Neural Network based Modeling of SRM in Electromechanic Brake System

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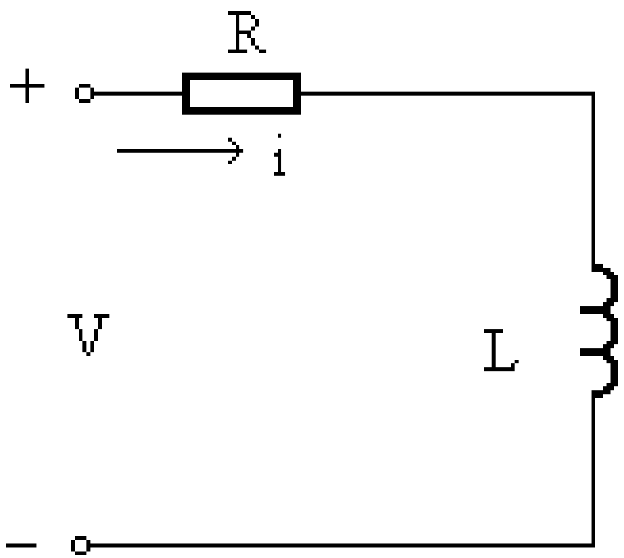
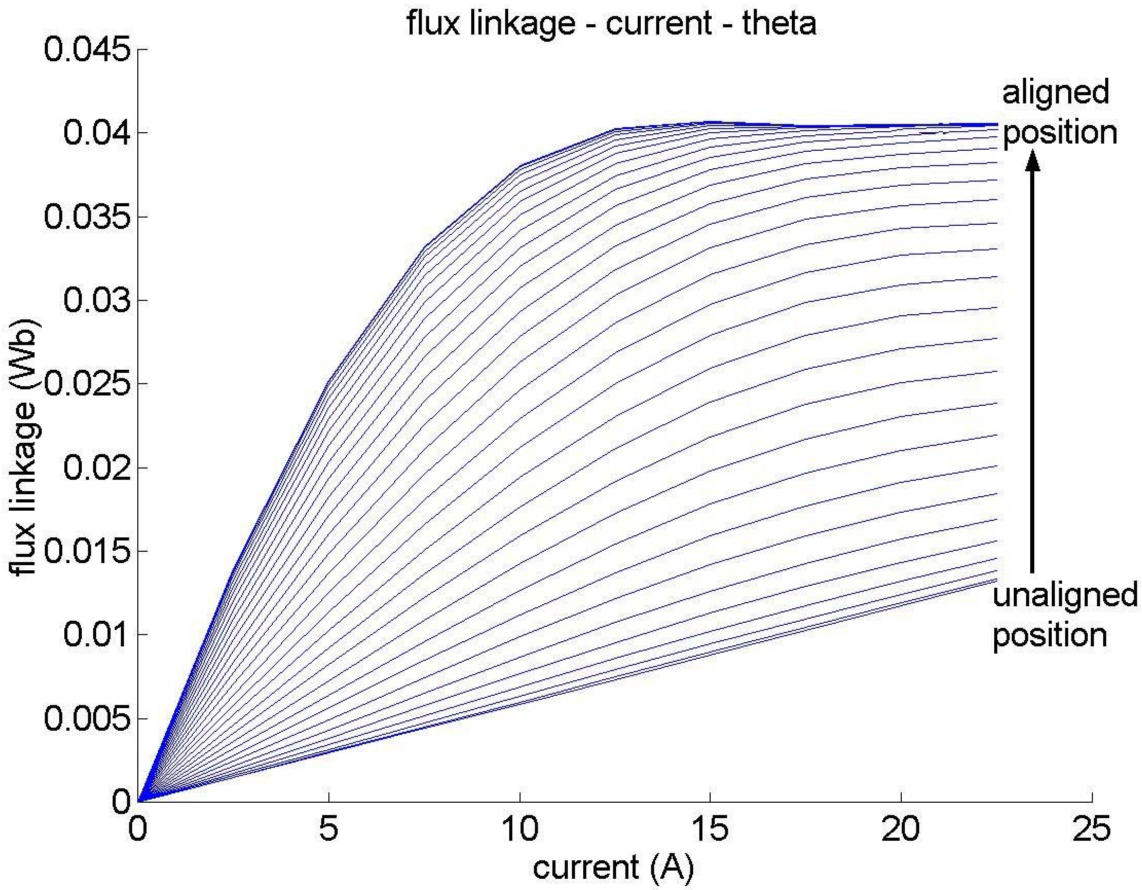
Standstill SRM Model



