Analysis of Dynamic Characteristics of Switched Reluctance Motor Based on SPICE

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***Abstract*—A method for calculating the dynamic characteristics of Switched Reluctance Motor (SRM) has been proposed. The inductance model of SRM that is changed following the rotor position can be estimated from FEM analysis. Based on the model, we design a circuit simulation of SRM using SPICE, which can simulate voltages, currents, torque and rotation speed of the SRM.**

***Index terms*—Switched Reluctance Motor, Reluctance, Dynamic characteristics, Circuit simulation**

I. INTRUDOCTION

SWITCHED Reluctance Motor(SRM), using reluctance torque which comes from the change of the relactance of magnetic circuit, can be thought of as a type of synchronous motor. However, compared with a regular synchronous motor, no field winding, slip ring and brush are used. In addition, instead of using a permanent magnet, a pole configuration shaped by stacked-Si-Fe will be used as rotor. The SRM has desirable features including simple construction, high reliability and lower cost. Recently, following the development of power electronics, the interest in SRM has risen year after year [1], [2], even though it also has some bad performance, for example, low power factor, large torque ripple and that the rotor position must be detected. However, analysis and optimum design have not been clarified fully [3]. A main reason for this is that it is dependent so much on experimental knowledge in making and controlling of a SRM. Thus, a computer-based simulation tool of SRM including a model of SMR and driving circuit will be useful in design of SRM and in the development of various control algorithms.

In this paper, we present a method for calculation of dynamic characteristics of SRM. Based on the method, a computer simulation tool in order to analyze the dynamic characteristics of SRM also has been proposed. Because the reluctance of SRM is variable following the rotor position, the FEM analysis was applied to estimate the inductance depending on the rotor position. Then using inductance characteristics, an analysis model of SRM was constructed using a SPICE simulator. The calculation method will be discussed in section 2, the SPICE model will be found at section 3, and section 4 is conclusion.

II. RELUCTANCE ESTIMATION

The magnetic coenergy will be used to estimate the reluctance of SRM. The magnetic coenergy can be calculated from magnetic field analysis. But the magnetic coenergy can not be measured directly, so we measure the output torque of SRM in order to verify the estimated reluctance.

A. Reluctance Estimation using magnetic field analysis

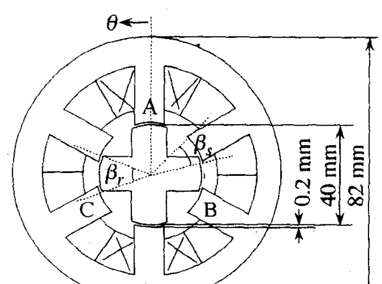
Fig.1 is the schematic diagram of a six-stator pole, four-rotor pole, three phase motor with phase A stator winding.

Assume that the magnetic characteristics of the Si-Fe in both stator and rotor to be linear and that the motor shape is constant in axis direction. Let the relative permeability of Si-Fe be 3000 and the relative permeability of the winding part be 1. A FEM program, ANSYS, has been used to magnetic field analysis and the boundary condition of the vector potential at the outermost contact circle is set to be zero. Consider that only phase A has been excited when the rotor rotates 90 degree. The same magnetic circuit will be reconstructed due to the four-rotor pole. We assume the zero position as that when the center of both excited stator pole and the rotor pole just meet. Then we calculate the magnetic coenergy from 0 deg to 45 deg on 3 deg steps.

It is well known that the magnetic coenergy and the reluctance has following relation

$$W' = \frac{1}{2} L(\theta) i^2 , \qquad (1)$$

where W' is magnetic coenergy, i is exciting current, $L(\theta)$ is reluctance and θ is the position of rotor. So the reluctance can be obtained for every 3 degree from 0 to 45 degree. The result of the reluctance as a function of θ in the case of $i = 2$ A is shown in Fig.2. It can be obtained from Fig.2 that the reluctance decreases with increasing θ and after $\theta = 33$ deg, the reluctance appears constant. The outcome of flux density distribution at $\theta = 24$ deg is shown in Fig.3.



Stator pole arc β_s	30 deg.
Rotor pole arc β_r	32 deg.
Stack length	51 mm
Number of windings / phase	72 turns

Fig. 1. The structure of the SRM with parameters

Manuscript received October 13, 1997.

B. Calculation of Torque

To verify the estimated reluctance of SRM, the following indirect method is used.

