*LabView*를 이용한 Switched Reluctance Motor 설계기술 개발

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Switched Reluctance Motor Design and Analysis with *LabView* Program

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Abstract - A design and analysis program is proposed for switched reluctance motor using an analytical method and a CAD program *LabVIEW*. The algorithm uses conventional permeance method, in which flux linkages, inductances and torques are calculated numerically. In order to analyze a dynamic characteristics of the motor, voltage control scheme is taken and a single pulse operation is applied. 2 SRM models are analyzed under the given specifications and constraints. The results compared with measured data.

1. INTRODUCTION

There are lots of applications of SRM thanks to its advantages such as rotor simplicity, high speed operation, ease of repair, short end turn, and law inertia. An SRM design and simulation program is implemented with an interactive *LabVIEW* program. The program's follows a five-step approach: Steps 1 through 3 input data defining the motor. Step 1 inputs the desired primary performance, electrical and topological specifications (mean torque, revolutions per minute, supply voltage, number of phases, number of stator poles and number of rotor poles). Step 2 inputs the envelope dimensions of the rotor and stator. Step 3 inputs the internal dimensions such as pole and slot depths and widths. Step 4 sizes the motor, makes a scaled drawing of the stator and rotor and computes estimates of inductance, resistance and performance parameters such as currents, power output, efficiency and motor weight using RMS type of algorithms. Steps 1 through 4 are interactive, that is, any change of input values triggers automatic redrawing and recalculation of the performance parameters. Step 5 provides a more detailed analysis based on waveforms instead of RMS estimated values. The waveform-based simulation algorithm performs a position dependent flux-linkage analysis for the source voltage, current control, and firing and turn-off angles specified by the user. Phase current, back emf, inductance, average torque and output power are thus computed for a phase and cloned for the rest of phases.

2. NUMERICAL FORMULATION

2.1 Unalignrd Inductance and Flux linkages

In order to estimate the performance of SRM, inductances and flux linkages are calculated at each position as function of current. For the unaligned rotor position, there is no magnetic saturation for any practical winding current so that only the unaligned inductance needs to be found. A reasonable estimation of the unaligned inductance can be calculated by modeling the machine geometry as shown in Fig. 1.

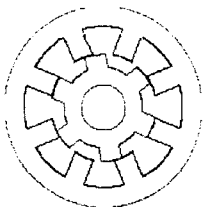

Fig. 1 A simulation model of 8/6 poles 12kW SRM

Fig. 1 shows the shape of the 12 kW SRM simulation model. The motor has 6-poles rotor and 8 slots of stator. The steel core is a silicon steel PN30 of which the initial relative permeability is 5500 and the saturation flux density is 1.75 [T]. The motor has a 4-phase series connected stator windings. The power supplier for the SRM is a 4-phase inverter with 220 [V] DC source.

Assumptions to calculate the unaligned inductance are (1) the conventional predominant flux path, tangential field condition, and Amperes law along its magnetic path. The unaligned flux linkage can be calculated by integrating the field from 0 to L_{stk}(motor stack length) and multiplying by $2N_{tp}$ as

$$\lambda_u = 2N_{tp}\,\mu_0\left[\int_0^{l_{rsw}} H_y\,dx\right]L_{stk} \qquad (1)$$

The unaligned inductance is identified from the flux linkage expression[2] as,

$$L_u(\theta,i) = \frac{n_{ser}}{n_{par}}\,4\mu_0\,N_{tp}^{\,2}\,L_{stk}\,l_{rsw} \sum_{nodd}\frac{\sin[\frac{n\pi d_1}{l_{rsw}}]/l_1 + \sin[\frac{n\pi d_2}{l_{rsw}}]/l_2}{(n\pi)^2\tanh[\frac{n\pi d_r}{l_{rsw}}]} \qquad (2)$$

where N_{tp} is number of turns per pole, l_{rsw} is rotor slot width, L_{stk} is motor stack length, l_1 is distance from stator pole to rotor pole(l_1 is function of position angle), n_{par} is the number of pole windings in parallel and n_{ser} is the number of pole windings in series. The unaligned

inductance computed using Eq.(2) does not include the contribution to the inductance from the end-turns, which can be calculated by the conventional equation[2]. The value is so small that it can be neglected. When $l_1 = l_2$, the unaligned inductance is minimum. The flux linkage at the unaligned position is computed as

$$\lambda(\theta,i) = L_u(\theta,i)\,i(\theta) \tag{3}$$

An estimation of the fluxlinkage and inductance of SRM seems to be the most important and difficult part, especially on the transition position from the unaligned to the aligned. In this paper, an interpolation algorithm is applied to calculate fluxlinkages between two positions.

