Driving Characteristics of SRM with an Auxiliary Fully Pitched Winding

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ABSTRACT - In this paper, we analyzed the characteristics and source of vibration and acoustic noise in SRM drives. This paper study the reduction technique of those by new SRM which has auxiliary field winding. The operating mechanism and vibration and acoustic noise characteristics is examined.

This paper suggests the control strategies of auxiliary field winding in order to reduce vibration and acoustic noise.

1. INTRODUCTION

The intrinsic simplicity, ruggedness, and simple power electronic drive requirement of a switched reluctance motor(SRM) make it possible to use in many commercial adjustable speed applications.

But, the large vibration and acoustic noise of SRM is an obstacle. It has been reported that the dominant source of the vibration and acoustic noise radial vibration of the stator[1-3]. Prof. Pollock suggested the reduction technique of vibration by Multi step switching method[2]. but, other reduction strategy is not reported yet.

In this paper, we should study about vibration and acoustic noise characteristics, and investigate new SRM with auxiliary fully pitched filed winding so as to reduce these advantages by this field winding. This magnetic configuration which is called "SRDC" is suggested by prof. Lipo to enlarge output power. Up to this time the analysis concerned about operating mechanism and characteristics of SRDC is not sufficient.

This paper presents the operation mechanism of SRDC, and suggests SRDC is very useful to reduce vibration and acoustic noise by control of field winding.

2. Vibration Characteristics of SRM

2.1 Operation of SRM Drives

The SRM has doubly salient and singly excited construction. Torque is generated by the tendency that rotor will rotated to the minimum reluctance position in order to magnet flux can be increased. Inductance is varied in accordance with rotor position angle. Torque is generated by the inductance variation and phase current like as Eq.(1).

$$T(\theta) = \frac{1}{2}\, i^2(\theta)\, \frac{dL(\theta)}{d\theta} \qquad (1)$$

where, i: phase current, L: inductance, θ: rotor position

Voltage equation should be written as Eq.(2).

$$V = Ri(\theta) + \omega\left[L(\theta)\frac{di(\theta)}{d\theta} + i(\theta)\frac{dL(\theta)}{d\theta}\right] \qquad (2)$$

where, V: voltage, R: phase resistance, ω: angular speed

The torque of SRM is generated by one excited phase like pluse shape at each time, as rotor is rotated the excited phase is changed by switching sequence. Here, it is consider taht the force between excited stator pole and rotor contains a significant radial component in addition to the torque of tangential component.

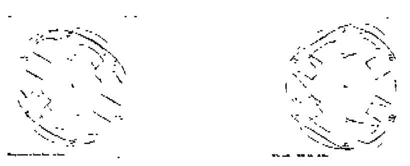
By this operation principle, SRM has large torque pulsation and instantenous variation of radial force. In particular the variation of radial force should deformed stator.

2.2 Vibration and acoustic noise of SRM

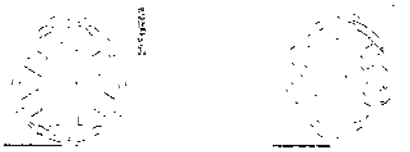
In general, rotor is stiffer than stator and not fixed by having bearings, so dominant vibration of electric machine is realated to that of stator

The vibration mode of stator is classified by some natural modes. Each vibration mode is generated at specified frequency. It's mode is called "natural mode" and that frequency is so called "natural frequency". If the vibration source is vibrated with the same frequency of natural mode, the vibration of natural mode is maximized.

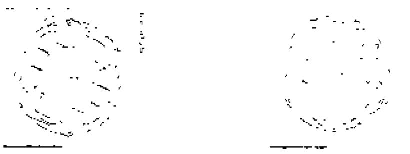
The natural mode of 6/4 SRM prototype which be adopt to this paper is simulated by FEA(:ANSYS). Fig.1 shows this FEA results.



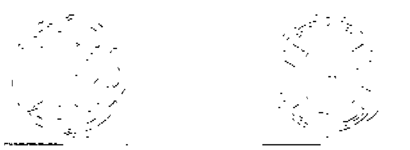
(a) 1st mode at 841Hz (b) 2th mode at 1441Hz



(c) 3th mode at 2492Hz (d) 4th mode at 3539Hz



(e) 5th mode at 3539Hz (f) 6th mode at 4782Hz



(g) 7th mode at 4782Hz (h) 8th mode at 4932Hz

Fig.1 Natural mode analysis result

To take more accuracy of natural mode, measurement of natural mode of prototype is accomplished by impluse impact hammer. This result is shown in Fig.2.

Summarizing the result of Fig.1 and 2, natural mode exists 350, 900, 1250 Hz and so on frequency.

Torque is generated by the flux of one stator and one rotor pole-pair in 6/4 SRM. So the dominant vibration mode will be that of fig.1(a) which is deformed radial direction, and natural frequency is about 900Hz.