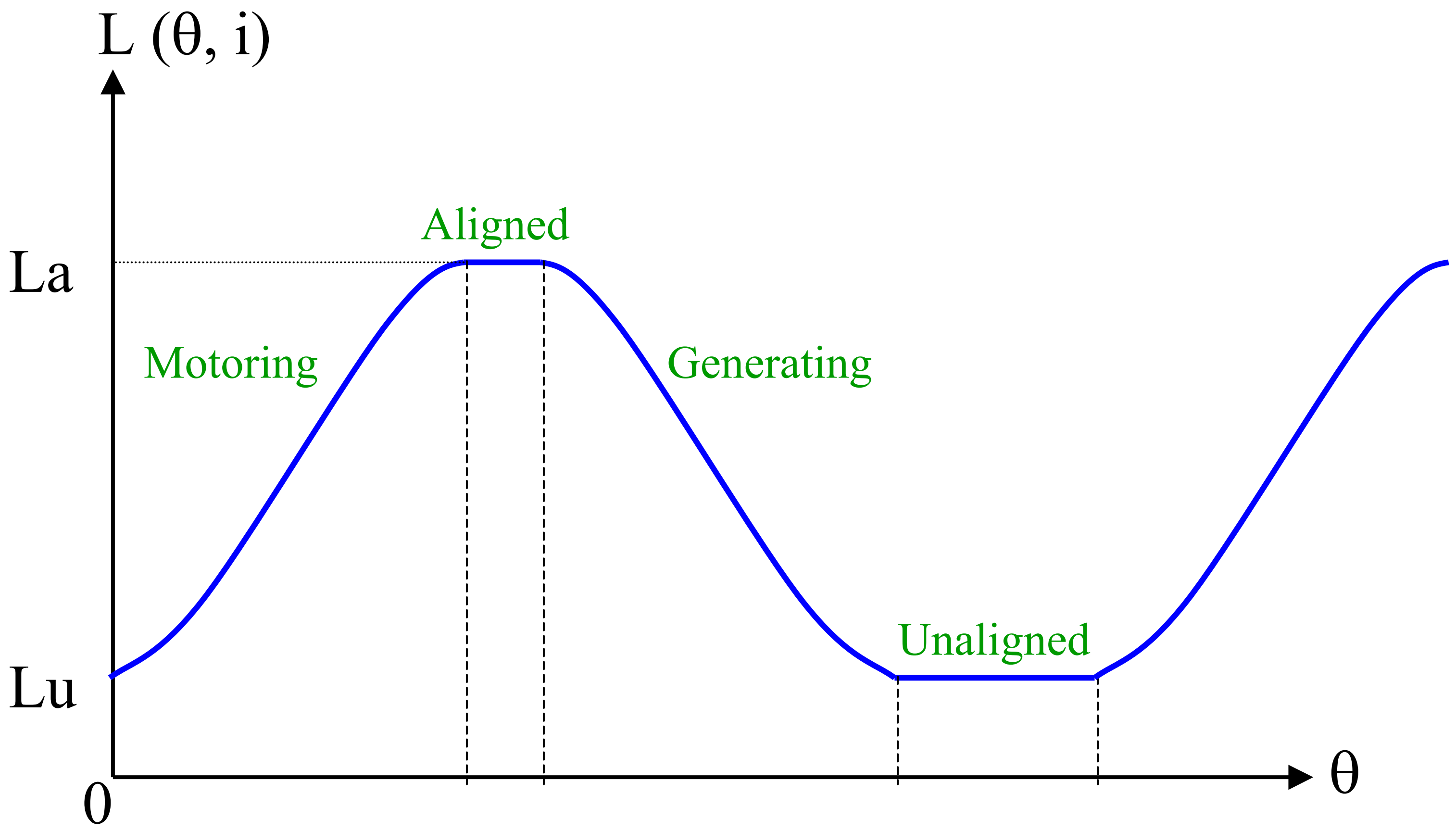
$$R = R(i)$$

$$L = L(\theta, i)$$

Flux Linkage As a Function of Phase Current and Rotor Position

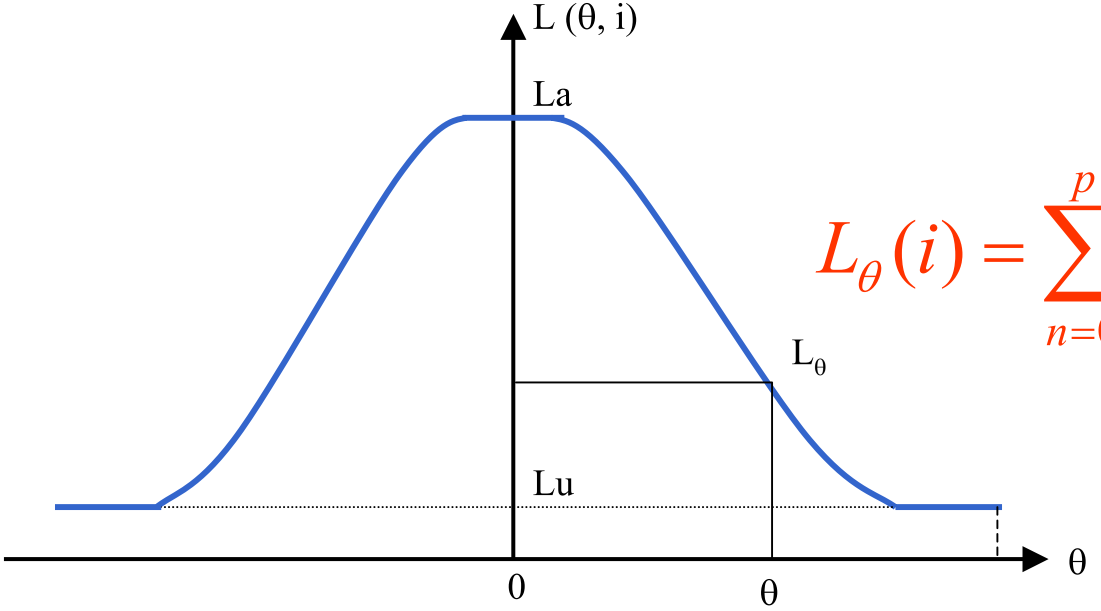


Phase Inductance Profile



Phase Inductance of SRM (1)

- Choosing Y-axis at aligned position and using Fourier series to represent phase inductance



$$L_\theta(i) = \sum_{n=0}^{p} a_{\theta,n} i^n$$

$$L(\theta, i) = \sum_{k=0}^{m} L_k(i) \cos k N_r \theta$$

Phase Inductance of SRM (2)

- Three-term Inductance Model (8/6 SRM)

$$L(\theta,i)=L_0(i)+L_1(i)\cos 6\theta+L_2(i)\cos 12\theta$$

$$\begin{bmatrix} L_{0^0} \\ L_{15^0} \\ L_{30^0} \end{bmatrix}=\begin{bmatrix} 1 & 1 & 1 \\ 1 & \cos(6*15^0) & \cos(12*15^0) \\ 1 & \cos(6*30^0) & \cos(12*30^0) \end{bmatrix}\begin{bmatrix} L_0 \\ L_1 \\ L_2 \end{bmatrix}=\begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & -1 \\ 1 & -1 & 1 \end{bmatrix}\begin{bmatrix} L_0 \\ L_1 \\ L_2 \end{bmatrix}$$

So

$$\begin{bmatrix} L_0 \\ L_1 \\ L_2 \end{bmatrix}=\begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & -1 \\ 1 & -1 & 1 \end{bmatrix}^{-1}\begin{bmatrix} L_{0^0} \\ L_{15^0} \\ L_{30^0} \end{bmatrix}=\begin{bmatrix} 1/4 & 1/2 & 1/4 \\ 1/2 & 0 & -1/2 \\ 1/4 & -1/2 & 1/4 \end{bmatrix}\begin{bmatrix} L_{0^0} \\ L_{15^0} \\ L_{30^0} \end{bmatrix}$$

where $L_{0^o}=L_{0^o}(i) \quad L_{15^o}=L_{15^o}(i) \quad L_{30^o}=const$

Phase Inductance of SRM (3)

- Four-term Inductance Model (8/6 SRM)

$$L(\theta,i) = L_0(i) + L_1(i)\cos 6\theta + L_2(i)\cos 12\theta + L_3(i)\cos 18\theta$$

$$\begin{bmatrix} L_{0^0} \\ L_{10^0} \\ L_{20^0} \\ L_{30^0} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & \cos(6*10^0) & \cos(12*10^0) & \cos(18*10^0) \\ 1 & \cos(6*20^0) & \cos(12*20^0) & \cos(18*20^0) \\ 1 & \cos(6*30^0) & \cos(12*30^0) & \cos(18*30^0) \end{bmatrix} \begin{bmatrix} L_0 \\ L_1 \\ L_2 \\ L_3 \end{bmatrix}$$

So

$$\begin{bmatrix} L_0 \\ L_1 \\ L_2 \\ L_3 \end{bmatrix} = \begin{bmatrix} 1/6 & 1/3 & 1/3 & 1/6 \\ 1/3 & 1/3 & -1/3 & -1/3 \\ 1/3 & -1/3 & -1/3 & 1/3 \\ 1/6 & -1/3 & 1/3 & -1/6 \end{bmatrix} \begin{bmatrix} L_{0^0} \\ L_{10^0} \\ L_{20^0} \\ L_{30^0} \end{bmatrix}$$

Phase Inductance of SRM (4)

- Five-term Inductance Model (8/6 SRM)

$$L(\theta,i) = L_0(i) + L_1(i)\cos 6\theta + L_2(i)\cos 12\theta + L_3(i)\cos 18\theta + L_4(i)\cos 24\theta$$

$$\begin{bmatrix} L_{0^0} \\ L_{7.5^0} \\ L_{15^0} \\ L_{22.5^0} \\ L_{30^0} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & \cos(6*7.5^0) & \cos(12*7.5^0) & \cos(18*7.5^0) & \cos(24*7.5^0) \\ 1 & \cos(6*15^0) & \cos(12*15^0) & \cos(18*15^0) & \cos(24*15^0) \\ 1 & \cos(6*22.5^0) & \cos(12*22.5^0) & \cos(18*22.5^0) & \cos(24*22.5^0) \\ 1 & \cos(6*30^0) & \cos(12*30^0) & \cos(18*30^0) & \cos(24*30^0) \end{bmatrix} \begin{bmatrix} L_0 \\ L_1 \\ L_2 \\ L_3 \\ L_4 \end{bmatrix}$$

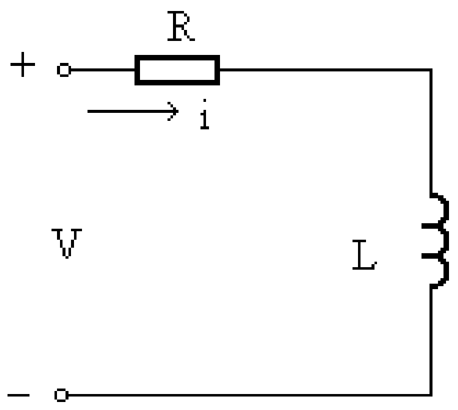
So

$$\begin{bmatrix} L_0 \\ L_1 \\ L_2 \\ L_3 \\ L_4 \end{bmatrix} = \begin{bmatrix} 1/8 & 1/4 & 1/4 & 1/4 & 1/8 \\ 1/4 & \sqrt{2}/4 & 0 & -\sqrt{2}/4 & 1/4 \\ 1/4 & 0 & -1/2 & 0 & 1/4 \\ 1/4 & -\sqrt{2}/4 & 0 & \sqrt{2}/4 & 1/4 \\ 1/8 & -1/4 & 1/4 & -1/4 & 1/8 \end{bmatrix} \begin{bmatrix} L_{0^0} \\ L_{7.5^0} \\ L_{15^0} \\ L_{22.5^0} \\ L_{30^0} \end{bmatrix}$$

Voltage Equation

$$V = R\cdot i + \frac{d(Li)}{dt} = R\cdot i + L\frac{di}{dt} + i\frac{dL}{dt}$$

$$= R\cdot i + L\frac{di}{dt} + i\left(\frac{\partial L}{\partial \theta}\omega + \frac{\partial L}{\partial i}\frac{di}{dt}\right)$$

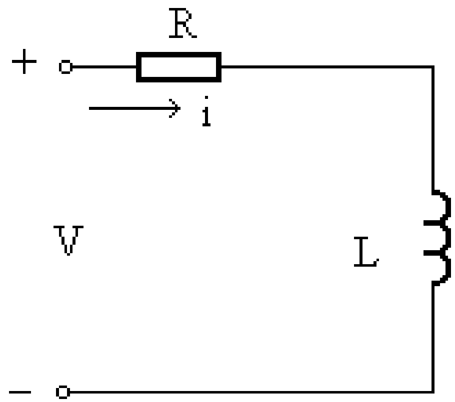


where

$$\frac{\partial L}{\partial i} = \sum_{k=0}^{m} \frac{\partial L_k(i)}{\partial i}\cos kN_r\theta$$

$$\frac{\partial L}{\partial \theta} = -\sum_{k=0}^{m} L_k(i)kN_r \sin kN_r\theta$$