2.2 Aligned Inductance and Flux linkages

When the rotor and stator poles overlap another equation is required to calculate flux linkages because magnetic saturation of the core governs the whole electromagnetic SRM system. There are some assumptions to calculate the aligned inductance: There are main flux, l_m, and fringing flux, l_f. Using the Amperes Law, the current at which a saturated behavior occurs can be calculated through the pole overlap region. The saturated part of the flux linked by the phase winding gives.

$$B_{sat} = \frac{\mu_0 N_{tp} I_{\phi sat}}{g} \tag{4}$$

where, $I_{\phi sat}$ is a current to saturate the core, and g is air gap length. The B_{sat} is specified in the design program. Then the flux linkage by a phase can be approximated as

$$\lambda_\phi = \alpha L_{stk}\, t_{spw}\, k_{stf}\, B_{sat}\, 2N_{tp} \tag{5}$$

where α is the fraction of rotor and stator pole overlap.
To compute the flux linkage curves of the SRM analytically, the model of the overlap configuration will be used. The core characteristics (B-H) for the calculation of the flux linkage is modeled in the conventional way[3] and the yoke is assumed to have infinite permeability. To solve the magnetic field, Amperes law is first applied to the closed contour lines.

$$H_{fe}\, 2\, l_p + H_g 2g = 2N_{tp}\, I_p \tag{6}$$

where, H_{fe} is a field intensity in the core and in the rotor, l_p is a total pole length($d_r + d_s$), and I_p is the pole current. The I_p is equal to the phase current I_{ph} if the pole windings are in series, and it is equal to the phase current divided by the number of poles per phase if the pole windings are in parallel. In the core along the main flux contour,

$$B_m(H_{fe}) = \tilde{\mu} H_{fe} / (1 + \frac{\tilde{\mu} H_{fe}}{B_{sat}}) + \mu_0 H_{fe} \tag{7}$$

A quadratic equation for B_m can be obtained and solved as which includes core saturation and described by 2 parameters. the permeability associated with the magnetization which includes $M = \mu_0 \chi_m H$.

$$B_m(\theta, I_{ph}) = \frac{\mu_0 N_{tp}}{2(1+\frac{g}{l_p})g}[1 + \frac{2g}{l_p})\frac{I_p}{n_{par}} + \frac{l_{m1} B_{sat}}{\mu N_{tp}} - \sqrt{\left(\frac{l_{m1} B_{sat}}{\mu N_{tp}}\right)^2 + \frac{2l_{m2} B_{sat}}{\mu N_{tp}} \frac{I_p}{n_{par}} + (\frac{I_p}{n_{par}})^2}] \tag{8}$$

where $l_{m1} = l_p + (\mu_r + 1)g$, $l_{m2} = l_p - (\mu_r - 1)g$ and $l_p = d_s + d_r$. This flux density in turn can be integrated over the cross-sectional area of the pole overlap to obtain the contribution of main flux path to the flux linked by the phase. After some algebra, the main flux contribution to the total flux linked by a phase is found as the following equation.

$$\lambda_m(\theta, I_{ph}) = n_{ser} N_{tp} L_{stk} k_{stf} R_g\, \theta\, B_m \tag{9}$$

where, R_g is the outer radius of the rotor.

Some of the fringing flux from the stator pole goes to the rotor yoke, while some of it goes to the rotor pole. The fringing flux is calculated using the following equation.

$$\lambda_f(\theta, I_{ph}) = n_{ser} N_{tp} L_{stk}\, k_{stf} \left(\frac{t_{spw} - R_g\theta}{g_f}\right) B_m \tag{10}$$

Fig. 2. shows the flux linkage curves for a simulation model(6/4 poles 3 phase 2000 rpm SRM) as functions of current and rotor position. The calculations were done by using the model, a relative permeability of μr = 2500, and saturation flux density B_{sat} = 1.95 T and stacking factor = 0.95. The flux linkage of the transition position is calculated by using an adjusting factor in order to remove the discontinuity of the flux linkages. In the case at hand, the measured flux-link curves supplied exhibit a slope in the saturated aligned region that is several times the theoretical slope. Consequently, an adjustable fudge factor was implemented in the program to forcefully fit the measured flux-link data. It is calculated by where, $g_f(\theta) = g + g_0(1 - R_g\theta / t_{spw})$, $l_{f1} = l_p + (\mu_r + 1)g_f$, $l_{f2} = l_p - (\mu_r - 1)g_f$, and mr is a relative permeability of the core. In this program, g_0 is chosen to obtain the required value of inductance L_{po} at the rotor position where the rotor and stator poles just start to overlap at q = 0 . The total flux linked by the phase is the sum of the main flux l_m and the fringing flux l_f.

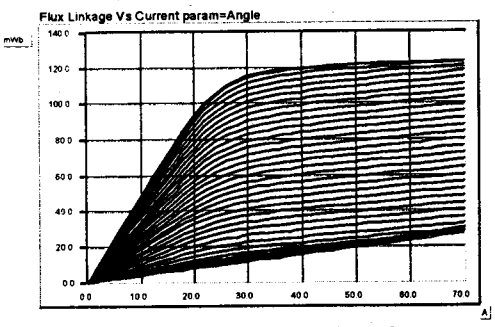

Fig. 2 Flux linkage curves as function of current and rotor position

During the advanced period, the unaligned inductance has a minimum value of 0.45mH and slightly increases when the rotor approaches to the stator pole. When the poles are overlap, the inductance is linearly increased to its maximum aligned value of 5.41mH. This value is a little smaller than the calculated value of 5.98 mH because the core saturation is considered in the simulation program.

