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A new Measuring Method of Flux Linkage of SRM

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***Abstract*—This paper presents a indirect method of measuring flux characteristics based on DSP. By measuring current and voltage on a phase winding circuit and transfer them to PC by communication program, combined with the Simpson's rule, the magnetization characteristics are obtained. The experimental instruments needed in this method are common, and the test platform is easy to be built, thus the expense is lowered in measurement of flux. The test indicates the measuring process is simple to implement, and the experimental results are accurate.**

***Index Terms*—SRM, Flux linkage characteristics, Simpson's rule**

I. INTRODUCTION

Growing interest on the switched reluctance motor drives has raised many analysis, design and measurement issues [1]. One of the most important aspects is the measurement of motor parameters to use in the analysis and design of the converter, prediction of the performance of drive etc. Recently the switched reluctance motor (SRM) is drawing considerable attention over AC & DC drives because it has several advantages over AC & DC drives like simple and robust construction, no brushes, Low inertia and high torque to weight ratio, no rotor windings, simple power converter circuit etc.

The switched reluctance motor presently used in two main fields of application [2]:

1) Variable speed-variable torque drive system where the medium and small size motors are used

2) Servo drives for position, speed or torque control where small size variable reluctance motors are used for incremental motion.

There are many approaches for measuring the flux linkage of SRM, such as finite-element analysis [3], direct measuring flux linkage [4], direct measuring winding inductance:

1) Finite-element analysis method – We can calculate the magnetization curve of SRM by using finite-element analysis, but the different measuring interval that we select will cause different precision and the calculation is extremely complex. In addition, the modeling of this measuring method is very difficult because the structure of SRM is irregular. What's more, the result need to check eventually even if it is calculated by using this method [5].

2) Method of direct measuring flux linkage – The flux linkage of SRM can be measured by a magnetic sensor and the sensor must be installed in the motor when the SRM was assembled. Therefore, the design of motor becomes complex and the measuring cost is very expensive. It is hardly assured the measurement accuracy to measure the flux linkage by using the magnetic sensor, so this method is rarely used.

3) Method of direct measuring winding inductance – The winding inductance of SRM can be measured by using the method of an AC bridge, and if the current is confirmed we can calculate the flux linkage characteristic. However, an AC pulse signal must be exerted on the SRM winding and the measuring method is very complex. Moreover, the result should be measured repeatedly at different rotor position and it will consume much more time.

In order to overcome the disadvantage of the above methods, this paper presents a new measuring method. For proper design of measuring system and performance analysis of the SRM, the knowledge of accurate flux linkage characteristics is necessary. The flux linkage of the SRM is depend on the rotor position and phase current, the family of the flux linkage characteristics (for different rotor positions) will have to be determined as accurately as possible in this paper we present the method for obtaining the flux linkage characteristics of SRM [6]. The experimental instruments needed in this method are common, and the test platform is easy to be built, thus the expense is lowered in measurement of flux. The test indicates the measuring process is simple to implement, and the experimental results are accurate.

Firstly, this paper describes the operating principle of SRM and the measurement principle puts forward theoretical basis. Then, the hardware structure, software flow chat and measurement steps are detailed introduced [7]. The experimental results are analyzed and the magnetization curve are plotted at the end of the paper.

II. PRINCIPLE OF MEASUREMENT

A. Operating Principle of SRM

The cross section of 8/6 SRM is shown in Fig. 1, in which both the stator and the rotor are salient poles [8]. The stator winding consists of a set of coils, each of which is wound on one pole. The reluctance of the flux path between the two diametrically opposite stator poles varies as a pair of rotor poles rotates in and out of alignment. Since inductance is inversely proportional to reluctance, the inductance of a phase winding is a maximum when the rotor is in the aligned position and a minimum when the rotor is in the non-aligned position. The rotor teeth tend to align with an energized phase in order to minimize the reluctance path.