Torque Computation



$$T = \frac{\partial W_c(\theta, i)}{\partial \theta} = \frac{\partial\{\int [L(\theta, i)i]di\}}{\partial \theta} = \frac{\partial\{\int \sum_{k=0}^{m} [L_k(i)\cos(kN_r\theta)i]di\}}{\partial \theta}$$

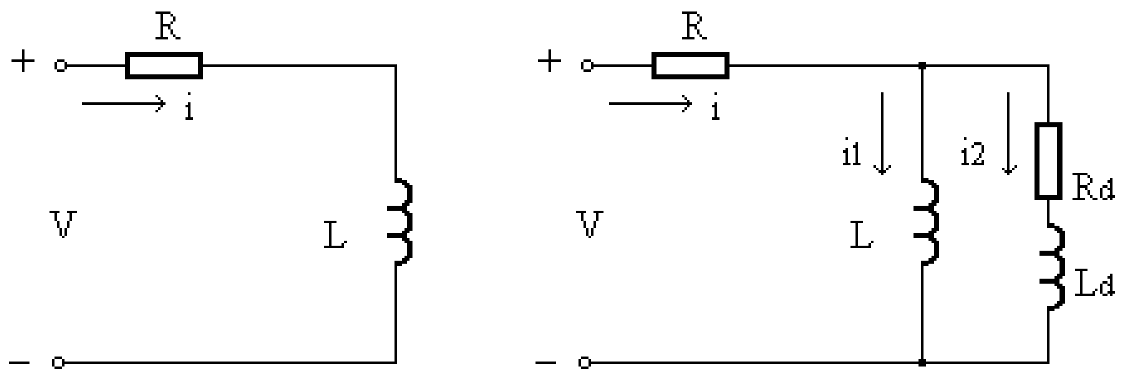
$$= -\sum_{k=0}^{m} \{kN_r \sin(kN_r\theta) \int [L_k(i)i]di\}$$

Identification of Inductance from Standstill Test Data (1)

- Obtaining L_θ
  - Finite element analysis
  - Standstill test
  - Online test
- Basic idea of standstill test
  - Move the rotor to a specific position (θ) and block it
  - Inject a voltage pulse to the phase winding
  - Measure the current generated in the phase winding
  - Select a model structure and use MLE to estimate phase parameters

Identification of Inductance from Standstill Test Data (2)

- System Model Structures



$$\dot{X}(k+1) = A(\theta_s) \cdot X(k) + B(\theta_s) \cdot u(k) + w(k)$$

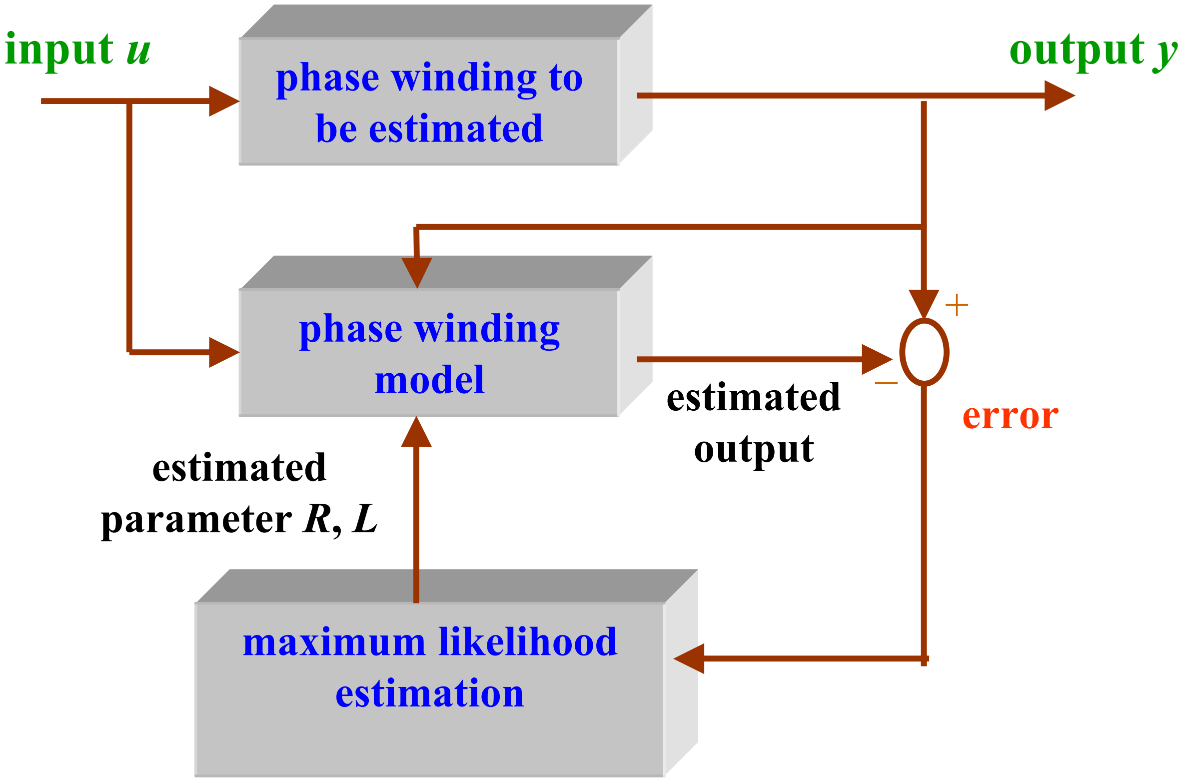
$$Y(k+1) = C(\theta_s) \cdot X(k+1) + v(k)$$

$X=[i_1, (,i_2)]$ $Y=[i]$ $u=[V]$ $\theta_s=[R, L\ (,R_d, L_d)]$

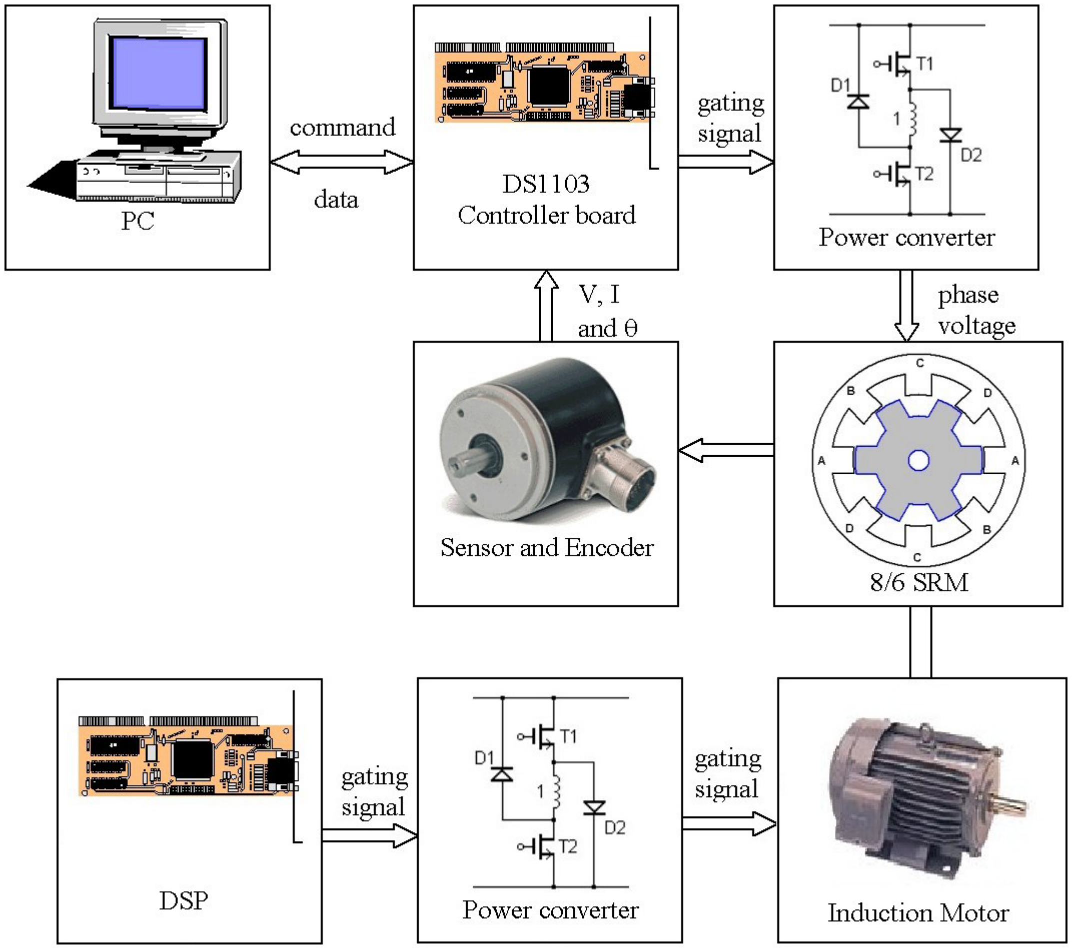
w: process noise v: measurement noise

Identification of Inductance from Standstill Test Data (3)