2.3 Waveform Analysis of SRM

The SRM terminal voltage equation is

$$V_s = R_{ph} i_{ph} + \frac{\partial \lambda_\phi}{\partial i_{ph}} \frac{di_{ph}}{dt} + \frac{\partial \lambda_\phi}{\partial \theta_m} \omega_m \qquad (11)$$

where, R_{ph} is the phase resistance of SRM and ω_m is an angular speed of the rotor. The second term in (11) is the usual inductive voltage drop term and is equal to the slope of the flux linkage curves with current at a fixed angle. The third term of (11) is the Back EMF term due to the motion of the rotor and is the term where the electromechanical energy conversion takes place. The differential equation (11) can be solved by an iterative numerical method.

The flux linkage increases linearly up to the angle θc and the peak flux-linkage occurs at that angle. This flux-linkage should ideally be reduced to zero before the poles are separating, otherwise the torque changes to negative and becomes a braking torque. In order to reduce the flux-linkage to zero, the supply voltage Vs must be reversed at θ_c, If Rph $i$ph << Vs the flux-linkage falls linearly, and at constant speed the angle traversed is nearly equal to the dwell angle, both being equal to l_{peak}/Vs.

Using the differential rate of fluxlinkage and phase current with time at the same position, the inductance can also be calculated by the following equation.

$$L(\theta, i_{ph}) = \left[\Delta\lambda / \Delta i_{ph} \right]_{\theta = const} \qquad (14)$$

Also, the torque can be calculated as

$$T_{static}(\theta, i_{ph}) = \left[\frac{\partial W_{co}(\theta, i_{ph})}{\partial \theta} \right]_{i_{ph} = const} \qquad (15)$$

where, W_{co} is a co-energy calculated using the fluxlinkage - current curves. Fig. 3 shows a schematic diagram for an incremental of co-energy(OAB) to calculate a torque at a rotor position in the simulation program. Fig.4 shows waveforms of input voltage, phase current and torque curves of 8/6 12 kW SRM model. Fig.5 shows the fluxlinkage-current curves of the same model and it was compared with the measured data under condition of 220V, 200A at 5000 rpm.

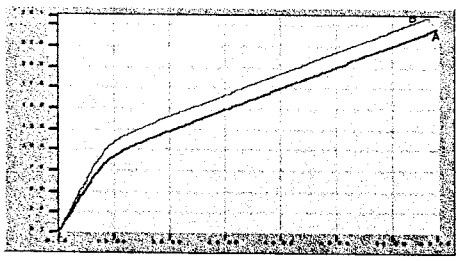

Fig. 3 The incremental co-energy calculation from flux linkage-current curves of 6/4 poles 2000 rpm model .

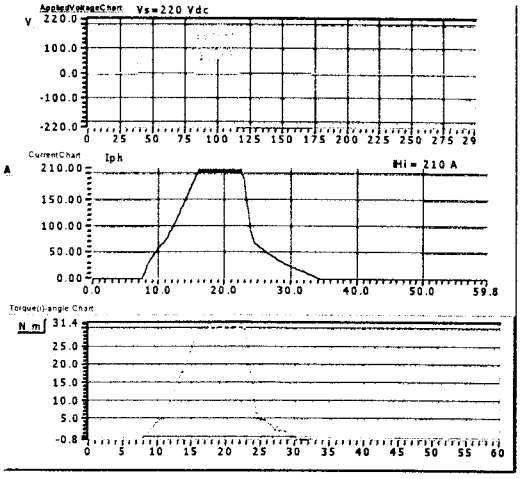

Fig.4 Waveforms of input voltage, phase current and torque curves of 8/6 12 kW SRM model.

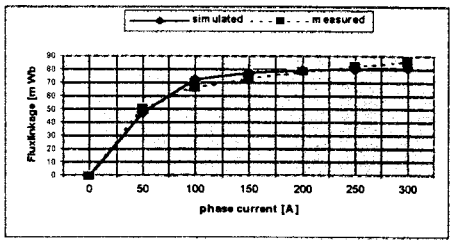

Fig. 5 Fluxlinkage of 8/6 12 kW SRM model

3. SUMMARY

A design and analysis program is proposed for switched reluctance motor using an analytical method and a CAD program *LabVIEW*. The algorithm uses conventional permeance method, in which flux linkages, inductances and torques are calculated numerically. In order to analyze a dynamic characteristics of the motor, voltage control scheme is taken and a single pulse operation is applied. An SRM model, 8/6 poles 4 phase 12 kW was analyzed under the given specifications and constraints. The results compared with measured data, which showes that by using the control algorithm, constant output power can be achieved in SRMs operation.

Acknowledgement

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