Chapter 6

Algorithm Development And Implementations

6.1 Switched reluctance motor design and performance analysis

The switched reluctance motor design and performance analysis consists of several sets of program written in Borland C++. The major divisions of the software are as follows:

a) Modified unaligned permeance

b) Static analysis

c) Steady state and dynamic analysis

6.2 Modified unaligned permeance

The use of modified unaligned permeance for single-tooth and multi-tooth per pole SRMs based on AFP method (Chapter 3) is proposed as a part of the CAD system for SRMs design evaluation. The program simulation is to compute the following data:

I)   Unaligned permeance for single-tooth per pole (6/4) SRM

II)   Unaligned permeance for multi-tooth per pole (12/10) SRM and

III)   Unaligned permeance for multi-tooth per pole (24/22) SRM.

6.3 Procedure for determining the unaligned permeance

6.3.1 Single-tooth per pole (6/4) SRM

The steps taken in the computation of the unaligned permeance for single-tooth per pole (6/4) SRM as follows:

I)   Read the control data of motor parameters

a) Number of stator tooth (N_s)

b) Number of rotor tooth (N_r)

c) Split ratio

d) Back of core width (BOC)

e) Stator outer diameter (SOD)

f) Rotor outer diameter (ROD)

g) Stator tooth width (T_s)

h) Rotor tooth width (T_r)

i) Rotor slot depth (RSD) and

j) Air-gap width (g)

II)   Construct the algorithm based on equations (3.6.2.1) to (3.6.2.69) (refer Figs. 3.3 to 3.7 and Appendix 3.6.2) using the parameters mentioned above.

III)   Compute the P_1, P_3 and P_4 from equations (3.8), (3.16) and (3.19).

IV)   Determine the effective unaligned permeance, P_{2eff} from equation (3.21).

6.3.2 Multi-tooth per pole (12/10) SRM

The computational sequence for calculating the unaligned permeance for multi-tooth per pole (12/10) SRM are as follows:

I)   Read the control data of motor parameters

        a) Air-gap width (g)

        b) Pole neck height (Pnh)

        c) Back of core width (BOC)

        d) Stator outer diameter (SOD)

        e) Rotor outer diameter (ROD)

        f) Stator tooth width (T_s)

        g) Rotor tooth width (T_r) and

        i) Rotor slot depth (RSD)

II)   Construct the algorithm based on equations (3.7.1.1) to (3.7.1.151) (refer Figs. 3.9 to 3.14 and Appendix 3.7.1).

III)   Determine P_1, P_2, P_3, P_4 and P_5 from equations (3.25), (3.32), (3.35), (3.38) and (3.42).

IV)   Determine the effective unaligned permeance, P_{2eff} from equation (3.44).

6.3.3 Multi-tooth per pole (24/22) SRM

The steps in program simulation are as follows:

I)   Read the control data of motor parameters.

a) Pole neck height (Pnh)

b) Pole neck width (Pnw)

c) height of stator tooth (H_t)

d) Back of core width (BOC)

e) Stator outer diameter (SOD)

f) Rotor outer diameter (ROD)

g) Stator tooth width (T_s)

h) Rotor tooth width (T_r)

i) Air-gap width (g)

j) Taper tooth angle

k) Number of stator pole and

l) Rotor slot depth (RSD)

II)   Construct the algorithm based on equations (3.7.2.1) to (3.7.2.106)
        (refer Figs. 3.17 to 3.22 and Appendix 3.7.2).

III)   Compute the P_1, P_2, P_3, P_4, P_5 and P_6 from equations (3.51), (3.60),
        (3.62), (3.66), (3.68) and (3.73).

IV)   Determine the total unaligned permeance, P_{2eff} from equation (3.75).

6.4 Static Analysis

The static analysis is proposed as a part of the CAD system for SRMs

design evaluation. The program simulation is to obtain the following data:

I)   The aligned and unaligned flux-linkage against current for single-tooth
        per pole (6/4) SRM.

II)   Average torque for single-tooth per pole (6/4) SRM.

III)   The aligned and unaligned flux-linkage against current for multi-tooth
        per pole (24/22) SRM and

IV)   Average torque for multi-tooth per pole (24/22) SRM

6.4.1 Procedure for determining the aligned and unaligned flux linkage against current for single-tooth per pole (6/4) SRM.

The computational procedure for calculating a complete set of flux-linkage against current (aligned position) indices from equations (4.15) to (4.29) is as follows:

I)   Read the motor parameters

        a) Stator outer diameter (SOD)

        b) Stator tooth width (T_s)

        c) Rotor tooth width (T_r)

        d) Bore diameter (BD)

        e) Air-gap width (g)

        f) Bore length (BL)

        g) Rotor slot depth (RSD) and

        h) Turn per phase (T_{ph})

II)   Find the aligned permeance from equation (3.3).

III)   Construct the area (region) from block modeling as shown in equations (4.15), (4.20) and (4.22).

IV)   Set the initial flux and aligned current to zero.

V)   Construct the mmf from the equations (4.19), (4.21), (4.23) and (4.24).

VI)   Increment the flux by 0.0001 every time step.

VII)   Find the total mmf from equation (4.26)

VIII)   Find the aligned current, $I_{aligned}$ from equation (4.28).

IX)   Construct the aligned flux linkage, $\varphi_{aligned}$

The computational procedure for calculating a complete set of flux linkage and current (unaligned position) induces from equations (4.15) to (4.29) is as follows:

I)   Follow step (I) for aligned position as mentioned above.

II)   Find the unaligned permeance from equation (3.21).

III)   Follow step (III) for aligned position as mentioned above.