- Maximum Likelihood Estimation



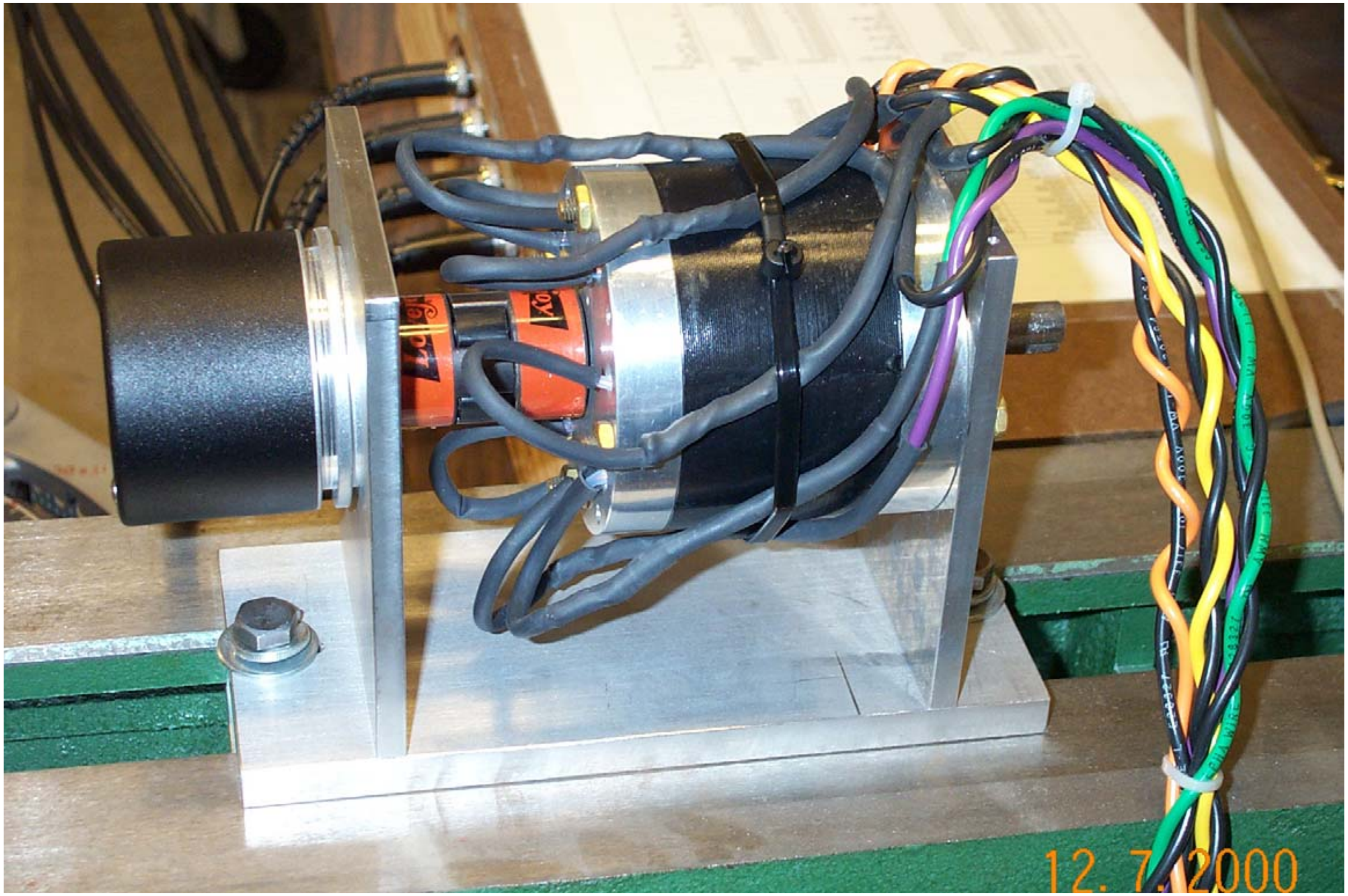
Experimental Setup with dSPACE DS1103



Pictures of Test-bed (1)

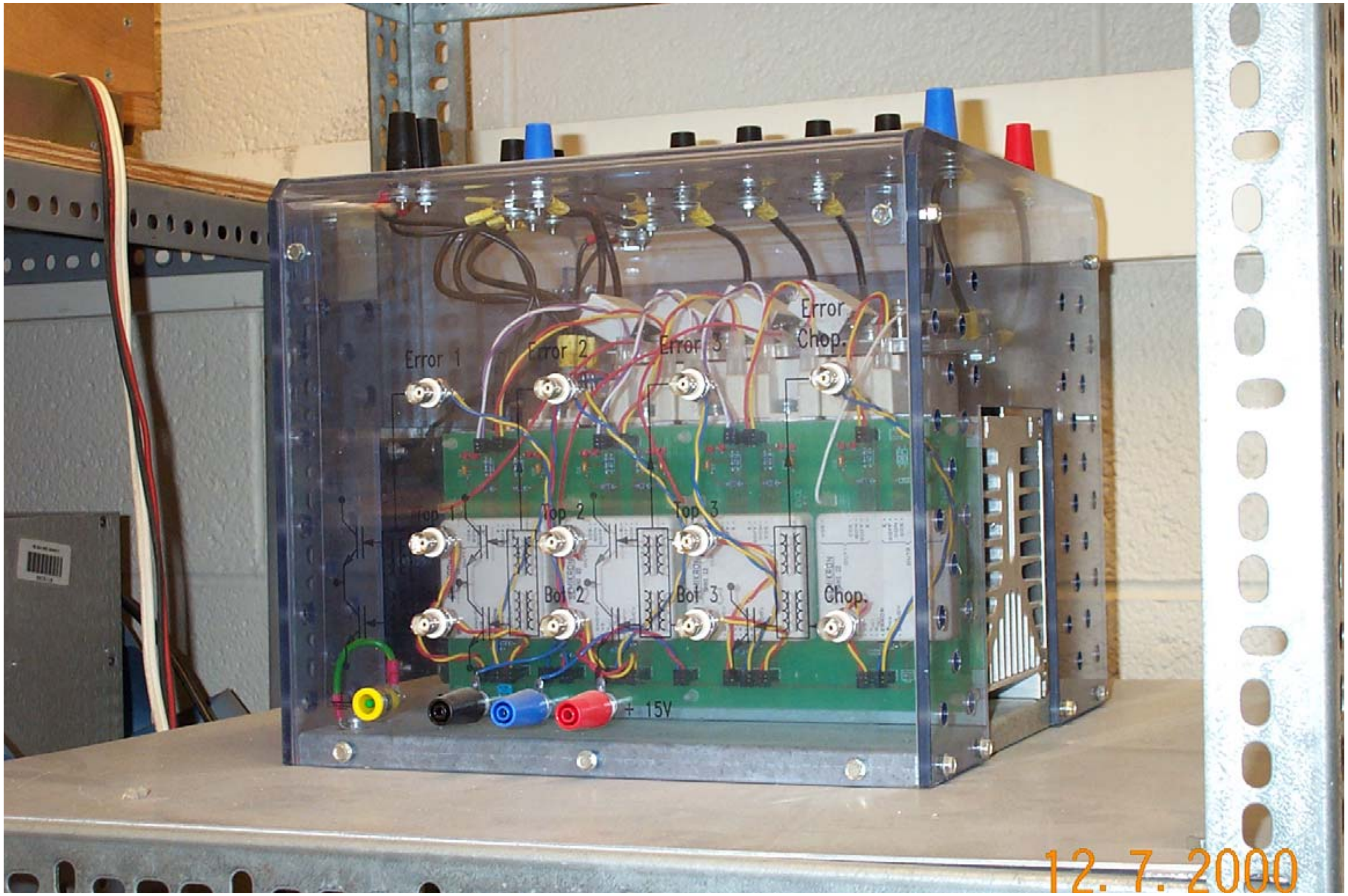
Complete Experimental System

Pictures of Test-bed (2)



8/6 SR motor with ROC 412 Single-turn Rotary Encoder

Pictures of Test-bed (3)



