. At 25 seconds, Speed and torque break, the system operate in the rated flux, which can track the given speed and torque, At 38 seconds, put the efficiency optimizing control in gear, the motor loss is reduced to 24.78 kW and the efficiency is 81.56%, which was increased by 5.7% and the loss was reduced by 10.1 kW.

EXPERIMENT ON BENCH OF POWER TRAIN

Power train test bench is composed of a power supply system, driving system, dynamometer system and data acquisition and control system etc. the parameters of three-phase induction motor in drive system: rated power is100 kW, the peak power is 200 kW, the maximum speed is 3600 r min^{-1},the rated speed is 1480 r min^{-1}, the rated torque is 640 N.m.IPC send control packets to the CAN bus to control three-phase induction motor working in constant speed mode and the dynamometer working in constant torque mode. Set the operating point of drive motor according to the reports of Electric city bus power system based on the measurement of the real vehicle, the output torque of the dynamometer was adjust according to the drive motor speed (Fig. 3). efficiency testing were carried out after the motor temperature reaching to thermal equilibrium, the motor temperature were set at 75±5°C and the battery pack temperature were set at 15±5°C, drive system efficiency tests were completed at the 100 kW power train test bench, which were shown in Fig. 3. The experimental results show that the average efficiency of conventional vector control was 59.93% and the efficiency optimization control of the hybrid method was 84.92%, the efficiency was increased by 24.99%.

CONCLUSION

When electric city bus driving system operates under light load, its efficiency will drop obviously, according to the problem above, efficiency optimization control method combined LMC with LC is presented and simulation experiment was carried out in MATLAB/Simulink, the following conclusions can be obtained:

- The loss model of three-phase induction motor is established and it is used to determine the optimal flux search range, which can shorten search time and the dynamic response speed of drive system is improved
- The reactive power theory and the theory of model reference adaptive are used to identify the parameters of rotor resistance and inductance coefficient, which can solve the problem of decline in efficiency control accuracy of the driving system caused by the motor parameters changing, so as to improve the control precision of efficiency loss model and provide the more accurate search range of flux
- General regression neural network is designed, take motor speed and torque, rotor resistance and inductance coefficient which are identified online as the input of generalized regression neural network, optimal flux is estimated on the search range which is determined by the loss model, this method patch the deficiency of the LMC and SC methods, which develop their advantages and avoid disadvantages
- In the simulation experiment, when speed and torque breaks, the vector control system operate in the rated flux, which can track the given speed and torque and when the system is stable, put the efficiency optimizing control in gear, the loss was reduced to 3.22kW in the condition of 1003 r/min/200 N.m, the corresponding efficiency of motor was 86.72%, which was increased by 23.77% than that before efficiency optimizing; the motor loss is reduced to 24.78 kW in the condition of 1691 r/min/619 N.m and the efficiency is 81.56% and the efficiency increased by 5.67%
- The efficiency of drive motor is test at the 100 kW power train test bench, the efficiency optimization control of the hybrid method was 84.92% and the efficiency was increased by 24.99%

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