To know the vibration characteristics in driving, we attached accelero-sensor to the back of stator pole. we measured the insatant vibration of stator and accomplished FFT analysis.

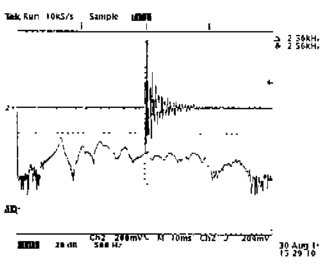
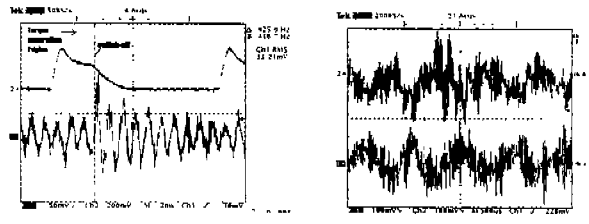


Fig.2 Measured natural frequency of stator

(a) In the case of a phase being switched

Fig.3 shows the vibration in accordance with phase current.

In Fig.3, the vibration of switch off time is the largest, and fundamental frequency of that is about 900Hz which coincides with second natural mode deformed radial direction. At this time, the vibration of other phase displaced 60° is opposite direction as Fig.3(b). So this vibration map also prove that vibration is generated like the smae type of second mode.



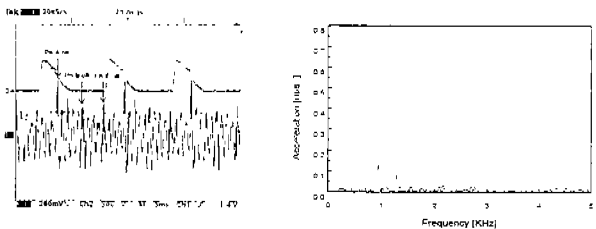
(a) (b)

Fig.3 Vibration acceleration when a phase is excited

(a) pahse current and stator vibration of the phase.

(b) Stator vibration of two phases

(b) In the case of all phases being switched



(a) (b)

Fig.4 Phase current and vibration acceleration(30kg.cm, 1000rpm)

(a) upper:phase current, low:vibration acceleration, (b) FFT results

When all phase is switched, the vibration generated by switched a phase is to be pilled up one the other. At this state, the vibration is like Fig.4.

The vibration characteristics is identical with Fig.3, the largest vibration is generated at switched-off time and the frequency is near 900Hz neverthless speed is changed.

The switch-off time of phase is located aligned position of stator and rotor pole. This rotor position has large radial force and small tangential force(torque). So this time the phase is switched off, radial force is reduced to be sudden, this variation of radial force produces large vibration. By these result, dominant vibration is generated by radial deformation of seitched-off time.

3. Operation Mechanism of SRDC

3.1 Magentic circuit scheme

SRDC has the same magnetic scheme except fully pitched field winding. The configuration sceme of SRDC is presented in Fig.7.

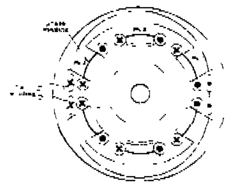


Fig. 5 Configuration scheme of SRDC

The magnetic polarity of stator ploe produced by phase winding and field winding. So phase winding and field winding is magnetically coupled each other. By this magnetic scheme, flux variation of phase winding produce induced voltage in field winding. This paper utilize field winding as absorbent of vibration generated by switching off phase winding.

The invert topologies is described in Fig.6. There is two control method to control field winding. One is to be field winding short, and the other is to control field winding to flow constant current.

Fig. 6 Invert topology of SRDC (a) short circuit, (b) constant current control

Fig. 7 shows the ideal state of inductnace profiles of SRDC.

Mutual inductance is varing same shape according to phase inductance variation. Self inductance is designed to be constant in order to have optimal performance characteristics.

The generated torque T of SRDC can be represented by Eq.(3).

$$T = \frac{1}{2} i_p^2 \frac{dL_p}{d\theta} + i_a i_f \frac{dM}{d\theta} \quad (3)$$

where, i_p :phase current, L_p :phase inductnace, θ:rotor angular position, i_f :field current, M:mutual inductance

Here, So as to have unidirection torques generated by phase windinds and field winding, field current must be the same direction of Fig.6 and Fig.7. If field current flow negative direction, the generated torque by field cinding will be negative.

