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Energy-Saving Control of Induction Motor for Electric Vehicle Based on Online Parameter Estimation

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Abstract. In order to improve the problem of insufficient endurance mileages of pure electric vehicles, an energy-saving control strategy of induction motor based on the online parameter estimation is proposed. Considering the model of considering the iron loss of the stator of the induction motor, the loss minimization model is used to control the energy of the motor to reduce the steady-state loss of the motor. At the same time, an observer with the model reference adaptive system (MRAS) is designed to online estimated the rotor time constant and stator resistance of the motor, and reduce the influence of parameter variation on the loss minimization control, which makes the loss model more accurate and the energy-saving effect is more ideal. Finally, the control strategy is verified by simulation. The simulation results show that the energy-saving effect of this algorithm is obvious when the motor runs at a high speed under a light load.

1. Introduction

With the popularity of new energy vehicles, there are more and more related studies. The new energy vehicle enterprises have paid more attention to Battery Electric Vehicle (BEV) due to its advantages in no emission pollution and low noise. However, the problem of short mileage of BEV has been limiting its further promotion. Because the battery technology is on the bottleneck stage at present, it has become a solution to reduce the energy consumption from the aspect of motor control before no key breakthrough has been made in the battery capacity and life of electric vehicles. Induction motor is widely used in the drive motor of low speed electric vehicle because of its simple structure, cheap price, reliable feature and easiness to maintain [1].

At present, the commonly used energy-saving control is divided into two control strategies: loss model control and search-based control. Loss model control can reduce the loss model based on the mathematical model of motor, finally calculate the magnetic flux of minimum loss, and reduce the loss through reducing the flux linkage in the steady state [2]. Search control can compare the optimal controlled quantity and minimize the input power in case of constant motor rotation speed and torque according to the functional relationship between the controllable loss of the motor and a measured motor parameter [3]. Because the former is the optimal magnetic flux obtained by direct calculation, the response speed is the fastest, which is suitable for the working conditions where the speed and torque change from time to time, but it depends heavily on the parameters of the motor [4]. Although the latter does not rely too much on motor parameters, its functional relationship is complex and the search speed is limited, so it is only suitable for long-term steady-state working conditions [5]. To sum up, the control strategy based on loss model is suitable for energy saving control of working conditions of BEV motor.

In reference [6-9], most of them are based on loss model control. Although the response speed is fast, the optimal flux linkage is calculated based on motor parameters. During the operation of the motor, the increase of temperature and magnetic saturation will lead to the change of resistance and inductance of the motor, which will make the minimum loss model deviate and make the energy saving effect not ideal [10]. Therefore, the addition of motor parameter estimation algorithm can achieve energy-saving control.

In this paper, a loss minimization control strategy based on online estimation for electric vehicles is studied. During the operation of the motor, the varying rotor time constant (T_r) and stator resistance (R_s) are identified at the same time. The improved flux linkage observer is used to identify the motor parameters online, and the energy saving operation is switched in steady state. The simulation results verify the feasibility of the algorithm.

2. Loss minimization control algorithm

Generally speaking, the induction motor runs with the highest efficiency under 75% of the rated load, and usually leaves a certain margin when selecting the type. When the motor is lightly loaded, the efficiency will be low [1-9]. At this time, it is necessary to control and reduce the loss of the motor.

Motor loss can be divided into stator and rotor copper loss, stator and rotor iron loss, mechanical loss and stray loss. Among them, the first two are called controllable losses, and the latter two are also called uncontrollable losses [2-9]. The controllable loss accounts for about 80% of the total loss, and can be adjusted by the control strategy [3-8]. Therefore, the improvement of the traditional motor control algorithm can achieve the effect of energy-saving operation.

When the motor is lightly loaded, the iron loss accounts for a large proportion[2-9]. Therefore, in order to ensure the control accuracy, it is necessary to consider iron loss in energy saving control. When the motor runs at medium and high speed, the slip frequency is usually low because of light load. Rotor iron loss is much smaller than stator iron loss, so only stator iron loss is considered [5-9].

Voltage equations are

$$\begin{aligned} U_{sq} &= R_s i_{sq} + p\psi_{sq} + \omega_1 \psi_{sd} \\ U_{sd} &= R_s i_{sd} + p\psi_{sd} - \omega_1 \psi_{sd} \\ U'_{rq} &= R'_{rq}\, i'_{rq} + p\psi'_{rq} + (\omega_1 - \omega_r)\psi'_{rd} \\ U'_{rd} &= R'_{rd}\, i'_{rd} + p\psi'_{rd} - (\omega_1 - \omega_r)\psi'_{rq} \end{aligned} \tag{1}$$

Wherein

$$\begin{aligned} \psi_{sq} &= L_s i_{sq} + L_m i'_{rq} \\ \psi_{sd} &= L_s i_{sd} + L_m i'_{rq} \\ \psi'_{rq} &= L'_r\, i'_{rq} + L_m i_{sq} \\ \psi'_{rd} &= L'_r\, i'_{rd} + L_m i_{sd} \\ L_s &= L_{ls} + L_m \\ L'_r &= L'_{lr} + L_m \end{aligned} \tag{2}$$

Torque equation is

$$T_e = 1.5 n_p \frac{L_m}{L_r} (\psi_{rd} i_{sq} - \psi_{rq} i_{sd}) \tag{3}$$

Motion equation is

$$\frac{J}{n_p} \frac{d\omega_r}{dt} = T_e - T_L \tag{4}$$

According to the voltage equations, flux linkage equations, torque equations and motion equation in the mathematical model of induction motor, it can be obtained by neglecting some differentiation elements:

$$(R_s + R_m + L_{\delta s} p) i_{sd} = u_{sd} - \frac{R_m}{L_{\delta r}} \psi_{rd} + \frac{L_r R_m}{L_{\delta r}} i_{md} + \omega_1 L_{\delta s} i_{sq} \tag{5}$$

$$(R_s + R_m + L_{\delta s} p) i_{sq} = u_{sq} - \frac{R_m}{L_{\delta r}} \psi_{rq} + \frac{L_r R_m}{L_{\delta r}} i_{mq} - \omega_1 L_{\delta s} i_{sd} \tag{6}$$

$$(\frac{L_r R_m}{L_{\delta r}} + L_m P) i_{md} = R_m i_{sd} + \frac{R_m}{L_{\delta r}} \psi_{rd} + \omega_1 L_m i_{mq} \tag{7}$$

$$(\frac{L_r R_m}{L_{\delta r}} + L_m P) i_{mq} = R_m i_{sq} + \frac{R_m}{L_{\delta r}} \psi_{rq} + \omega_1 L_m i_{md} \tag{8}$$

$$(\frac{R_r}{L_r} + P)\psi_{rd} = \frac{L_m}{L_r} R_r (i_{sd} + i_{dfe}) + \omega_s \psi_{rq} \tag{9}$$

$$(\frac{R_r}{L_r} + P)\psi_{rq} = \frac{L_m}{L_r} R_r (i_{sq} + i_{qfe}) + \omega_s \psi_{rd} \tag{10}$$

$$\omega_r = \int \left[\frac{n_p}{J} (T_\omega - T_f) \right] \tag{11}$$

$$\omega_s = \frac{R_r L_m i_{sq}}{L_r \psi_{rd}} \tag{12}$$

The equivalent circuit of induction motor in two-phase synchronous coordinate system considering iron loss is as follows:

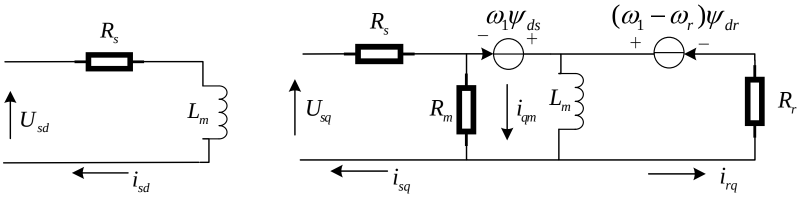

Figure 1. Equivalent Circuit of Induction Motor in Two-phase Synchronous Coordinate System Considering Iron Loss.