IV)   Set the initial flux and unaligned current to zero.

V)   Construct the mmf from equations (4.19), (4.21), (4.23) and (4.25).

VI)   Increment the flux by 0.0001 every time step.

VII)   Find the total mmf from equation (4.27).

VIII)   Find the unaligned current, $I_{unaligned}$ from equation (4.29).

IX)   The computational sequence to find the unaligned flux-linkage,

$\varphi_{unaligned}$ is as follows:

a) Find the slope using numerical analysis.

b) An updated value of $I_{unaligned}$ for every time step.

c) Construct the unaligned flux-linkage, $\varphi_{unaligned}$. This can be

represented   as:

$$\varphi_{unaligned} = slope \times \left(I_{aligned\,(i)} - I_{unaligned\,(i-1)}\right) + flux \times T_{ph} \qquad (6.1)$$

d) An updated value of $I_{aligned}$ and $I_{unaligned}$ for every time step.

6.4.2 Procedure for determining average torque

The average torque can be estimated from the area between the extreme aligned and unaligned flux-linkage against current curves. It can be calculated using equations (4.41) to (4.50). Steps taken to compute the average torque in program simulation are as follows:

I)   Set the initial ΔW to zero.

II)   Find the $\Delta W_{aligned}$ from the mathematical procedure for aligned position as   mentioned above, the $\Delta W_{aligned}$ can be represented as:

$$\Delta W_{aligned} = (\Delta I)(\varphi_{aligned}) \qquad (6.2)$$

III)   Compute the $\Delta W_{unaligned}$ based on the unaligned position. Thus,

$$\Delta W_{unaligned} = (\Delta I)(\varphi_{unaligned}) \qquad (6.3)$$

IV)   Construct the ΔW from steps (II) and (III). Therefore,

$$\Delta W = \Delta W_{aligned} - \Delta W_{unaligned} \qquad (6.4)$$

V)   Find the total work, W. This can be represented as:

$$W = W + \Delta W \qquad (6.5)$$

VI)   Calculate the average torque, T_{ave} from equation (4.29).

where ΔW, ΔI, $\Delta W_{unaligned}$ and $\Delta W_{aligned}$ are updated every time step.

6.4.3 Procedure for determining the aligned and unaligned flux-linkage against current curves for multi-tooth per pole (24/22) SRM.

The algorithm used to evaluate the permeance and areas of discretised blocks are different from that used in single-tooth per pole (6/4) SRM. The aligned and unaligned permeances can be found from equations (3.3) and (3.44). The area of block modeling is similar to the one presented in equations (4.15), (4.20) and (4.22).

6.5 Steady state and dynamic analysis

The use of nonlinear theory of steady state and dynamic analysis (Chapter 5) is proposed as a part of the CAD system for SRMs design evaluation. The program simulation is to obtain the following data:

I)   The magnetisation characteristics at intermediate rotor positions. The data can be divided into two parts:

a)   Flux linkage against current (rotor position as a parameter) and

b)   Flux linkage against rotor position (current as an undetermined parameter)

II)   Instantaneous torque

III)   Energy conversion loop

IV)   Phase current variation $\left(\dfrac{i}{\theta}\right)$ and average electromagnetic torque and

V)   Dynamic Torque characteristic

6.6 Mathematical model

6.6.1 Magnetisation characteristics at intermediate rotor positions

The intermediate rotor position magnetisation curves are calculated based on aligned and unaligned magnetisation curves data. The curves are modeled using the functional equations (equations (5.8), (5.22) and (5.39)) which the Frö lich-like relationship is used to model the curves in region I and III see Fig. 5.2. The instantaneous torque is obtained from equations (5.58), (5.59) and (5.60) with current as a parameter.

6.6.2 Energy conversion loop

The basic algorithm is based on equation (5.61),

$$\varphi = \int (V - iR)dt \qquad\qquad (6.6)$$

or

$$V = iR + \frac{d\varphi}{dt} \qquad\qquad (6.7)$$

i.e voltage applied to the stator terminals equals the sum of voltage drop due to resistive losses and the induced voltage due to flux linkage variations [32].

The discrete form of this equation is

$$\Delta\varphi = (V - iR)\Delta t \qquad (6.8)$$

The mathematical procedure is described as follows,

I)   Initial flux linkage, φ_0 and current, i_o are set to zero.

II)   Control data: Δt, ω, V, R, turn on angle, θ_{on} and turn off angle, θ_{off} are given.

III) Applying numerical analysis method (i.e Runge-Kutta 4th order), the flux linkage is calculated for every time step. This can be represented by,

$$\Delta\varphi_n = (V - i_n R)\Delta t \qquad (6.9)$$

$$\varphi_{n+1} = \varphi_n + \Delta\varphi_n \qquad (6.10)$$

$$\theta_{n+1} = \theta_{on} + (n + 1)\Delta\theta \qquad (6.11)$$

IV)   An updated value of i is found from the magnetisation data $(\varphi / i / \theta)$ at the current rotor position. This value of current is used to calculate the flux linkage   for the next time step.

V)   Step (III) and (IV) are repeated until $\theta = \theta_{off}$ then

At θ_{off}, i will decrease to zero. The data for ω, $\Delta\theta$, V, θ_{on} and θ_{off} are from [5] which was provided by Prof. M.R. Harris.

6.6.3 Average electromagnetic torque

The average electromagnetic torque is calculated from the area under dynamic trajectory (loop conversion).

The average electromagnetic torque is given as in [3];

$$T_{em} = \frac{W.N_s.N_r}{4\Pi} \qquad (6.12)$$

where W = Total area, N_s and N_r are number of stator and rotor poles respectively.