Voltage equation can be written as Eq.(4) and (5).

$$\begin{aligned} V_p &= R_p i_p + \frac{d\lambda_p}{dt} \\ &= R_p i_p + L_p \frac{di_p}{dt} + i_p \frac{dL_p}{dt} + M \frac{di_f}{dt} + i_f \frac{dM}{dt} \end{aligned} \quad (4)$$

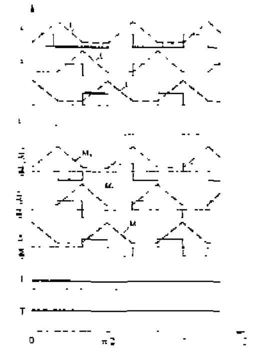


Fig. 7 The ideal inductance profile of SRDC

$$\begin{aligned} V_f &= R_f i_f + \frac{d\lambda_f}{dt} \\ &= R_f i_f + L_f \frac{di_f}{dt} + i_f \frac{dL_f}{dt} + M \frac{di_p}{dt} + i_p \frac{dM}{dt} \end{aligned} \quad (5)$$

where, R_p: resistance of phase winding, λ_p :flux linkages of phase winding, R_f : resistance of field winding λ_f :flux linkages of field winding, L_f :field inductnace

3.2 Operation characteristics analysis

Fig. 8 shows the phase current and induced voltage of field winding.

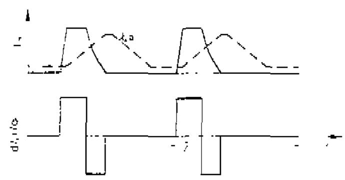


Fig. 8 Induced voltage of field winding by phase current

In Fig.8 when phase switch is turned-on induced voltage of filed winding is positive, and when phase switch is turned-off induced voltage of field winding is negative. These is resulted by flux variation of magnetic circuit.

Operation mechanism of each switching control region is analyzed as follows.

(a) current buld-up region

In this region, phase inductance and mutual inductance is constant as Fig.7, so no torque is generated.

The operation mode of this region is shown in Fig.9.

The voltage equation of phase and field can be written by Eg.(6)-(9) accoding to the control of field winding. (Where, R_p and R_f is ignored.)

Short circuit

$$V_p + M\frac{dI_f}{dt} = L_p\frac{di_p}{dt} \qquad (6)$$

$$0 = M\frac{di_p}{dt} - L_f\frac{dI_f}{dt} \qquad (7)$$

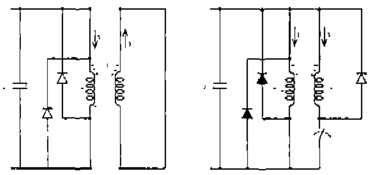


Fig. 9 Operating mode of current build-up region (a) short circuit, (b) constant current control

Constant current control

$$V_p = L_p\frac{di_p}{dt} \qquad (8)$$

$$V_f = M\frac{di_p}{dt} \qquad (9)$$

As written in Eq.(6)-(7), when field winding is short, excitation voltage is increased by $M\frac{dI_f}{dt}$, so phase current can build-up more quickly than SRM. But, when field current is controlled constant that is the same of SRM. So, it is more efficienct to fast phase current build-up that filed winding is short.

(b) Torque generation region

In this region, phase inductance and mutual inductance is increse as shown in Fig.7. Fig.10 shows the operation mode of this region.

The voltage equation of phase and field can be written by Eg.(10)-(13) accoding to the control of field winding.

Short circuit

$$V_p = L_p\frac{di_p}{dt} + i_p\frac{dL_p}{dt} + (M\frac{di_f}{dt} + i_f\frac{dM}{dt}) \qquad (10)$$

$$-(M\frac{di_a}{dt} + i_a\frac{dM}{dt}) = L_f\frac{di_f}{dt} \qquad (11)$$

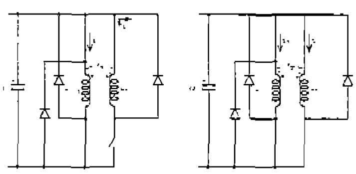


Fig. 10 Operating mode of torque generation region (a) short circuit, (b) constant current control

In Eg.(11), because $i_a[dM/dt]$ is positive field current i_f flow negative direction, and because ( ) of Eg.(10) is negative term so phase current is incresed.

As a result, the torque generated by field is negative direction so it is not good to torque utilization.

Constant current control

$$V_a = L_a\frac{di_a}{dt} + i_a\frac{dL_a}{dt} + i_f\frac{dM}{dt} \qquad (12)$$

$$V_f = M\frac{di_a}{dt} + i_a\frac{dM}{dt} \qquad (13)$$

If field current is controlled constantly, phase current will be decrease by $i_f[dM/dt]$, and torque generated by phase and field current is to be the same direction.