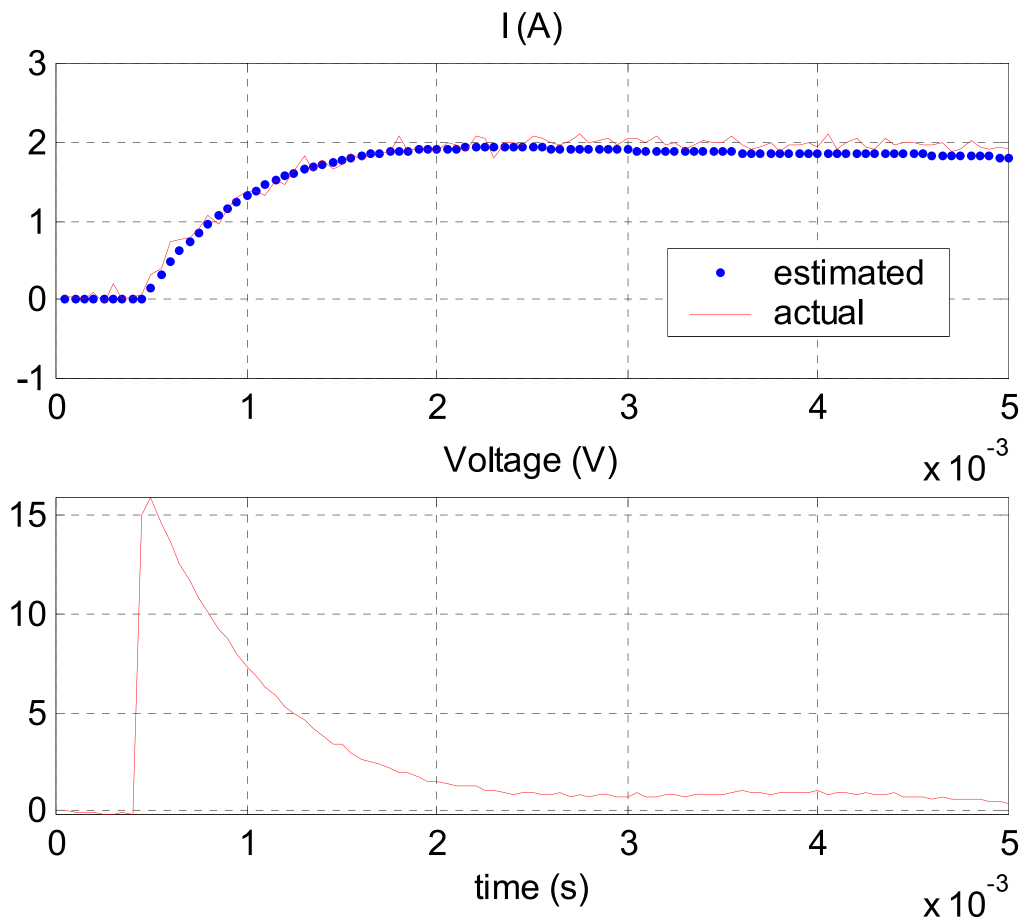
Flexible Power Converters

Pictures of Test-bed (4)

PC running dSPACE ControlDesk and Matlab

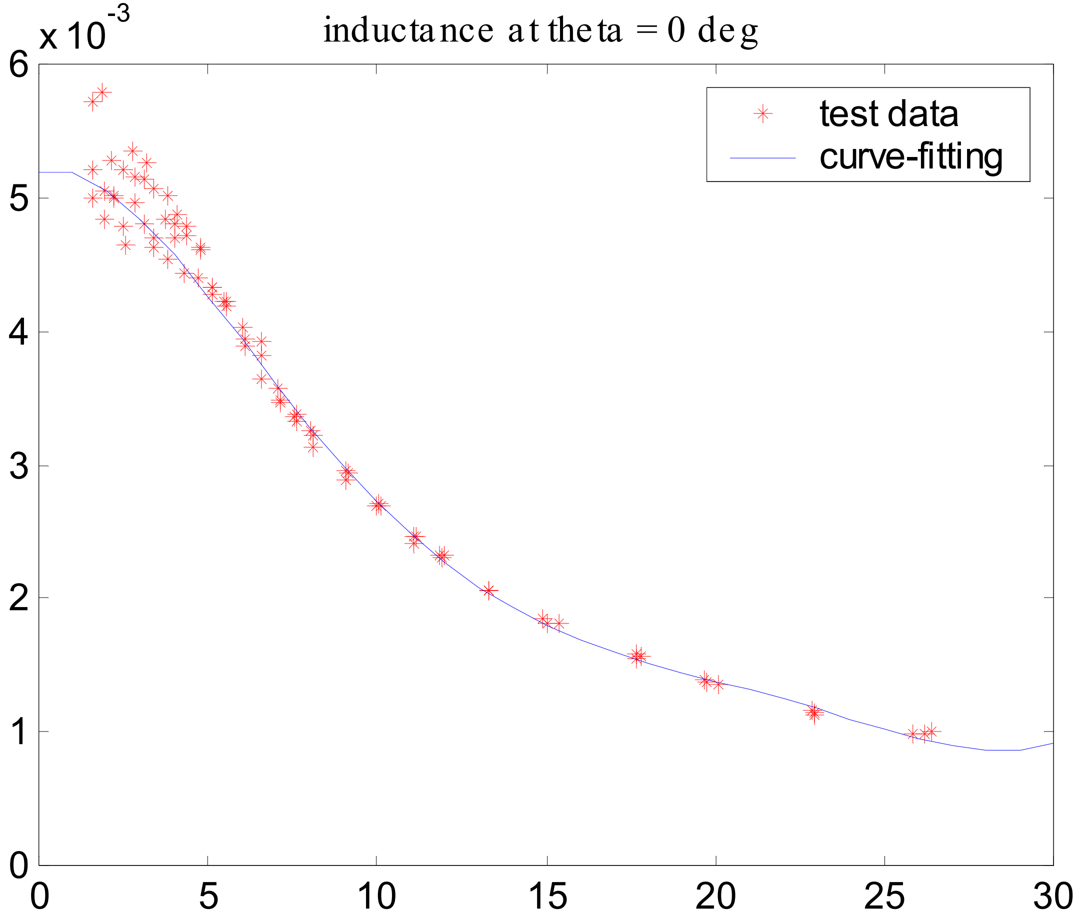
Standstill Test Results (1)

- Standstill Test Voltage and Current Waveforms



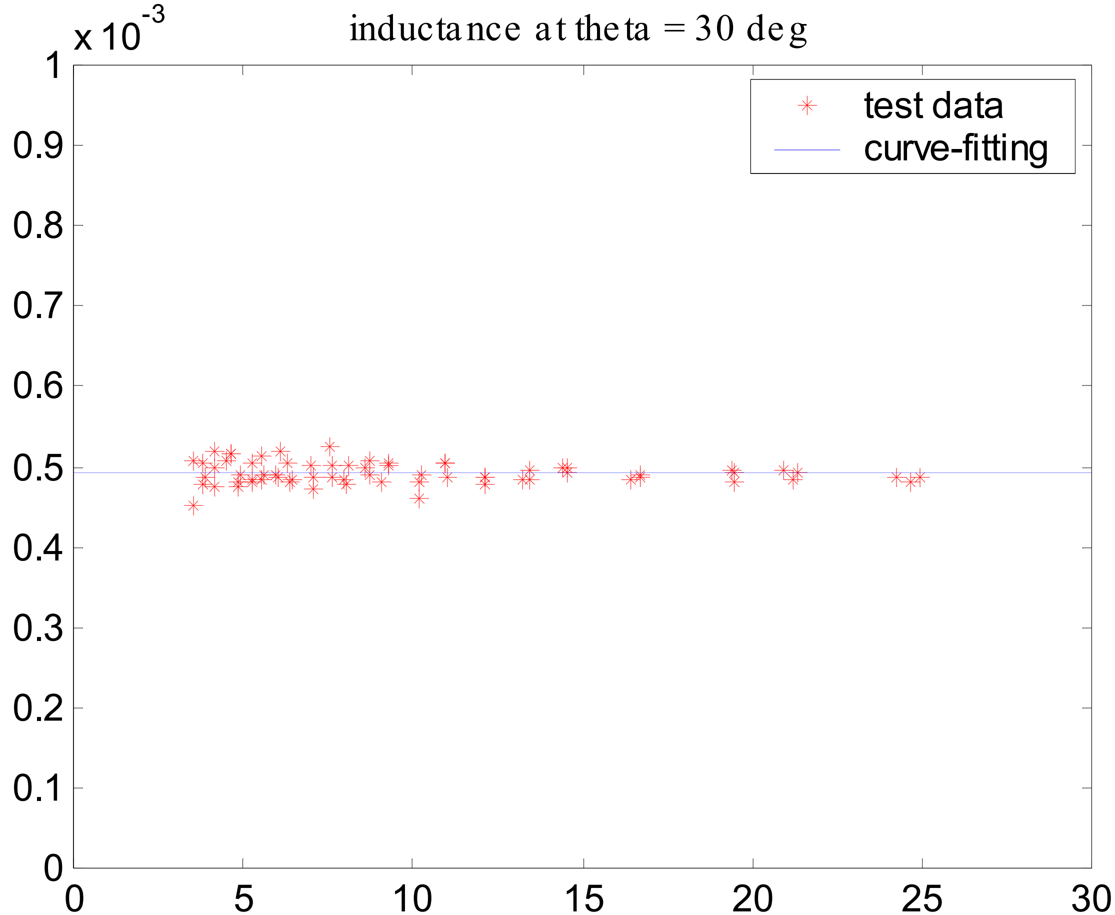
Standstill Test Results (2)