Using following well-known relation, the torque can be calculated easily from magnetic coenergy.

$$\tau = \frac{\partial W'}{\partial \theta} = \frac{1}{2} i^2 \frac{dL(\theta)}{d\theta} \tag{2}$$

From the above relation, reluctance torque occurs if we turn on the excitation current when the rotor is in the position where the differentiation of reluctance is positive. Clearly the torque and the reluctance depend on θ, and hence a rotor position detector is needed. The calculated value and the measured value of static torque under three values of exciting current is shown in Fig.4.

III. DYNAMICAL CHARACTERISTIC ANALYSIS OF SRM USING SPICE MODEL

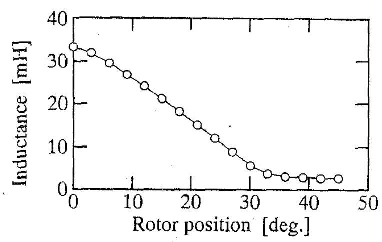


Fig.2. Variable Inductance as a function of position

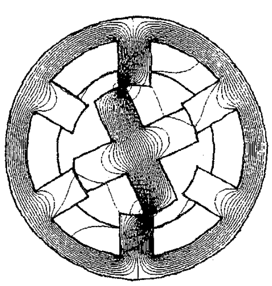


Fig.3. FEM analysis result when $\theta = 24\,\text{deg}$

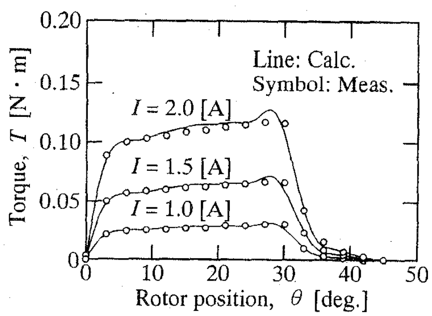


Fig.4. The characteristics of static torque

A. SPICE model of SRM

On the basis of inductance –rotor position characteristics, we can construct a circuit analysis model of SRM using SPICE simulator [4]. The SPICE model consists of a main circuit and four sub-circuits that express variable inductance, control signal, motor torque and equation of motion. The simulation flow diagram between main circuit and sub-circuit is shown in Fig.5.

The main circuit is shown in Fig.6, in which L_A, L_B and L_C are variable inductances that represent the SRM, V_1 and V_2 are the DC power sources, $Q_{A1},..Q_{C2}$ are the bipolar transistors used as switch, $D_{A1},..D_{C2}$ are the feedback diodes and $R_A,..R_C$ are the wiring resistances.

1) Inductance sub-circuit: The variable inductance characteristic shown in Fig.2 will be represented by Fourier series, so the inductance sub-circuit can be simulated by a multiplier of the signal source which depends on the position of the rotor and standard inductance L_{ref} such as shown in Fig.7.

2) Motor torque sub-circuit: A current source can be used to represent the torque for each phase. The total torque can be obtained by parallel cascade of each current source as shown in Fig.8.

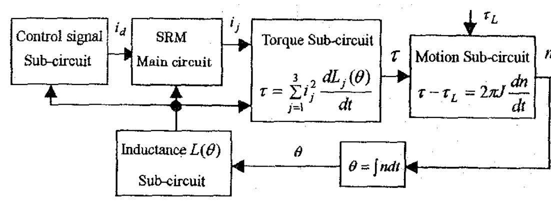


Fig.5. Simulation flow diagram

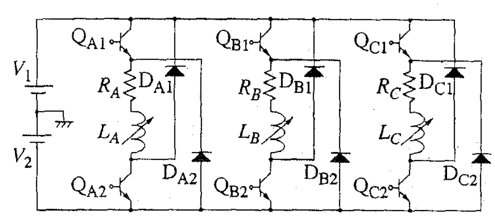


Fig.6. The main circuit of SRM model

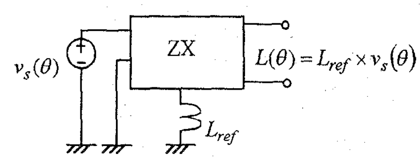


Fig.7. Inductance sub-circuit

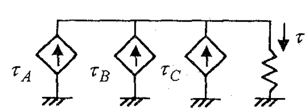


Fig.8. Motor torque sub-circuit

3) Control signal sub-circuit: The control signal must turn on when the differentiation of inductance is positive and turn off when the differentiation of inductance is negative. The control signal is used to open and close the transistors, in order to keep continually rotating. We take the control signal as a current source in Fig.9.

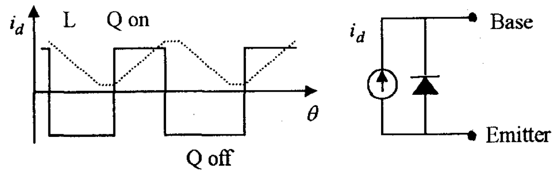


Fig.9. Control signal sub-circuit

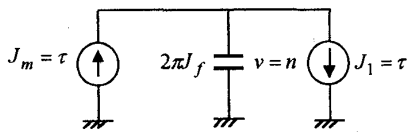


Fig.10. Equation of motion sub-circuit

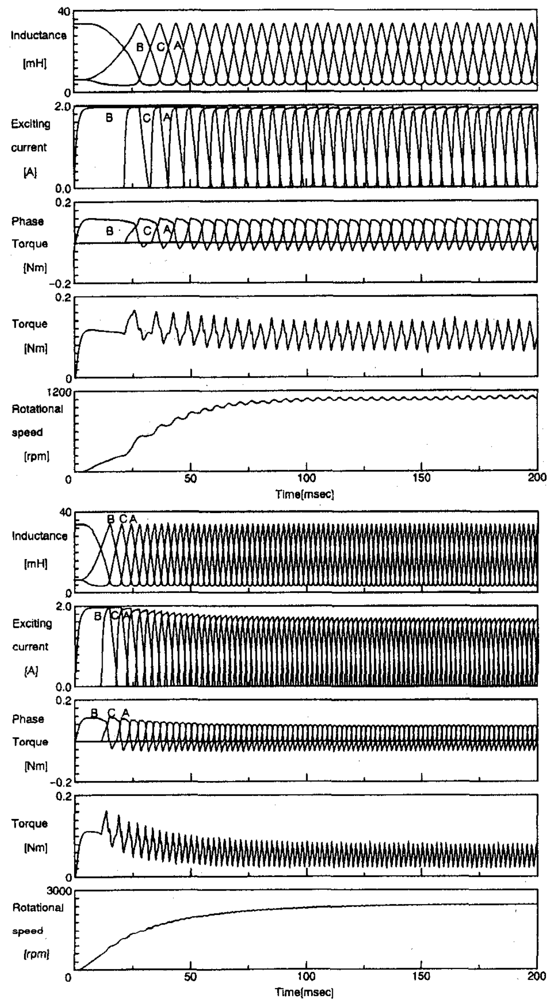


Fig.11. The results of dynamical characteristic of SRM

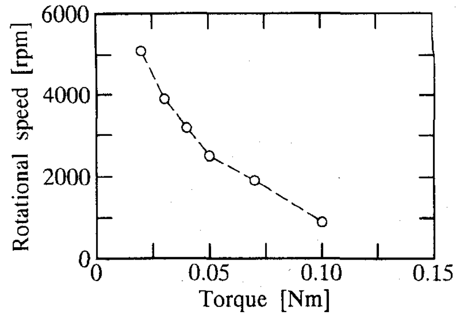


Fig.12. The characteristic of torque-speed

4) Equation of motion sub-circuit: The equation of motion sub-circuit is shown in Fig.10, the current sources of $J_m = \tau$ and $J_1 = \tau_L$ represents the superposition of motor torque and the load torque, respectively. The rotor speed is obtained from the voltage of the capacitor with capacitance $2\pi J_f$ acting like moment of inertia.

B. The results of simulation

The results of dynamical characteristic analysis of SRM when load torque is 0.1Nm and 0.05Nm are shown in Fig.11. From the results, the negative torque can be confirmed. Negative torque occurs because the current is flowing even when the derivative of inductance became negative.

Fig.12 show the characteristic of torque-speed. The relation between the load and speed of rotation is in inverse proportion.

IV. CONCLUSION

A useful simulation method used to analyze the dynamical characteristic of SRM has been presented. The key point is to estimate the reluctance of SRM. Because the result of proposed estimation method is certified well by experiments(see Fig.4), the proposed method is believed appropriate. Using the simulation tool, we can consistently design SRM from calculating the characteristics to evaluating performance.

As a future work, we will use the simulation tool to design some real SRM and measure their dynamical characteristics in order to improve our method and develop some excellent control algorithms.

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