(c) Demagnetizing region

Fig.11 shows of operation mode of demagnetizing region

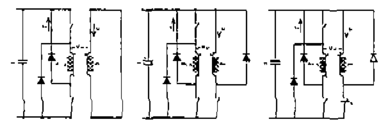


Fig.11 Operating mode of demagnetizing region
(a) short circuit, (b) constant current control

Voltage equation of phase can be writtren as Eq.(14) and (15)

short circuit

$$-V_a - (M\frac{di_f}{dt} + i_f\frac{dM}{dt}) = L_a\frac{di_a}{dt} + i_a\frac{dL_a}{dt} \qquad (14)$$

Constant current control

$$-V_a - (i_f\frac{dM}{dt}) = L_a\frac{di_a}{dt} + i_a\frac{dL_a}{dt} \qquad (15)$$

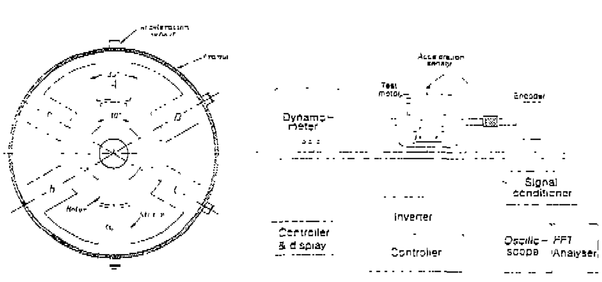
Because demagnetizing voltage is increases as much as ( ) term of Eq.(14) and (15), phase current is extinguished more quickly because field winding absorbs phase current.

Here now, field current is increases as phase current is decreased, so radial force is not varied quickly by field winding.

In SRDC, the variation of radial force produced when phase switch is commutated is to be smooth, so vibration of switch-off time is decreased.

4. Experimental Analysis

The experimental system is constructed illustated as Fig.12 and Table.1



(a) (b)

Fig.12 The construction scheme of experimental system

The vibration is measured two piezo type accelero sensor which is attached to the back of stator pole, sound power level is measured 30cm distance position from the prototype.

Table 4.1 specification of prototype motor

stator pole no.: 6	rotor pole no.: 4
stator pole arc: 35°	rotor pole arc: 30°
stator out dia.: 220mm	rotor out dia: 119.3mm
stator inner dia.: 120mm	stack length: 90mm
phase winding turns:144/pole	min. phase inductance: 6.5mH
phase resistance: 1.2Ω	max. phase inductance: 112.7mH
field winding turns: 24	min. mutual inductance: 10.1mH
field resistance: 1.0Ω	max. mutual inductance: 144.4mH
	field self inductance : 13.1mH

Fig.13 shows the phase current waveforms of the same driving condition.

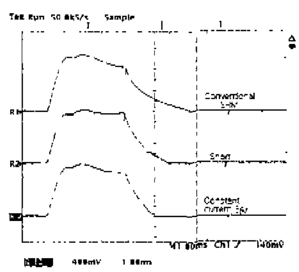


Fig.13 Phase current waveforms of each field control method(6.25A/V)

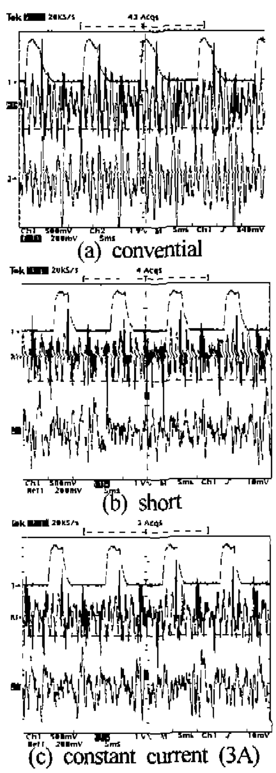


Fig.14 Phase current(Ch1), vibration(R1) and SPL(Ch2) (Ch1:6.2A/V, R1:9.95mV/g, Ch2:50dB/V)

Out of the phase current waveform of Fig.13, those of SRDC is extinguished more quickly than that of SRM and the output power is increased by about 100W.

In addition to it, the conduction region can be enlarged because of fast current extinguishment, so output power also be increased more and more.

Fig.14 shows the experimental results of SRDC and SRM which is concerned about vibration and acoustic noise. This is measured when the load torque is 50 kgfcm, and speed is 1300 rpm.

The vibration of switch-off time is more smaller than that of conventional SRM and total vibration and acoustic noise is decreased. In SRDC, Torque is generated both phase current and field current, also radial force to be the same. So radial force variation of switch-off time is decreased, because field winding absorbs the decreasement of phase current and then the radial force by field current is increased.

So, the ouput power will be increased and vibration and acoustic noise is reduced by using field winding

5. CONCLUSION

This paper studies the operation characteristics of SRM has auxiliary fully pitched field winding.

The fieldwing winding and filed current can do fast phase current commutation and can absorb radial shape vibration and acoustics noise.

As a result, auxiliary field winding is very useful to reduce vibration and acoustic noise of SRM, and output power also to be increased by wide conduction period.

6. REFERENCE

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