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Dynamic measurement of magnetic characteristics of switched reluctance motor

Introduction. *Switched reluctance motor (SRM) is a type of electric motor featuring nonlinear magnetic characteristics. The flux linkage or inductance profile of SRM is usually required for the purpose of high control performance, and can be normally obtained through conventional static test by using DC or AC method when the rotor is locked.* ***Problem***. *However, it is not practical to use the conventional method of measurement when the specific apparatus for locking the rotor is unavailable. Besides, due to the magnetic nonlinearity of SRM, the saturation effect makes it difficult to obtain the saturated magnetic characteristics, and the conventional static AC test fails to address this problem.* ***Novelty***. *In this paper, a dynamic measurement method of the magnetization curves of SRM is proposed which allows the measurement take place while the motor is running with load.* ***Methodology***. *Based on the conventional static AC test, the proposed measurement handles the saturation problem successfully by introducing a DC offset in the high frequency AC voltage. Phase inductance with different rotor positions and currents can be obtained by analyzing simple equivalent circuit.* ***Practical value***. *Simulation is conducted in MATLAB/Simulink environment and the results have verified that the proposed dynamic measurement can effectively obtain the magnetic characteristics of SRM.* References 16, table 1, figures 6.

Key words: **magnetic characteristics, saturation, switched reluctance motor.**

Вступ. *Вентильний реактивний двигун (ВРД) є типом електродвигуна з нелінійними магнітними характеристиками. Профіль потокозчеплення або індуктивності ВРД зазвичай потрібний для забезпечення високої ефективності управління і зазвичай може бути отриманий за допомогою звичайних статичних випробувань з використанням постійного або змінного струму, коли ротор заблокований.* ***Проблема***. *Однак недоцільно використовувати традиційний метод вимірювання, коли відсутній спеціальний пристрій для блокування ротора. Крім того, через магнітну нелінійність ВРД ефект насичення ускладнює отримання насичених магнітних характеристик, і звичайне статичне випробування змінним струмом не вирішує цю проблему.* ***Новизна***. *У цій роботі пропонується метод динамічного вимірювання кривих намагнічування ВРМ, який дозволяє проводити вимірювання під час роботи двигуна з навантаженням.* ***Методологія*** *Пропонований вимір, заснований на звичайному статичному випробуванні змінним струмом, успішно вирішує проблему насичення за рахунок введення зміщення постійного струму у високочастотну змінну напругу. Фазна індуктивність при різних положеннях ротора та струмів може бути отримана шляхом аналізу простої еквівалентної схеми.* ***Практична цінність***. *Моделювання проводилося у MATLAB/Simulink, і результати підтвердили, що пропонованим динамічним вимірюванням можливо ефективно отримати магнітні характеристики ВРД.* Бібл. 16, табл. 1, рис. 6.

Ключові слова: **магнітні характеристики, насичення, вентильний реактивний двигун.**

Introduction. There is an increasing popularity of the adoption of the switched reluctance motor (SRM) in areas such as industrial and home applications in recent years [1-8]. SRM is also considered as a strong competitor in electric vehicles due to its simple structure, high efficiency and low cost [9, 10].

However, the doubly salient structure of SRM makes the magnetic circuit highly non-linear, i.e., the flux linkage or inductance of SRM not only varies with rotor position but also level of current [11]. In order to achieve high performance control such as position sensorless control and instantaneous torque control, magnetic characteristics of SRM should be obtained in advance [12, 13].

There are various ways of obtaining the magnetic characteristics of an SRM, such as performing finite element analysis in computer simulation program, and carrying out measurement in hardware platform. The widely used method of inductance measurement is the locked rotor test. By locking the rotor using a heavy clamping device and applying a short voltage pulse in the phase winding, and monitoring the phase voltage and phase current waveform using oscilloscope, flux linkage can be calculated via integration and inductance can then be obtained [14, 15]. The static measurement method is simple yet tedious and requires special clamping device which might not be available. Thus, dynamic measurement is recommended in [16], in which the inductance profile can be measured while the motor is running. The principle of the dynamic method resembles that of the static method, there is no need to lock the rotor in the former method however. An alternative method of inductance measurement is by using static AC test proposed in [14], the phase winding becomes a sinusoidal circuit and the inductance can be simply estimated by using the RMS value of phase voltage and phase current. However, the static AC test method has two major drawbacks, one is that the rotor still needs to be locked to exclude the effect of the rotor position on the variation of the inductance, another is that saturation is ignored thus the inductance obtained is only linear inductance, while SRM is normally working under deep saturated condition, the nonlinear magnetic characteristics is not yet present.

In this paper, dynamic inductance measurement for SRM is proposed. By using high-frequency and small AC signal with a DC offset, the slope of flux linkage curve can be obtained from the proposed method. The utilization of the DC offset can cover the region where the motor is even magnetically saturated. Compared with the static measurement method where the rotor of SRM is required to be locked by a clamp, the proposed dynamic method can be applied when the rotor is rotating, which is more practical when the special clamping device is not available. Simulation results are given to prove the effectiveness of the proposed measurement method.

Conventional static AC measurement. In static AC measurement method, the shaft of SRM is locked by a clamp, the rotor is thus not moving due to friction even when current is flowing in the phase winding. By applying AC voltage of which the amplitude is small such that the generated current is lower than the saturated current, the phase winding can be considered as a simple RL circuit in which the inductance is constant. Then the inductance of the phase winding can be obtained from voltage vs current test.

The voltage equation of a phase can be written as:

$$u = R\cdot i + \frac{\mathrm{d}\psi}{\mathrm{d}t}, \tag{1}$$

where u is the phase voltage; i is the phase current; R is the phase resistance; ψ is the phase flux linkage; t is the time.