- Inductance at aligned position



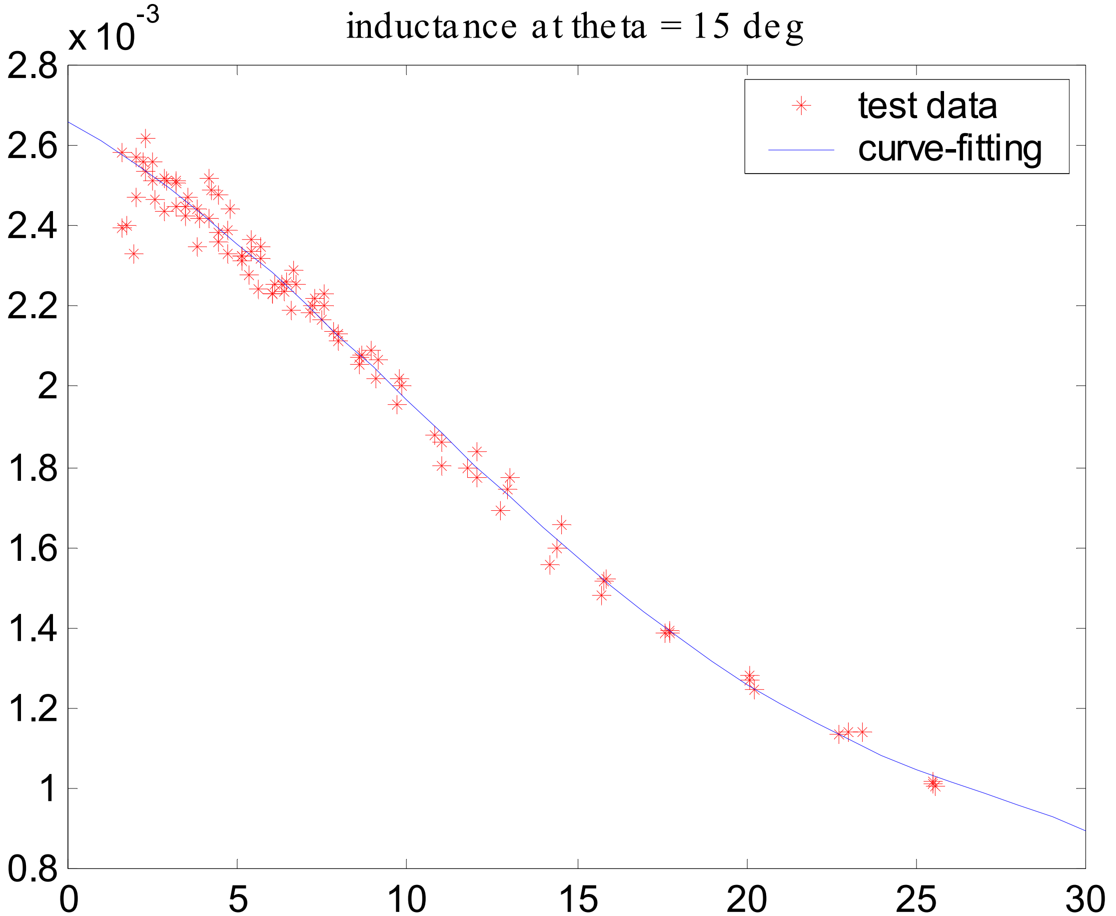
Standstill Test Results (3)

- Inductance at unaligned position



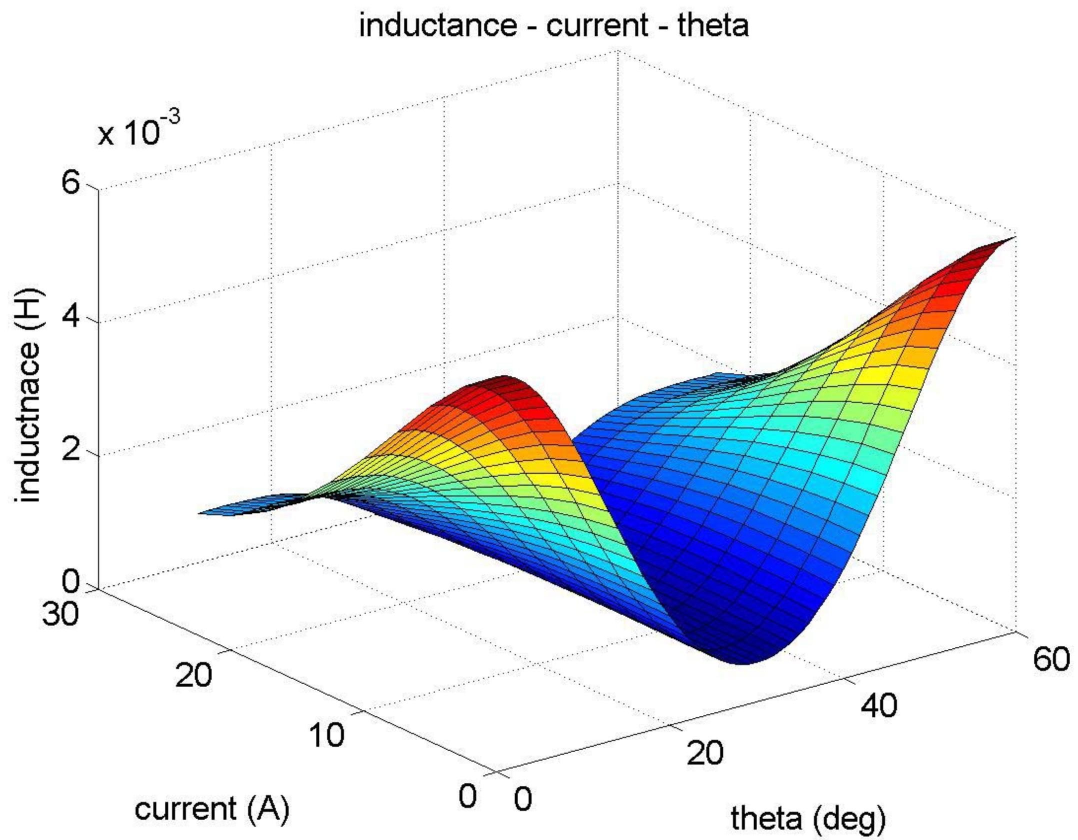
Standstill Test Results (4)

- Inductance at midway position



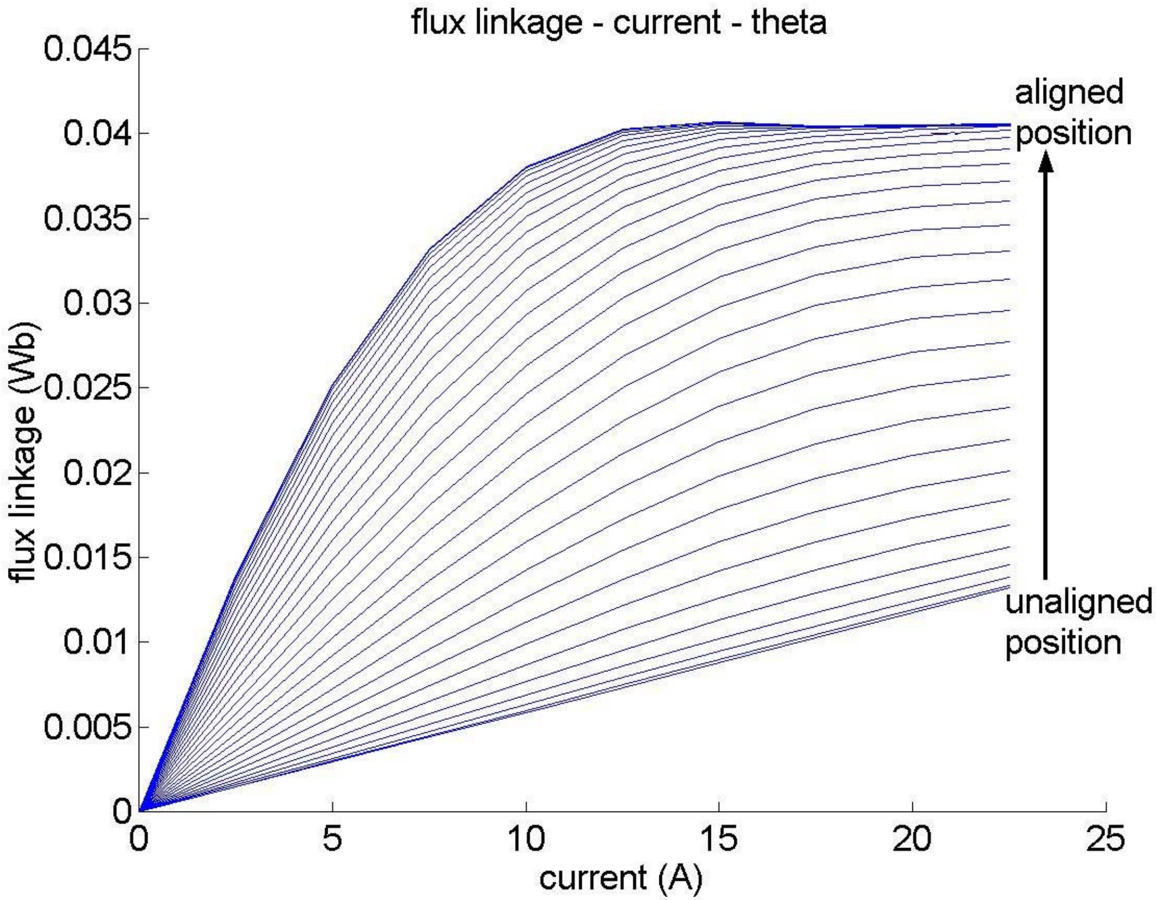
Standstill Test Results (5)

- Inductance under different currents at different rotor positions



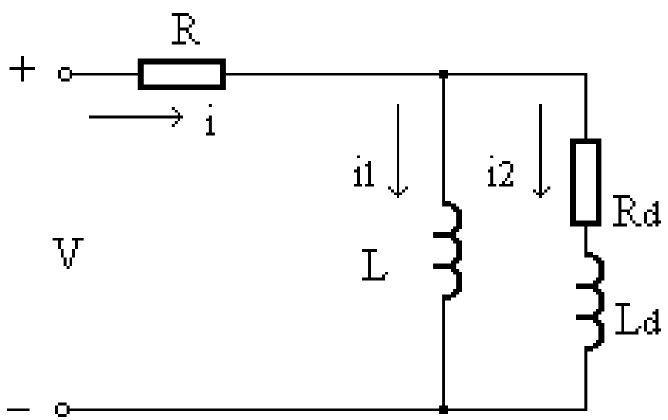
Standstill Test Results (6)

- Flux linkage



SRM Model for Online Operation (1)

- Model Structure



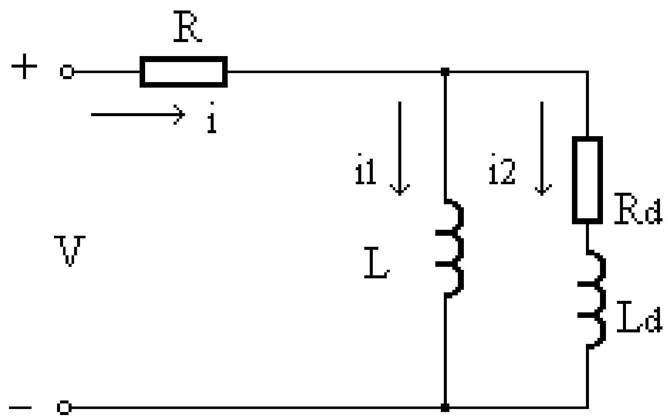
$$\begin{bmatrix} L & -L_d \\ 0 & L_d \end{bmatrix} \cdot \begin{bmatrix} \dot{i}_1 \\ \dot{i}_2 \end{bmatrix} = \begin{bmatrix} 0 & R_d \\ -R & -R-R_d \end{bmatrix} \cdot \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} V$$

SRM Model for Online Operation (2)

- State Space Representation

$$\dot{X} = AX + BU$$

$$Y = CX + DU$$



$$U = [V]$$

$$X = [i_1 \quad i_2]$$

$$Y = i_1 + i_2$$

$$A = \begin{bmatrix} L & -L_d \\ 0 & L_d \end{bmatrix}^{-1} \cdot \begin{bmatrix} 0 & R_d \\ -R & -R - R_d \end{bmatrix} \quad B = \begin{bmatrix} L & -L_d \\ 0 & L_d \end{bmatrix}^{-1} \cdot \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$C = [1 \quad 1] \qquad D = 0$$

SRM Model for Online Operation (3)

- Torque Computation

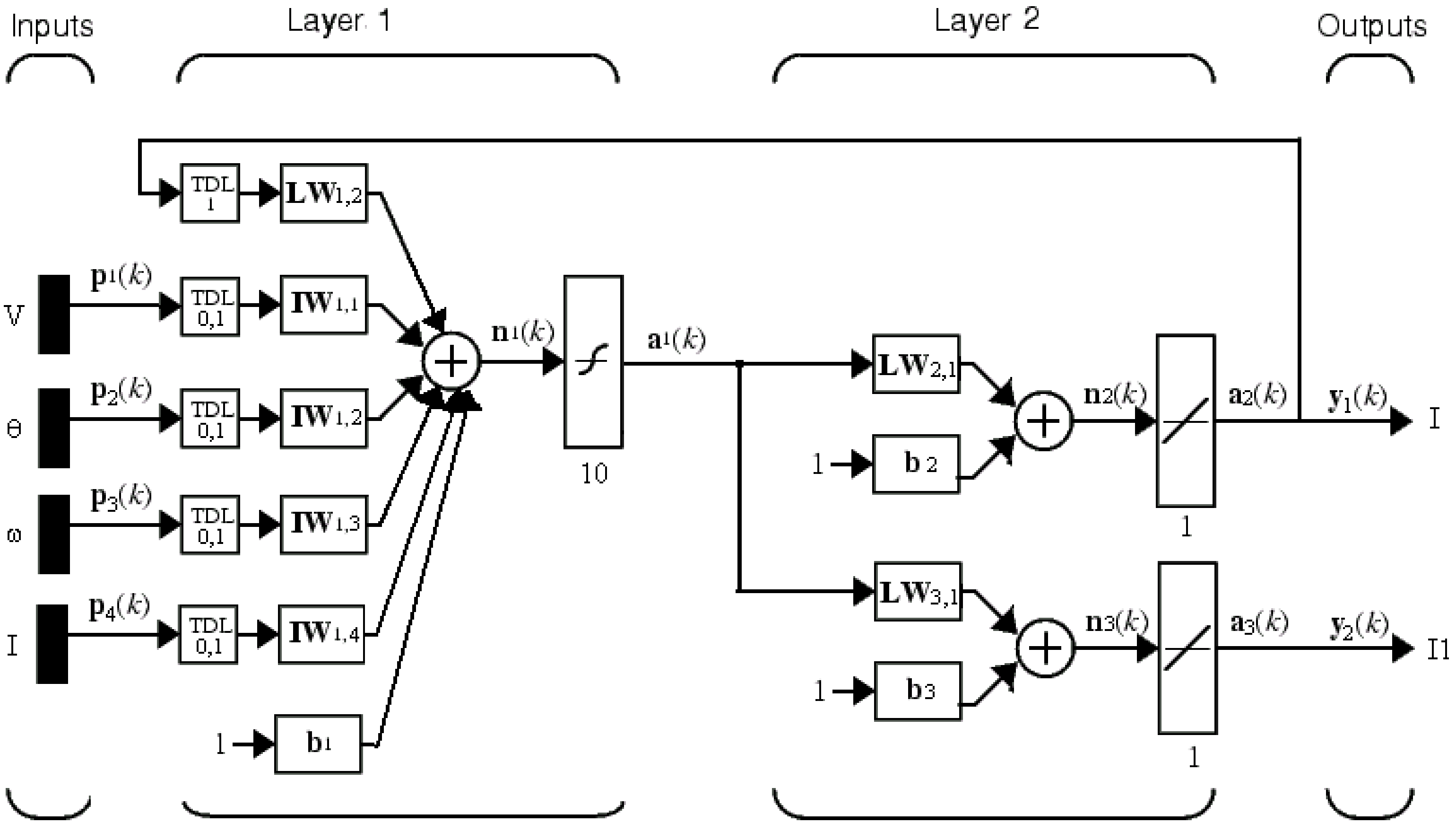
$$T = \frac{\partial W_c(\theta, i_1)}{\partial \theta} = \frac{\partial \{ \int [L(\theta, i_1) i_1] di_1 \}}{\partial \theta}$$

$$= \frac{\partial \{ \int \sum_{k=0}^{m} [L_k(i_1) \cos(kN_r \theta) i_1] di_1 \}}{\partial \theta}$$

$$= -\sum_{k=1}^{m} \{ kN_r \sin(kN_r \theta) \int [L_k(i_1) i_1] di_1 \}$$

Neural Network Mapping (1)

- 2-Layer Recurrent Neural Network



Neural Network Mapping (2)

- Input to Neural Network
  - Phase voltage V
  - Phase current i
  - Rotor position θ
  - *Rotor speed* ω
- Output from Neural Network
  - Phase current i
  - Magnetizing current i_1

Neural Network Mapping (3)

- A hyperbolic tangent sigmoid transfer function is chosen to be the activation function of the input layer

$$n_1 = \sum_{i=1}^{4} IW_{1,i} \cdot p_i + LW_{1,2} \cdot y_1 + b_1$$

$$a_1 = tansig(n_1) = \frac{2}{1+e^{-2n_1}} - 1$$

- A pure linear function is chosen to be the activation of the output layers

$$n_2 = LW_{2,1} \cdot a_1 + b_2 \qquad n_3 = LW_{3,1} \cdot a_1 + b_3$$

$$y_1 = a_2 = purelin(n_2) = n_2 \qquad y_2 = a_3 = purelin(n_3) = n_3$$

Neural Network Mapping (4)

- Application of Neural Network to Estimate Rd and Ld

After the neural network is trained with simulation data (using parameters obtained from standstill test). It can be used to estimate exciting current during on-line operation. When i_1 is estimated, the damper current can be computed as

$$i_2 = i - i_1$$

and the damper voltage can be computed as

$$V_2 = V - i \cdot R$$

then the damper resistance R_d and inductance L_d can be identified using output error or maximum likelihood estimation.

Neural Network Mapping (5)

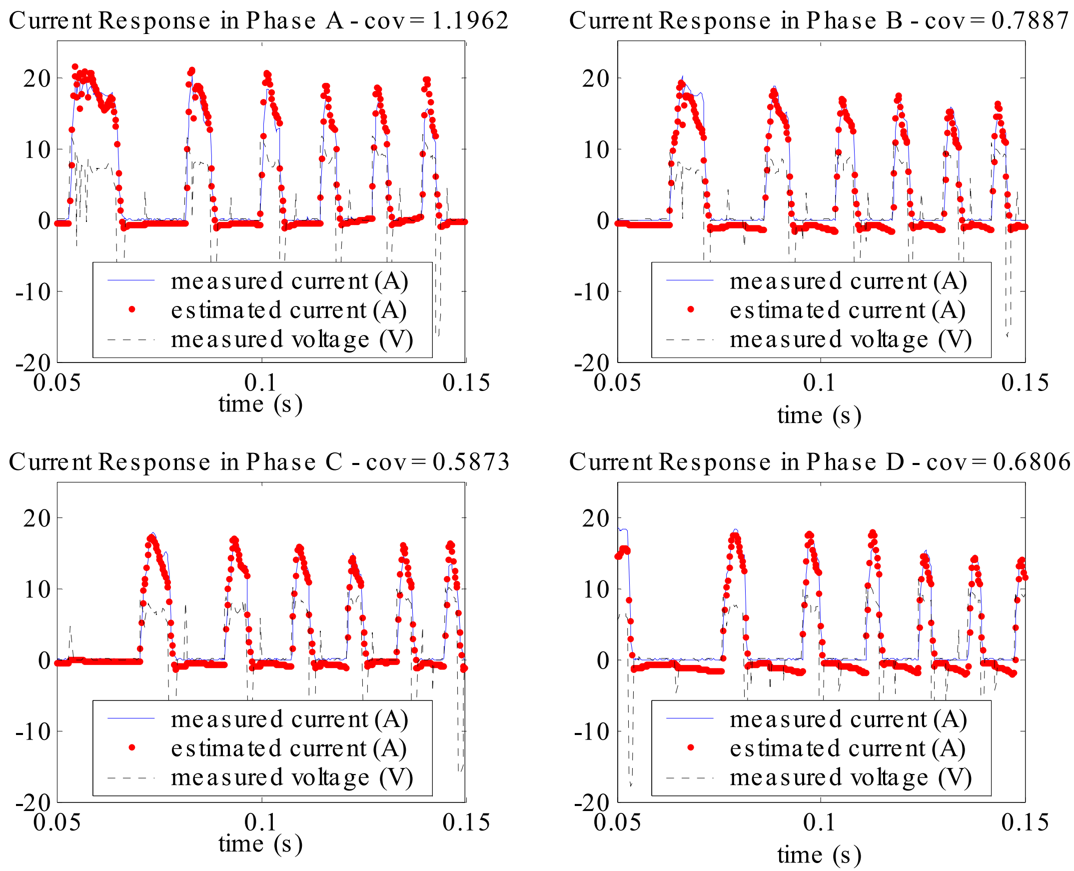
- Training of Neural Network

- First, from standstill test result, we can estimate the winding parameters (*R* and *L*) and damper parameters (*Rd* and *Ld*). The *Rd* and *Ld* got from standstill test data may not be accurate enough for online model, but it can be used as initial values that will be improved later.
- Second, build an SRM model with above parameters and simulate the motor with hysteresis current control and speed control. The operating data under different reference currents and different rotor speeds are collected and sent to neural network for training.
- Third, when training is done, use the trained ANN model to estimate the magnetizing current (i_1) from online operating data. Then compute damper voltage and current and estimate *Rd* and *Ld* from the computed V_2 and i_2 using output error estimation. This *Rd* and *Ld* can be treated as improved values of standstill test results.

Repeat above procedures until *Rd* and *Ld* are accurate enough to represent online operation.

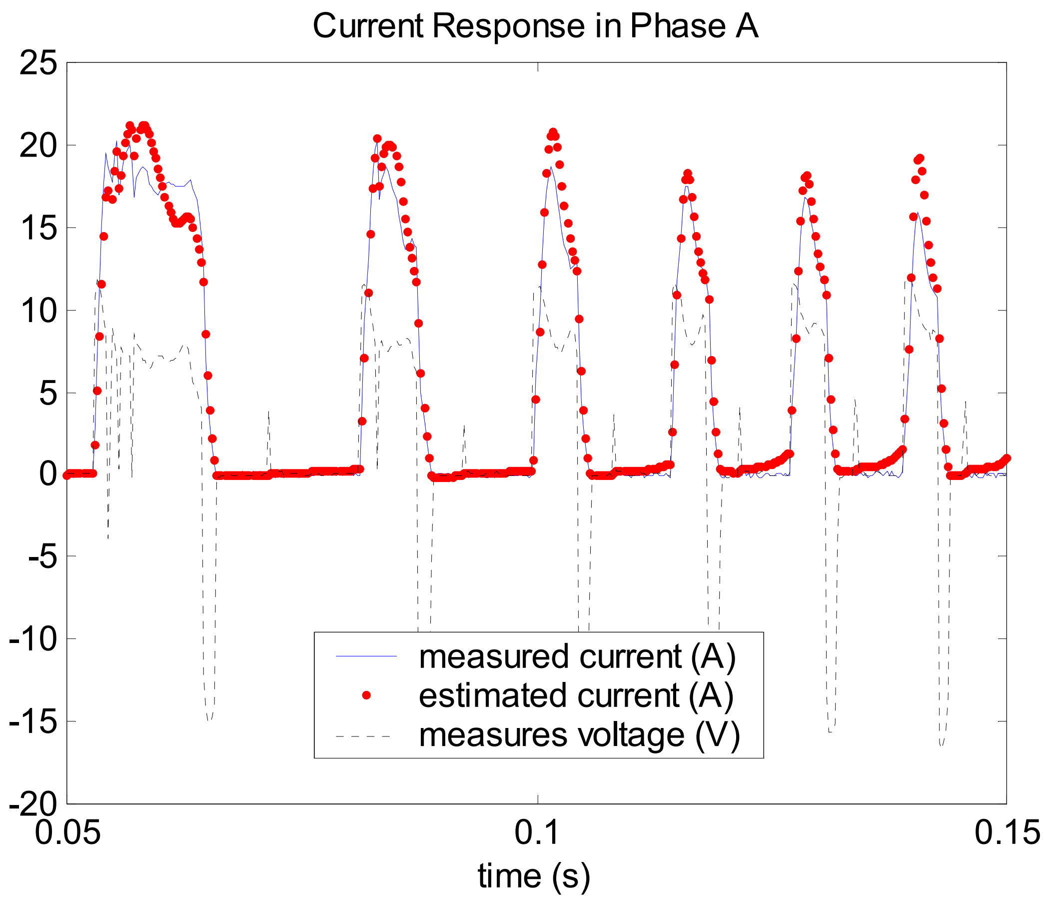
Model Validation (1)

- Model validation with operating data



Model Validation (2)

- Model validation with operating data



Conclusions

- The idea and procedure to use neural network to help identify the nonlinear model of SRM winding from operating data has been presented:

1. First the resistance and inductance of the phase winding are identified from standstill test data;
2. Then a 2-layer recurrent neural network is setup and trained with simulation data based on standstill model;
3. By applying this neural network to online operating data, the magnetizing current can be estimated and the damper current can be computed;
4. Then the parameters of the damper winding can be identified using maximum likelihood estimation.

- Tests performed on a 50-ampere 8/6 SRM show satisfactory results of this method