With successively energizing of phases, the rotor can step around in any direction as desired. The production of torque of the SRM depends upon the stator current magnitude regardless of the direction. A pulse of positive torque is produced if current flows in a phase winding as the inductance of that phase winding are increasing [9]. A negative torque contribution is avoided if the current is reduced to zero before the inductance starts to decrease again. If the main switch elements of every phase of SRM are opened and shut in sequence, the rotor will continuously spin in a certain direction. The process of converting phase of SRM is shown in Fig. 2. The rotor speed can be varied by changing the frequency of the phase current pulses while retaining synchronism with the rotor position.

B. Measurement Principle

The SRM drive system simulation is much more complex than AC & DC motor drives because its operational region is mostly nonlinear [10]. The nonlinearity is introduced by the three factors:

1) The nonlinear B-H characteristics of the magnetic material.

2) The dependence of phase flux linkages on both the rotor position and current magnitude while in other machine it is dependent only on current magnitude.

3) The single source of excitation.

By using the proposed method, a deviation of the current slope which is not influenced by the motor speed can be derived. The deviation of the current slope is only related to input DC voltage and self inductance of motor. As a result the self inductance of the motor can be precisely estimate by detecting current slope [11].

SRM models are generally made up of three parts: the electrical model, torque characteristics and mechanical model. The electrical circuit for one phase of SRM is shown in Fig. 3.

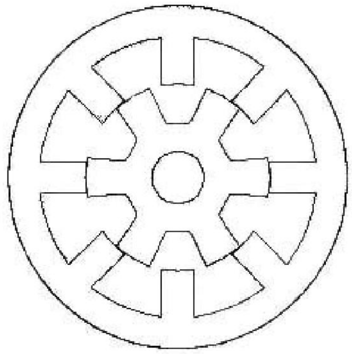

Figure 1. The cross section of 8/6 SRM.

Applying Kirchhoff voltage law and ignoring hysteresis, eddy current and the mutual inductance between the windings thus voltage given by (1).

$$v = ir + \frac{d\lambda(i,\theta)}{dt} \tag{1}$$

Where R is phase resistance and $\lambda(i,\theta)$ is magnetic flux is given by (2).

$$\lambda(i,\theta) = L(i,\theta)i \tag{2}$$

Where $L(i,\theta)$ is the phase inductance, which varies as a function of rotor position (due to varying reluctance) and phase current (due to magnetic saturation).

Solve (1) to calculate magnetic flux at various rotor angles and current magnitudes from measures stator voltages, currents and resistance as given in (3).

$$\lambda(i,\theta) = \int (v - ir)dt \tag{3}$$

The electrical model of the SRM can be compared with DC motor by substituting (2) in (1) as follows:

$$\begin{aligned} v &= ir + \frac{d(L(i,\theta)i)}{dt} \\ &= ir + L(i,\theta)\frac{di}{dt} + i\frac{d(L(i,\theta))}{dt} \\ &= ir + L(i,\theta)\frac{di}{dt} + i\frac{d\theta}{dt}\frac{d(L(i,\theta))}{d\theta} \\ &= ir + L(i,\theta)\frac{di}{dt} + i\omega\frac{d(L(i,\theta))}{dt} \end{aligned} \tag{4}$$

The phase inductance of the SRM is depends on both the excitation current and rotor position. The measurement of inductance can be performed while the phase winding is excited with the appropriate DC current.

A simplified measurement circuit for SRM flux linkage

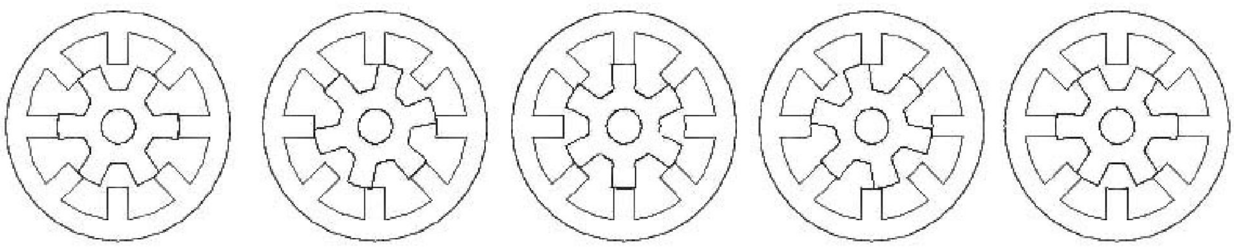

Figure 2. The process of converting phase of SRM

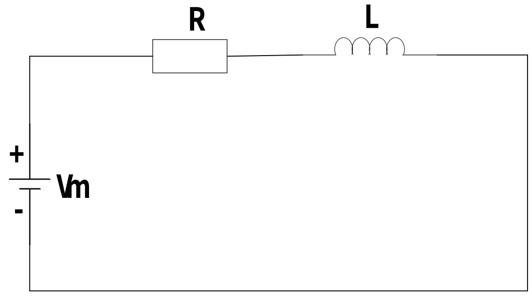

Figure 3. Electrical Model of One Phase of SRM

characteristics is shown in Fig. 4. When a voltage pulse applied to any phase of the SRM while all other phases are open the voltage given by (5)

$$v = ir + \frac{d\lambda(i,\theta)}{dt} \tag{5}$$

Where 'v' is voltage across phase winding

'i' is phase current

'r' is resistance of the phase winding

'λ' is flux linkage.

'θ' is rotor angle.

In a similar way, Solve (5) to calculate magnetic flux at various rotor angles and current magnitudes from measures stator voltages, currents and resistance as given in (6).

$$\lambda(i,\theta) = \int (v - ir)dt \tag{6}$$

From the (6) flux linkage can be calculated from any numerical integration technique, the above equation is performed by using Simpson's 1/3 rd rule.

Simpson's 1/3 rule :

Simpson's 1/3 rule is one of the popular method of numerical integration and it is used for the measurement of definite integrals.

$$\int Y(x)dx = \frac{h}{3}[Y0 + 4Y1 + 2Y2 + 4Y3 + \cdots\cdots + 2Yn - 2 + 4Yn - 1 + Yn] \tag{7}$$

In (7), $Y(x)$ is the function and $Y0, Y1$……… are the values of function at specified intervals and 'h' is the interval period [7].

Therefore, we can make $Y(x) = v - ir$,the flux linkage

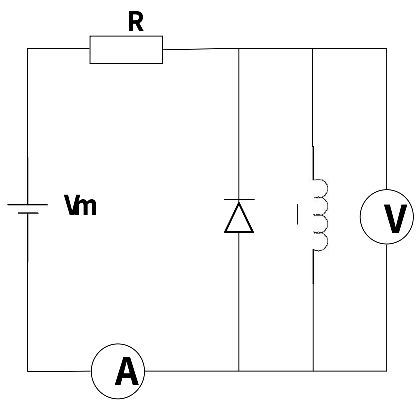

Figure 4. Measuring Circuit for SRM Flux Linkage Characteristics

is given by (8).

$$\begin{aligned}\lambda(i,\theta) &= \int (v - ir)dt \\ &= \int Y(x)dx \\ &= \frac{h}{3}[Y0+4Y1+2Y2+4Y3+....+2Yn-2+4Yn-1+Yn]\end{aligned} \tag{8}$$

The resistance of a phase winding of the SRM changes with the winding temperature, In order to reduce the error of measurement caused by the change of the winding resistance, we will galvanize the measured winding before measuring the flux characteristics to make the motor winding have a certain temperature. In this condition, the measured resistance is regarded as the real value of the motor winding [5].

III. METHOD OF MEASUREMENT

A. *Hardware Structure of Measuring Device*

In this paper, the experiment instrument required in the measurement of flux linkage includes a 0.5-kw 4-phase 8/6 SRM, a mechanical protractor, a controller based on DSP, a three-phase rectifier, a three-phase transformer, a Hall current sensor and a voltage sensor etc. The experimental instrument is shown in Fig. 5.

DC voltage is provided by the three-phase rectifier and the voltage value can be adjusted by three-phase transformer lest the SRM winding exceeds its rated current value when its value reached the peak current [12].

IGBT which is the key component of driving circuit is used to control the voltage applied to winding, its base connects with the I/O port of DSP.

The current and voltage of the SRM phase winding are respectively measured by a Hall current sensor and a voltage sensor, its measured values input into the A/D port and the value is converted to digital quantity to be processed in the DSP [13].

The mechanical protractor which distribute a lot of hole with equal spacing is coaxially installed on the output axis of SRM and it can be used to put the SRM rotor at a given angle position.

B. *Software Design*

The DSP controller is the core of the measuring device for SRM flux linkage and the program in the controller control the whole measuring process. The flow chart of flux linkage measurement is shown in Fig. 6.

The current and voltage collected by the sensors and stored by the DSP controller are transmitted to the upper computer by the serial port [14]. The DSP chip has a programmable SCI module which follows the RS-232 protocol. Thus, the initialization program is as follows.

LDP #00E0h; Load the data page

SPLK #0017h, SCICCR; Eight bit word size, one stop bit, no parity check bit

SPLK #0013h, SCICTL1; Initialize serial communication interface

SPLK #0001h, SCICTL2; Permit the interrupt of TX.

SPLK #0004h, SCIHBAUD

SPLK #0011h, SCLBAUD; The baud rate is 1200 bps receive buffer

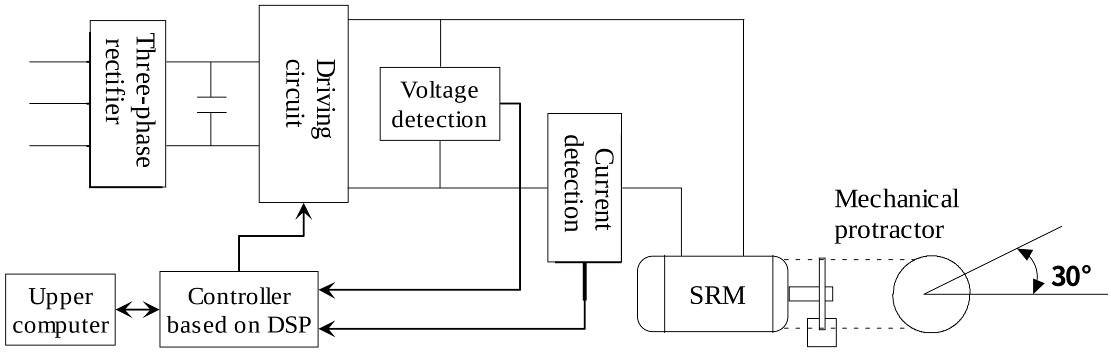

Figure 5. Measuring device for SRM flux linkage

SPLK #0022h, SCIPC2; Set up SCIRXD and SCIRTXD to be communication port

SPLK #0033h, SCICTL1;

The initialization program of the upper computer is as follows [15].

MSComm 1.CommPort=1; Set up the port of com1

MSComm l.Settings=”1200,N,8,1”; The baud rate is 1200 bps, no parity check bit, Eight bit word size, one stop bit

MSComm l.InputLen=0; Read all the data of the receive buffer

MSComm l.RThreshold=10;

MSComm l.SThreshold=0;