Considering the aforementioned condition, (1) can be rewritten as:

$$u = R\cdot i + L\cdot\frac{\mathrm{d}i}{\mathrm{d}t}, \tag{2}$$

where L is the unvaried phase inductance. It should be noted that magnetic saturation is not consider in this equation.

The inductance can then be calculated as:

$$L\big|_{\theta=\theta_l} = \frac{1}{2\cdot\pi\cdot f}\cdot\sqrt{\frac{U^2}{I^2}-R^2}, \tag{3}$$

where θ is the rotor position; θ_l is the rotor position where the rotor is locked; U is the RMS value of the applied AC voltage; I is the RMS value of the phase current; f is the frequency of the AC voltage.

By changing the clamped rotor position manually and repeating the above process, the linear inductance at different rotor position can be obtained.

However, the static AC test not only is tedious but also requires the clamping apparatus to lock the rotor which might not be available. Besides, the method is only capable of obtaining the unsaturated inductance, while the saturation is not yet present due to the nonlinearity, i.e., the inductance is no long constant when the current goes above the saturation point. The drawbacks of the static AC test method hamper the wide application of this method and make it less appealing compared with the static DC test.

Proposed dynamic AC measurement. In order to overcome the disadvantages in the static AC test, a dynamic AC test method is proposed in this paper. The test setup is shown in Fig. 1. Sensors are used for sensing phase voltage and phase current to be used in the calculation of the magnetic characteristics. Incremental encoder is adopted to obtain the rotor position. A DC offset is adding to the AC voltage source to encounter the unsolved saturated condition in the static AC test. The adoption of DC voltage has two main functions, one is to freely move the equilibrium point beyond saturated current, the other is to rotate the rotor.

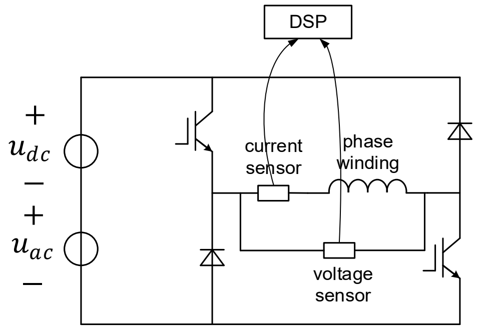

Fig. 1. Setup for magnetic characteristics measurement

Considering a short time of which the period is far longer than the cycle of the AC voltage, and during which the rotor barely rotates. In this condition, the rotor position can be considered constant. Assuming the current is reaching steady state and it will swing back and forth around the equilibrium point I_{dc} due to the existence of the AC component. By observing the flux linkage vs current curve of the particular rotor position in the vicinity of the equilibrium point, if the variation of the current is small enough, local linearization can be applied and the segment of the curve can be replaced by a linear line segment, as shown in Fig. 2.

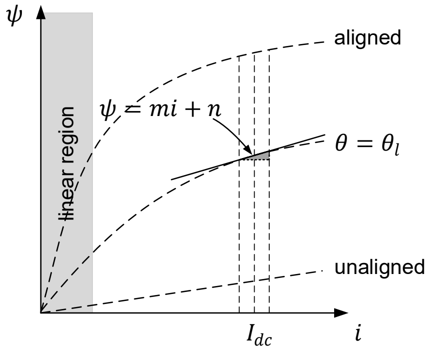

Fig. 2. Local linearization of flux linkage curve

The locally linearized curve can be expressed as:

$$\psi = m\cdot i + n, \tag{4}$$

where m and n are the coefficients of the linear line segment; m is the slope of the curve at the equilibrium point, which can be written as:

$$m = \frac{\mathrm{d}\psi}{\mathrm{d}i}\bigg|_{i=I_{dc}}. \tag{5}$$

By substituting (5) into (1), the voltage equation can be rewritten as:

$$u = R\cdot i + m\cdot\frac{\mathrm{d}i}{\mathrm{d}t}, \tag{6}$$

The coefficient m is also known as the dynamic inductance. Thus, the equivalent circuit of (6) can be constructed with a real resistor and an imaginary inductor in series connection as shown in Fig. 3,*a*. In the circuit shown in Fig. 3,*a*, superposition theorem is applicable. The circuit can be divided into two sub-circuits as shown in Fig. 3,*b* and Fig. 3,*c*, where only one voltage source is present in each sub-circuit. The current of the equilibrium point is determined by the DC voltage source, while the imaginary inductance can be obtained from the sub-circuit with the AC voltage source.

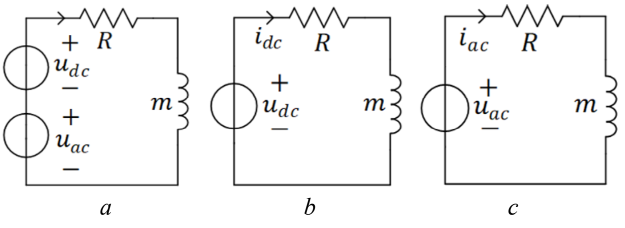

Fig. 3. *a* – equivalent circuit at equilibrium point; *b* – sub-circuit with DC voltage source; *c* – sub-circuit with AC voltage source

The current in the AC circuit can be obtained from performing Fast Fourier Transform (FFT) on the phase current and the slope of the flux linkage curve can still be calculated by (3). Once the slope is obtained for all the current, flux linkage can be calculated by performing integration. Then dividing the flux linkage by current can yield the inductance. By changing the DC voltage, the equilibrium current I_{dc} can be adjusted. Repeating the above process at different equilibrium point, inductance profiles can be obtained.

It should be noted that the speed of the motor should be kept low enough to ensure that the current can reach the desired level and the circuit can reach steady state quickly. