An Extended Kalman Filtering Approach for Estimation of Winding Temperature in Switched Reluctance Motors

S. R. Khayam Hoseini
M.S. Student
School of Electrical and Computer Engineering
Shiraz University
Shiraz, Iran
Email: seyed.reza.khayam.hu@gmail.com

E. Farjah
Professor
School of Electrical and Computer Engineering
Shiraz University
Shiraz, Iran
Email: farjah@shirazu.ac.ir

T. Ghanbari
Assistant Professor
School of Advanced Technologies
Shiraz University
Shiraz, Iran
Email: ghanbarih@shirazu.ac.ir

H. Givi
Ph.D. Student
School of Electrical and Computer Engineering
Shiraz University
Shiraz, Iran
Email: hadi.givi@shirazu.ac.ir

Abstract—**Switched Reluctance Motors (SRMs) have absorbed a great deal of attention in various industrial applications such as Electric Vehicles (EVs) due to their robust and fault tolerant structure. However, thermal protection of the SRM windings in case of overload conditions or abnormal cooling situations is essential to prevent the reduction of the winding insulation lifetime. This paper presents a model-based technique to estimate the phase winding temperature in the SRMs. The winding resistance is an outstanding indicator of the winding temperature due to the linear relationship between these two quantities. As a result, the proposed technique applies an Extended Kalman Filter (EKF) to estimate the phase winding resistance and as well as the winding temperature. The detailed theoretical formulations and analysis are presented. Furthermore, the effectiveness of the proposed approach is verified using simulations for a three phase, 6/4 SRM. The results confirm the capability of this technique for estimating the phase winding temperature during different operating conditions including variations in the load power and speed in the SRM.**

Keywords- extended kalman filter; model-based estimation; switched reluctance motors; temperature estimation; winding insulation

I. INTRODUCTION

Due to widespread applications of SRMs, their reliability is an important concern. The degradation or deterioration of the winding insulation due to overheating is one of the important factors which may result in the SRM malfunction. The motor winding may experience temperatures higher than its specific thermal limit under some circumstances such as transient overload conditions, running overload conditions and abnormal cooling situations [1]. As a rule of thumb, every 10°C increase above the winding temperature limit reduces the motor lifetime by 50%. Hence, it is essential to monitor the winding temperature to prevent the insulation damage as well as the motor failure.

Different approaches have been proposed for monitoring the winding temperature in electrical machines. Some approaches are based on direct temperature measurement using temperature sensors which has some disadvantages such as additional cost and increasing the weight especially in case of small and medium size machines. Furthermore, implementation of these approaches may be impossible for some of the already fabricated machines. [2-4]. Other monitoring schemes which require no placement of temperature sensors use an estimation of the temperature to protect the winding against overheating. Popular temperature estimation techniques could be categorized into thermal-model-based and parameter-based techniques [5]. The parameter-based approaches are in turn divided into signal-injection-based and model-based schemes [6].

Most of the thermal-model-based techniques apply a lumped parameter thermal circuit which consists of several resistances and capacitances. These parameters could be predetermined for a class of machines based on the dimensions, materials, full load current, service factor and the cooling system [5], [7-10]. Although the temperature estimation achieved by these techniques could be accurate enough, they are associated with some disadvantages. First, the parameters of the thermal model depend on the machine type and the cooling system. Furthermore, these models are not capable to detect the abnormal behavior of the machine since the model parameters could not be modified in real time. [9-10].

The signal-injection-based estimators are independent of the machine type, machine characteristics as well as the cooling system. They calculate the winding resistance and temperature through injection of an ac or dc signal. Injection of a high frequency ac signal to the winding has been utilized for temperature estimation in drive-fed machines [11-12]. Due to the sensitivity of these techniques to variations of the machine parameters and the dependency of the estimated resistance to the frequency of injected signal (due to stray losses), it is difficult to achieve an accurate estimation for the winding temperature [13-14]. These problems would not be encountered in case of dc signal injection approaches [2], [15]. However, the major drawback of these techniques is production of torque ripples during the intervals in which the dc signal is injected [4], [13]. This problem is critical for the SRMs where the torque pulsation is a major concern. As the amplitude of torque ripples are increased by increasing the dc signal magnitude, a trade off should be made between the torque pulsation and the estimation accuracy.

The model-based temperature estimators do not produce any torque oscillation. However, they may suffer from inaccuracies in case of extremely high speed operating conditions. Most of the model based techniques estimate the winding resistance which is an effective indicator of the winding temperature [1]. Due to noninvasive nature of the model-based techniques, they are suitable for estimation of the SRM winding temperature.

This paper presents a model-based technique for calculating the winding temperature in the SRMs. The proposed approach estimates the winding resistance based on the state space equations of the SRM by means of an EKF. Due to the direct relationship between the winding resistance and temperature, the proposed technique could simply estimate the winding temperature. To confirm the validity of this technique, it is implemented for a three phase, 6/4 SRM using MATLAB software. The estimated winding temperature for different operating conditions including variations in the load torque and speed are presented. The results prove the capability of the proposed EKF based technique.

II. STATE SPACE MODEL OF THE SRM

In this Section, the state space model of a three phase, 6/4 SRM is presented. Fig. 1 shows the structure of the proposed SRM. As seen, the rotor consists of four poles while the stator includes six poles. The red rectangular parts illustrate the phase windings wound on the stator poles.

The state vector for this SRM at the step k is $x(k)$ which could be expressed as:

$$x(k) = [i_1(k)\ i_2(k)\ i_3(k)\ \theta(k)\ \omega(k)]^T \tag{1}$$

In (1), i_1, i_2 and i_3 represent the currents of the three phases. θ and ω denote the rotor angular position and the rotational speed, respectively. To estimate the resistance of each phase, one differential equation should be added to the SRM state space equations. For the purpose of simplicity, only the resistance of the first phase of the SRM would be estimated in this paper. However, the resistance of other phases could be

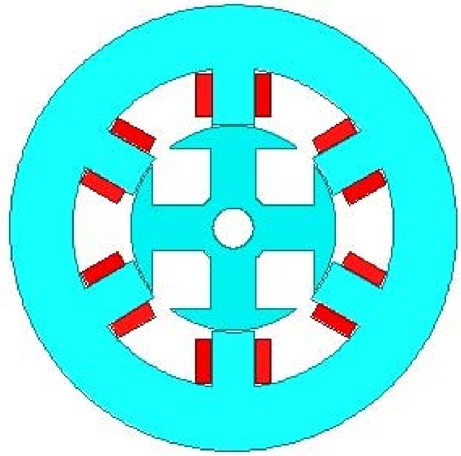


Figure 1. Structure of a three phase, 6/4 SRM

estimated in the same manner. The state space equation for the phase 1 resistance is expressed as:

$$\dot{r}_1 = 0 \tag{2}$$

The state vector is now modified to:

$$x(k) = [i_1(k)\quad i_2(k)\quad i_3(k)\quad \theta(k)\quad \omega(k)\quad r_1(k)]^T \tag{3}$$

The discrete state equations of the SRM are as follows:

$$\begin{aligned} i_1(k+1) &= f_1 = i_1(k) + \frac{T_s}{L_1(\theta)}\{v_1(k) - r_1 i_1(k) - \tfrac{dL_1(\theta)}{d\theta} i_1(k)\omega(k)\} \\ i_2(k+1) &= f_2 = i_2(k) + \frac{T_s}{L_2(\theta)}\{v_2(k) - r_2 i_2(k) - \tfrac{dL_2(\theta)}{d\theta} i_2(k)\omega(k) \\ i_3(k+1) &= f_3 = i_3(k) + \frac{T_s}{L_3(\theta)}\{v_3(k) - r_3 i_3(k) - \tfrac{dL_3(\theta)}{d\theta} i_3(k)\omega(k)\} \end{aligned} \tag{4}$$

Where $L_1(\theta)$, $L_2(\theta)$ and $L_3(\theta)$ are the inductances of the three phases. r_1, r_2 and r_3 denote the three phase resistances and T_s indicates the sampling period.

$$\theta(k+1) = f_4 = \theta(k) + T_s\omega(k) \tag{5}$$

$$\omega(k+1) = f_5 = \omega(k) + \frac{T_s}{2J}\{\sum_{n=1}^{3} i_n(k)^2 \frac{dL_n(\theta)}{d\theta} - 2T_l(k) - 2B\omega(k)\} \tag{6}$$

$$r_1(k+1) = f_6 = r_1(k) \tag{7}$$

T_l and B represent the load torque and the friction constant, respectively.

The entries of the Jacobean matrix A are achieved using the following equations:

$$A[1,1]=\frac{\partial f_1}{\partial i_1}=1+\frac{T_s}{L_1(\theta(k))}\{-r_1-\frac{dL_1(\theta(k))}{d\theta}\omega(k)\} \tag{8}$$

$$A[1,5]=\frac{\partial f_1}{\partial \omega}=\frac{-T_s}{L_1(\theta(k))}i_1(k)\frac{dL_1(\theta(k))}{d\theta} \tag{9}$$

$$A[1,6]=\frac{\partial f_6}{\partial r_1}=\frac{-T_s}{L_1(\theta)}i_1(k) \tag{10}$$

$$A[2,2]=\frac{\partial f_2}{\partial i_2}=1+\frac{T_s}{L_2(\theta(k))}\{-r_2-\frac{dL_2(\theta(k))}{d\theta}\omega(k)\} \tag{11}$$

$$A[2,5]=\frac{\partial f_2}{\partial \omega}=\frac{-T_s}{L_2(\theta(k))}i_2(k)\frac{dL_2(\theta(k))}{d\theta} \tag{12}$$

$$A[3,3]=\frac{\partial f_3}{\partial i_3}=1+\frac{T_s}{L(\theta(k))}\{-r_3-\frac{dL_1(\theta(k))}{d\theta}\omega(k)\} \tag{13}$$

$$A[3,5]=\frac{\partial f_3}{\partial \omega}=\frac{-T_s}{L_3(\theta(k))}i_3(k)\frac{dL_3(\theta(k))}{d\theta} \tag{14}$$

$$A[4,4]=\frac{\partial f_4}{\partial \theta}=1 \tag{15}$$

$$A[4,5]=\frac{\partial f_4}{\partial \omega}=T_s \tag{16}$$

$$A[5,1]=\frac{\partial f_5}{\partial i_1}=\frac{T_s}{J}i_1(k)\frac{dL_1(\theta(k))}{d\theta} \tag{17}$$

$$A[5,2]=\frac{\partial f_5}{\partial i_2}=\frac{T_s}{J}i_2(k)\frac{dL_2(\theta(k))}{d\theta} \tag{18}$$

$$A[5,3]=\frac{\partial f_5}{\partial i_3}=\frac{T_s}{J}i_3(k)\frac{dL_3(\theta(k))}{d\theta} \tag{19}$$

$$A[5,5]=\frac{\partial f_5}{\partial \omega}=1-\frac{T_s B}{J} \tag{20}$$

$$A[6,6]=\frac{\partial f_6}{\partial r_1}=1 \tag{21}$$

As a result, the Jacobean matrix A could be expressed as:

$$A=\begin{bmatrix} A[1,1] & 0 & 0 & 0 & A[1,5] & A[1,6] \\ 0 & A[2,2] & 0 & 0 & A[2,5] & 0 \\ 0 & 0 & A[3,3] & 0 & A[3,5] & 0 \\ 0 & 0 & 0 & A[4,4] & A[4,5] & 0 \\ A[5,1] & A[5,2] & A[5,3] & 0 & A[5,5] & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{22}$$

V is the Jacobean matrix relevant to partial derivatives of the process respect to noise terms. The Jacobean matrix W denotes the partial derivatives of measurements respect to noise terms. As a result:

$$V=I_2 \tag{23}$$

$$W=I_6 \tag{24}$$

I_2 and I_6 are the identity matrixes of the orders of 2 and 6, respectively. H is the matrix of partial derivatives of measurement functions respect to state variables expressed in (3). Therefore:

$$H=\begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{25}$$

The matrixes Q and R utilized in the Kalman filter estimation indicate the covariance matrixes of process and measurement noise, respectively and are defined as:

$$Q=10^{20}\times I_6 \tag{26}$$

$$R=10^{10}\times I_2 \tag{27}$$

III. Resistance Estimation Using EKF

Fig. 2 represents the procedure of estimating the SRM winding temperature using the proposed EKF based technique. As seen, the SRM is supplied by a Miller converter which is discriminated by black colors in Fig. 2. A control unit is employed to generate the gate signal for the PWM switch *Q4*. The temperature estimator unit is fed by the rotor position and the current signals to estimate the winding resistance. EKF algorithm is utilized to estimate the resistance using the state space equations presented in Section II. The estimated resistance is then given to a simple block which calculates the temperature using equation (28):

$$R_{est}=R_0\left[1+\alpha\left(T_{est}-T_0\right)\right] \Rightarrow T_{est}=T_0+\frac{\left(\frac{R_{est}}{R_0}-1\right)}{\alpha} \tag{28}$$

R_{est}, T_{est}, R_0, T_0 and α represent the estimated resistance, estimated temperature, resistance at the ambient temperature, ambient temperature and the temperature coefficient of resistivity, respectively.

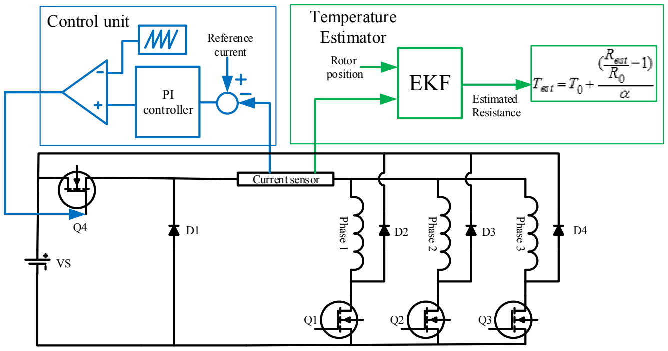


Figure 2. The procedure of the winding temperature estimation using EKF

IV. Simulation Results

In this section, the proposed EKF based algorithm for estimation of the winding resistance is implemented for a three phase 6/4 SRM using MATLAM/Simulink. The specifications of the SRM are tabulated in Table. I.

In order to verify the effectiveness of the proposed temperature estimation approach, the two following scenarios are considered. Two important factors that affect the winding temperature are the variations of the load power and the motor speed which are analyzed in this Section.

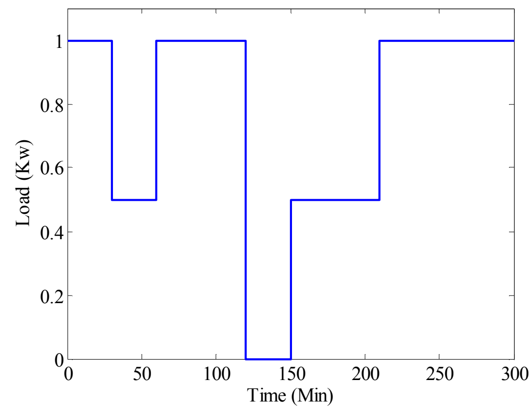
TABLE I. Specifications of the SRM Drive

Parameter	Value
Number of phases	3
Number of stator poles	6
Number of rotor poles	4
Rated power	500 W
Rated speed	1500 rpm
Rated voltage of the DC supply	50 V
Number of phase turn	400 turns
Normal phase resistance	4 Ω

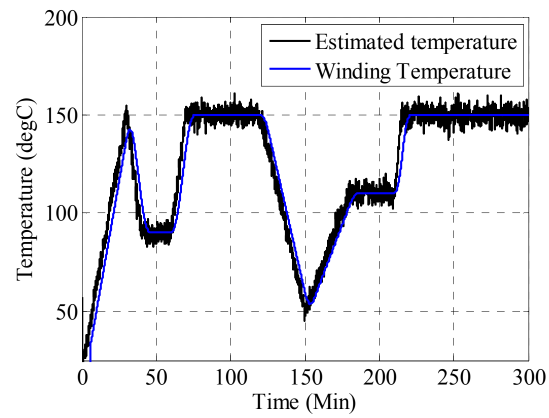
A. *Temperature estimation in case of load power variations*

To evaluate the accuracy of temperature estimation in case of load power variations, the load power profile illustrated in Fig. 3(a) is applied to the SRM. In all time intervals in Fig. 3(a), the motor speed is equal to its nominal value. The corresponding winding actual temperature and the estimated temperatures are shown in Fig. 3(b).

As seen in Fig. 3(a), the motor is started at t=0 and the load power between *t=0* until *t=30 min* is equal to *P=1 kW*. Hence, the winding temperature increases. At *t=30 min*, a step load change occurs and the load power decreases to *P=0.5 kW*. As a result, the winding temperature decreases. In a similar manner, due to step load increases at *t=150 min* and *t=210 min*, the winding temperature increases while at *t=120 min*, it reduces as a result of load power decrease. According to Fig. 3(b), in all



(a)



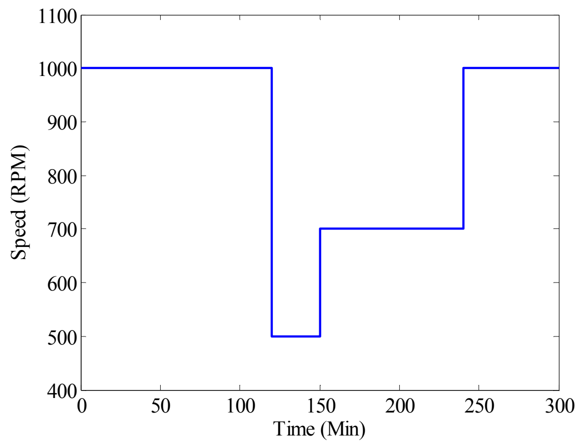
(b)

Figure 3. Estimation of the SRM winding Temperature in case of load power variations: (a) load power profile, (b) actual and estimated temperatures

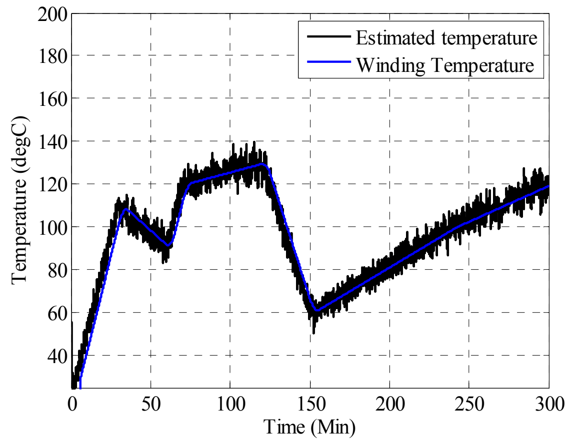
of the mentioned intervals, the winding temperature estimated by the proposed algorithm has followed the actual winding temperature desirably.

B. *Temperature estimation in case of motor speed variations*

In this part, the accuracy of the proposed Kalman filter based algorithm for estimating the winding temperature in case of variations in the SRM speed is verified. The SRM speed profile is depicted in Fig. 4(a). In all of the time intervals in this figure, the motor power is equal to the rated value. The motor has been started and the speed is equal to *ω=1000 rpm* from *t=0* to *t=120 min*. The winding temperature increase until *t=150* in which a step speed variation occurs and the speed decreases to *ω=500 rpm*. Hence, the winding temperature starts to decrease. Similarly, due to speed step increases in *t=150 min* and *t=250 min*, the winding temperature increases. Fig. 4(b) shows that in all of the time instants, the estimated temperature follows the actual winding temperature appropriately which confirms the effectiveness of the proposed EKF-based technique.



(a)



(b)

Figure 4. Estimation of the SRM winding Temperature in case of speed variations: (a) speed profile, (b) actual and estimated temperatures

V. Conclusion

This paper presents an EKF-based technique to estimate the winding temperature in the Switched reluctance motors. Kalman filter is a suitable algorithm for online estimation which is robust against measurement noises as well as model uncertainties. Furthermore, it could be simply implemented. The proposed approach requires no additional sensors. Due to the linear relationship between the winding resistance and its temperature, the winding resistance is estimated to achieve the winding temperature. The proposed method has been validated for different operating conditions including step variations in the load power and motor speed. The simulation results prove that the estimated temperature follows the actual winding temperature satisfactorily.

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