MSComm l.InBufferCount=0; Clear the data of the

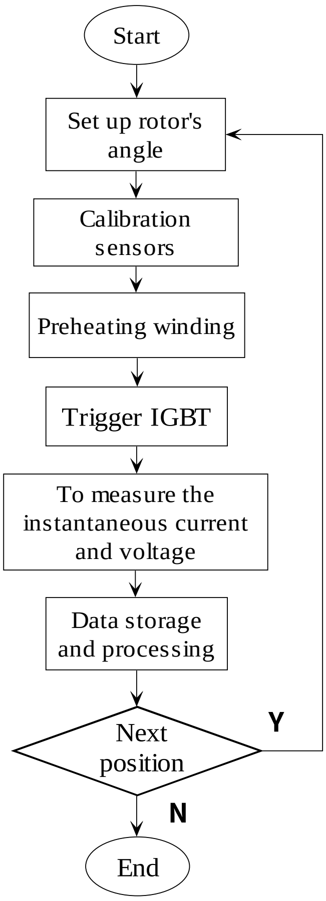

Figure 6. Flow chart for flux linkage measurement

MSComm l.OutBufferCount=0; Clear the data of the send buffer

MSComm 1.Handshaking=comNone

MSComm l.InBufferSize=10

MSComm l.OutBufferSize=1024

MSComm l.InputMode=comInputModeBinary; The transmission mode is binary mode

MSComm l.PortOpen=True; Open the serial port

By using equation (6) and equation (7), the value of flux linkage can be obtained in the upper computer. Thus we can sum up the magnetization characteristic of SRM [16].

C. Measuring Steps

The steps of measurement is listed as follows:

1) A length of DC plus the low voltage is exerted on the SRM winding. The motor is stopped at a phase equilibrium position and this position is fixed by the mechanical protractor as a starting point of measurement.

2) The Hall current sensor and voltage sensor are calibrated after cutting off the power source.

3) The IGBT is opened and shut repeatedly for a short time to make the SRM winding close to the measuring temperature [17].

4) To trigger the IGBT, the timer of DSP control the conduction time of the DC voltage source. At this moment, the A/D converter is started to sample the voltage and current of the phase winding [18]. The DC voltage source is shut off when the timer reached the set time.

5) Data storage and handling according to demand.

6) The datum of voltage and current are sent to the upper computer for handing after acquired and stored by the DSP controller.

7) Fixing the motor rotor at a new position and to repeat the process.

IV. RESULT OF MEASUREMENT

The experimental results were obtained on the basis of captured voltage and current waveform at different rotor position, flux linkage is calculated using Simpson’s 1/3 rule as per equation (7). The flux linkage at different rotor position for various current values is given in Tab. I.

Because the SRM we use in this experiment is a 4-phase 8/6 motor, the measuring range according to the

TABLE I.
FLUX LINKAGE CHARACTERISTICS

Current in Amp	Flux Linkage in mWb at Different Rotor Position				
	0°	7.5°	15°	22.5°	30°
0.000	0.0	0.0	0.0	0.0	0.0
0.500	1.2	1.8	2.4	2.7	4.8
0.947	2.1	3.0	3.9	4.8	6.8
1.481	3.3	3.9	5	6.6	9.8
2.105	4.5	5.0	7.2	9.3	13.4
2.667	5.7	6.6	8.7	11.7	16.1
3.288	6.6	7.8	11.0	14.4	19.5
3.763	7.5	8.5	12.3	16.8	22.2
4.433	8.7	10.1	15.2	20.0	26.7
5.030	9.6	11.0	17.4	23.0	30.0
5.671	10.7	12.6	19.2	26.1	35.2
6.450	11.7	13.5	22.8	30.8	39.8
7.045	13.0	15.2	25.0	34.1	44.6
7.510	14.0	16.6	26.9	37.0	47.3
8.021	15.0	17.9	28.5	39.7	50.0
8.510	16.0	19.3	30.0	41.8	52.0
9.013	16.5	20.5	31.5	43.5	54.0
9.510	17.0	21.0	33.1	45.0	55.8
10.008	18.1	22.4	34.0	46.0	57.3
10.500	19.1	22.9	35.6	46.8	58.0
11.012	19.6	24.0	36.5	47.5	58.5
11.980	22.2	27.2	38.2	48.5	58.8

above-mentioned method is between the minimum angle when the rotor is in the unaligned position (marked as 0°) and the maximum angle when the rotor is in the aligned position(marked as 30°). As the geometrical symmetry of the SRM structure, we can get the complete flux lunkage characteristics of the SRM by only measuring this range. The result of measurement is shown in Fig. 7.