Stator copper loss

$$p_{Cus} = (i_{sd}^2 + i_{sq}^2) R_s \tag{13}$$

Rotor copper loss

$$p_{Cur} = i_{rp}^2 R_r = \frac{R_r}{R_r + R_m}(i_{sq}R_m - \omega_r \psi_r)^2 \tag{14}$$

Stator iron loss

$$p_{Fe} = \frac{R_m}{(R_r + R_m)^2}(R_r^2 i_{sq}^2 + 2R_r i_{sq}\omega_r \psi_r + \omega_r^2 \psi_r^2) \tag{15}$$

Therefore, the total controllable loss of the motor is

$$p_{loss} = (k_1 + k_2\omega_r^2)\psi_r^2 + k_3\frac{T_e^2}{\psi_r^2} \tag{16}$$

Wherein:

$$\begin{aligned} k_1 &= \frac{R_s}{L_m^2}, k_2 = \frac{1}{R_r + R_m}, \\ k_3 &= \frac{L_r^2}{n_p^2 L_m^2}(R_s + \frac{R_r R_m}{R_r + R_m}) \end{aligned} \tag{17}$$

It can be seen that motor controllable loss is related to rotor magnetic flux when the rotation speed and torque are constant, and the loss can be reduced by adjusting the magnetic flux.

Considering only the controllable loss, the efficiency of the motor is

$$\eta = \frac{\omega_r T_e}{p_{loss} + \omega_r T_e} = \frac{\omega_r T_e}{(k_1 + k_2\omega_r^2)\psi_r^2 + k_3\frac{T_e^2}{\psi_r^2} + \omega_r T_e} \tag{18}$$

According to the extreme value theorem, the first derivative of the loss function is obtained so that it is equal to zero, and then the second derivative is obtained to be greater than zero, so that the power point is the smallest. It is as follows:

$$\frac{\partial^2 p_{loss}}{\partial \psi_r} = 2(k_1 + k_2\omega_r^2)\psi_r - 2k_3 T_e^2 \psi_r^{-3} = 0 \tag{19}$$

$$\frac{\partial^2 p_{loss}}{\partial^2 \psi_r} = 2(k_1 + k_2\omega_r^2) + 6k_3 T_e^2 \psi_r^{-4} > 0 \tag{20}$$

Then the optimal rotor flux is obtained.

$$\psi_{r-opt} = \sqrt[4]{\frac{k_3}{k_1 + k_2\omega_r^2}}\sqrt{T_e} \tag{21}$$

Neglecting mechanical loss and stray loss, the corresponding maximum efficiency is

$$\eta_{opt} = \frac{\omega_r T_e}{(k_1 + k_2\omega_r^2)\psi_{r-opt}^2 + k_3\frac{T_e^2}{\psi_{r-opt}^2} + \omega_r T_e} \tag{22}$$

The following is the relationship among optimal flux, torque and rotation speed.

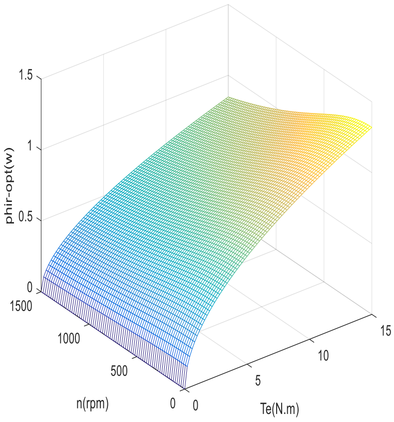

Figure 2. Relationship of Optimal Flux, Torque and Rotation Speed.

When the torque is constant, the optimal flux decreases with the increase of rotation speed; With the decrease of load torque, the optimal flux also decreases.

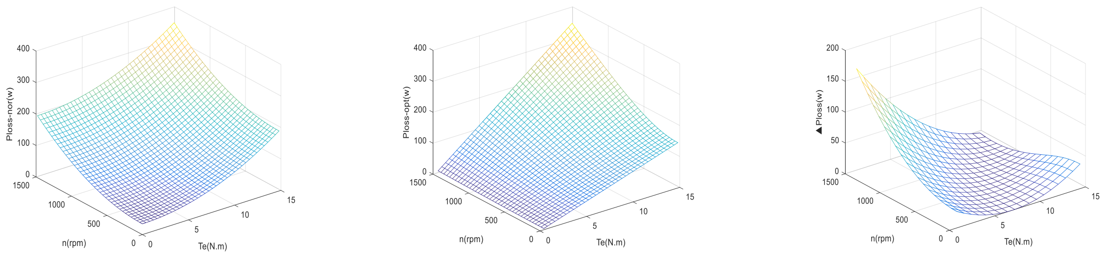

Figure 3. Controllable Loss of Two Control Modes: (a) Controllable Loss under Constant Flux Control; (b) Controllable Loss Under Optimal Flux Control; (c) Difference of Controllable Loss Between Two Control Modes

The comparison of controllable loss between two control modes is shown in the figure. When the traditional vector control motor runs below the fundamental frequency, the flux remains constant. In vector control, torque current and excitation current components are decoupling control, so the flux and the controllable loss of the motor can be reduced by properly reducing the excitation component.

The minimum loss control deduces the optimal flux based on the mathematical model of motor, so it heavily relies on the motor parameters.

3. Design of energy saving algorithm based on improved parameter estimation

During the operation of the motor, the parameters of the motor will change slowly, which will lead to the inaccurate mathematical model of the motor. Therefore, it is necessary to identify the online parameters of the motor while saving energy. This paper presents an energy-saving control algorithm based on improved MRAS parameter estimation, which makes the motor model more accurate.

3.1. Formatting Traditional model reference adaptive parameter estimation

Adaptive algorithm is a mature identification algorithm, which has been widely used in motor control [9-10]. The principle is to use the reference model and the adjustable model to output the same physical quantity to make the difference. The latter contains identification parameters and are then estimated as identification parameters by adaptive mechanism. The adaptive law is designed according to Popov hyperstability theory.

T_r and R_s can be identified by observing rotor flux linkage by voltage and current model. The specific models are as follows:

Voltage model flux linkage observer

$$\begin{aligned} \psi_{r\alpha} &= \frac{L_r}{L_m}[\int (u_{s\alpha} - R_s i_{s\alpha})dt - \sigma L_s i_{s\alpha} \\ \psi_{r\beta} &= \frac{L_r}{L_m}[\int (u_{s\beta} - R_s i_{s\beta})dt - \sigma L_s i_{s\beta}] \end{aligned} \tag{23}$$

Wherein, the magnetic leakage coefficient is

$$\sigma = 1 - L_m^{\ 2} / L_s L_r \tag{24}$$

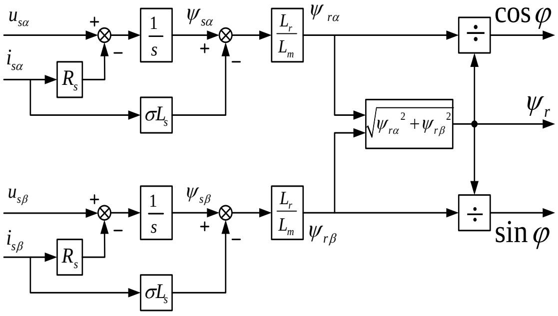

Figure 4. Voltage Flux Linkage Observer Based on Two-phase Static Coordinate System Current Model Flux Linkage Observer.

$$\begin{aligned} \psi_{r\alpha} &= \frac{1}{T_r s + 1}(L_m i_{s\alpha} - \omega_r T_r \psi_{r\beta}) \\ \psi_{r\beta} &= \frac{1}{T_r s + 1}(L_m i_{s\beta} + \omega_r T_r \psi_{r\alpha}) \end{aligned} \tag{25}$$

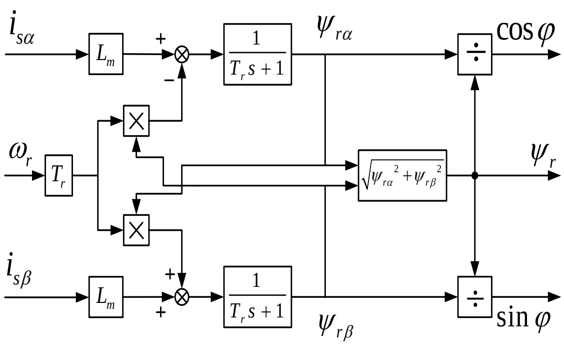

Figure 5. Current Flux Linkage Observer Based on Two-phase Static Coordinate System.

It can be seen that voltage model input includes Rs and current model input includes Tr. Therefore, the reference model selects the voltage model flux linkage observer, and the adjustable model uses the current model flux linkage observer to identify T_r; Instead, it can be used to identify R_s. In this way, the online estimation can be carried out at the same time. The identification schematic diagram is as follows.

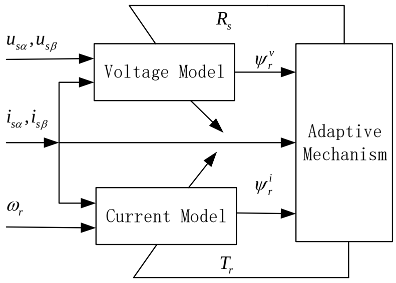

Figure 6. Schematic Diagram of Model Reference Adaptive Identification Based on Rotor Flux Linkage.

Among them, the adaptive law is adjusted with the proportional integral, and the formula is as follows:

$$\begin{aligned} 1/T_r &= K_{PT_r}[(L_m i_{s\alpha} - \psi^i_{r\alpha})(\psi^v_{r\alpha} - \psi^i_{r\alpha}) + \\ &(L_m i_{s\beta} - \psi^i_{r\beta})(\psi^v_{r\beta} - \psi^i_{r\beta})] \\ &+ K_{IT_r}\int \begin{matrix}[(L_m i_{s\alpha} - \psi^i_{r\alpha})(\psi^v_{r\alpha} - \psi^i_{r\alpha}) + \\ (L_m i_{s\beta} - \psi^i_{r\beta})(\psi^v_{r\beta} - \psi^i_{r\beta})]\end{matrix} dt \end{aligned} \qquad \begin{aligned} R_s &= K_{PR_s}[i_{s\alpha}(\psi^v_{r\alpha} - \psi^i_{r\alpha}) + i_{s\beta}(\psi^v_{r\beta} - \psi^i_{r\beta})] \\ &+ K_{IR_s}\int [i_{s\alpha}(\psi^v_{r\alpha} - \psi^i_{r\alpha}) + i_{s\beta}(\psi^v_{r\beta} - \psi^i_{r\beta})] \end{aligned} \tag{26}$$

3.2. Improved model reference adaptive algorithm

However, due to the pure integral link, the voltage model has the problem of initial value error and integral drift caused by DC bias, especially at low speed [7-10]. In order to ensure the accuracy of parameter estimation, it is necessary to improve the original flux linkage observer.

Through the literature [12], the influence of integral drift of traditional voltage model is eliminated by using low pass filter (LPF) and high pass filter (HPF) in series instead of pure integral to solve stator flux linkage. But due to the existence of low pass filter, the response speed of the system is reduced.

In reference [13], an orthogonal stator flux linkage observation algorithm based on flux linkage and counter-electromotive force is proposed. The low-pass filter is not used, and the dynamic response of the system is improved. However, the system is a high-order coupling system. When the parameters of PI regulator are large or small, it is easy to diverge or reduce the response speed. It is necessary to select the appropriate PI parameters and to compensate for the estimated stator flux linkage. Then according to the relationship between stator and rotor flux linkage, the rotor flux linkage is calculated. The following is the schematic diagram of the improved voltage model.

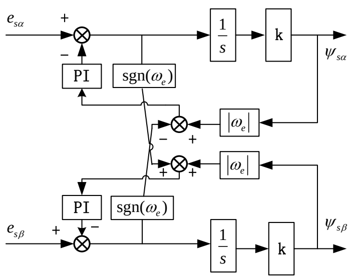

Figure 7. Block Diagram of Voltage Model Improved Algorithm Based on Orthogonality

 1449 (2020) 012130 doi:10.1088/1742-6596/1449/1/012130

$$
\begin{aligned}
e_{s\alpha c} &= (k_p + \frac{k_i}{s})(e_{s\beta} + e_{s\beta c} - \omega_e \psi_{s\alpha}) \\
e_{s\beta c} &= (k_p + \frac{k_i}{s})[-(e_{s\alpha} + e_{s\alpha c}) - \omega_e \psi_{s\beta})] \\
\psi_{s\alpha} &= \frac{k(e_{s\alpha} + e_{s\alpha c})}{s} \\
\psi_{s\beta} &= \frac{k(e_{s\beta} + e_{s\beta c})}{s}
\end{aligned}
\tag{27}
$$

The principle is to add the stator counter-electromotive force to the correction quantity and make it orthogonal to the stator flux linkage, so as to eliminate the DC bias in the estimated flux linkage. The following is the simulation comparison of flux linkage before and after the improvement of voltage model.

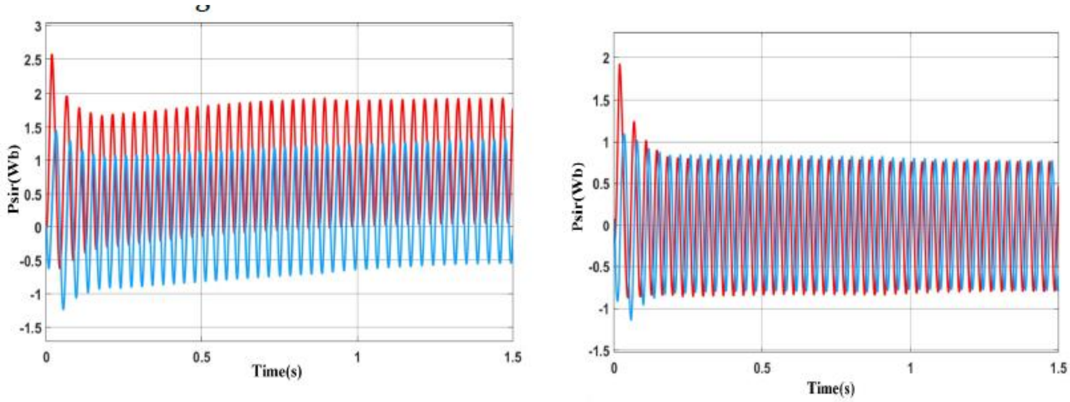

Figure 8. Comparison of Flux Linkage Output before and after Improvement of Voltage Model: (a) Traditional Voltage Model Flux Linkage Output; (b) Improved Voltage Model Flux Linkage Output

BEV requires high motor dynamic responses, so the latter is selected as the improved voltage model to identify the motor parameters.

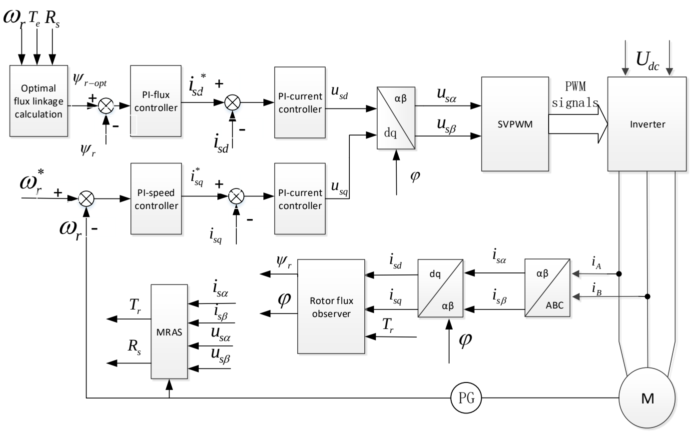

Figure 9. Block Diagram of Energy Saving Control Algorithm Based on Online Parameter Estimation

Block diagram of energy saving control algorithm based on online parameter estimation is shown in the figure. T_r and R_s of asynchronous motor are identified at the same time. When the motor is in steady state, the optimal solution of the motor model flux linkage is obtained on the basis of the identification parameters, and the energy-saving control is carried out.

 1449 (2020) 012130 doi:10.1088/1742-6596/1449/1/012130

4. Simulation Results

The simulation is carried out by matlab to verify the feasibility of the algorithm on the energy-saving control strategy of the motor. The parameters of the asynchronous motor are: stator resistance 5.5Ω, stator inductance 0.398H, rotor resistance 5.45Ω, rotor inductance 0.398H, rated power 1.1kW, rated voltage 380V, number of pole-pairs 2.

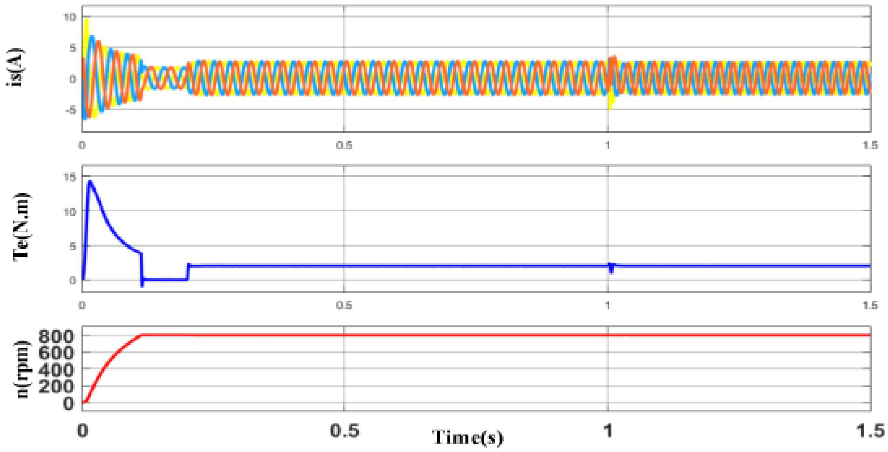

Figure 10. Motor Output Waveform.

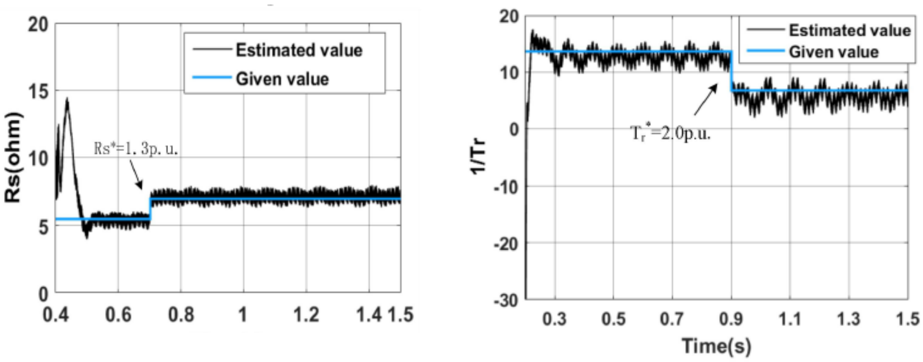

Figure 11. Online Parameter Estimation: (a) Online Estimation of Stator Resistance; (b) Online Estimation of Rotor Time Constant.

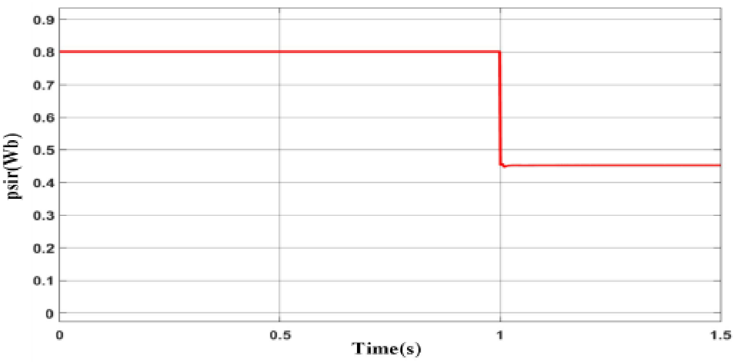

Figure 12. Given Rotor Flux.

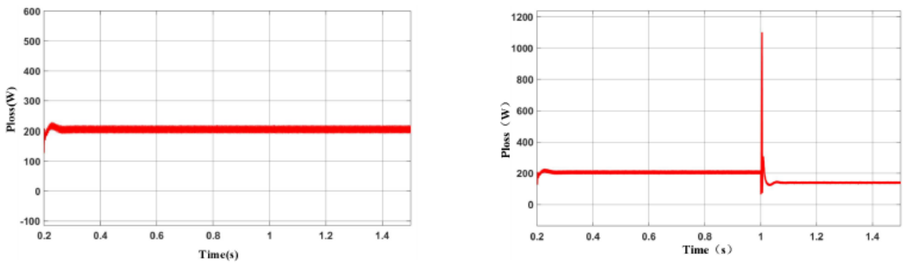

Figure 13. Motor Loss Comparison: (a) Constant Flux Control Motor Loss; (b) Optimal Flux Control Motor Loss.

As shown in the figures, the given rotation speed is 800r/min at no-load start of the motor. The stator resistance is increased from 5.5Ω to 7Ω at the time of 0.7s if applying 2N.m load at the time of 0.2s. The rotor time constant is increased by twice from the rated value at 0.9s. The identification value is followed gradually within the error of less than 17%, and the speed of the motor does not fluctuate much.

At 1.0s, the algorithm switches to the minimum loss control. It can be seen that the amplitude of the flux linkage is reduced from 0.8Wb to 0.45Wb, and the controllable loss is reduced from 200W to 170W.

5. Conclusions

The motor control algorithm used in this paper is to combine the Online Parameter Estimation with the energy-saving control. It is very suitable for the application of electric vehicle, which has high control precision requirements. Because the change of motor parameters is a gradual process, the response speed of parameter estimation is sufficient. When the motor is in steady state, the minimum loss control causes the loss of the motor to be reduced, in particular under the condition of light load and high speed. This verifies that when the electric vehicle is running on a flat and smooth road surface, the energy-saving operation can improve the endurance of the vehicle.

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