The flux linkage characteristics of SRM depend on the rotor position and the excited stator phase current. The flux linkage characteristics of SRM are represented in Fig. 7. The flux linkage characteristics at aligned position are represented, when the stator inter-polar axis is coincides with the rotor inter-polar axis and the flux linkage characteristics at unaligned position are also represented. The flux linkage characteristics at the intermediate position shown, as the rotor position is changed from unaligned position to aligned position till the overlap of the pole approached.

V. ANALYSIS OF RESULT

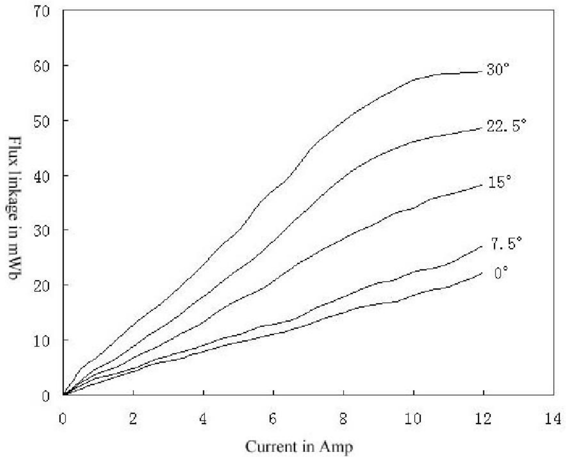

Figure 7. Flux lunkage characteristics of SRM

From magnetization curve in Fig. 7, we can know that the flux linkage is a nonlinear function of the rotor position and the excited stator phase current [19]. It have the following characteristics.

1) The relevance of the flux linkage to the phase current is linear when the rotor is in the unaligned position (marked as 0°) [20].

2) The relevance of the flux linkage to the phase current is badly nonlinear when the rotor is in the aligned position(marked as 30°).

3) The flux linkage is a periodic function to the rotor position as shown by (9)

$$\lambda(i,\theta+\frac{2\pi}{N})=\lambda(i,\theta) \tag{9}$$

' N ' is number of poles.

4) If the current is set for a definite value, the flux linkage is a monotone increasing function [21], when the rotor spins from the unaligned position to the aligned position as shown by (10)

$$\lambda(i,\theta_2)>\lambda(i,\theta_1) \qquad 0\le\theta_1<\theta_2\le\frac{2\pi}{N} \tag{10}$$

5) If the stator is fixed at a certain position, the flux linkage is a monotone increasing function when we change the phase current from 0 Amp to 12 Amp as shown by (11)

$$\lambda(i_1,\theta)>\lambda(i_2,\theta) \qquad i_1>i_2 \tag{11}$$

The relevance of flux linkage to the phase current is approximately linear when the winding is powered in a smaller current and it will become nonlinear when the winding is powered in a biggish current (the rater is not in the unaligned position) [22].

In addition, the torque characteristics is a influencing factor of the control accuracy of SRM, but it is very difficult to figure out the expression formula of the torque directly [23]. However, one of most important purpose of measuring flux linkage of SRM is to analyze characteristics of the torque [24]. We can work out the torque characteristics on the basis of the flux linkage characteristics as shown by (12) (13) (14).

$$T=\left.\frac{\partial W'}{\partial\theta}\right|_{i=const} \tag{12}$$

$$W' = \int_0^i \lambda(\theta, i) di \tag{13}$$

'T' is electromagnetic torque.

'W'' is magnetic field energy [25].

The expression formula of the torque can be figured out by substituting (13) in (12) as follows:

$$T = \frac{\partial}{\partial \theta}\left(\int_0^i \lambda(\theta, i) di \right)\Bigg|_{i=const} \tag{14}$$

Because the task of this paper is not to solve the problem about the torque characteristics, we have not further analyzed it here.

VI. CONCLUSION

The method of measurement is very simple and feasible, which is the biggest innovation in this paper. The experimental instruments needed in this method are common, thus the expense is lowered in the measurement of flux linkage and the experimental results are accurate and reliable. The flux linkage characteristics measured by this method can be based for the analysis and design of the control system of SRM.

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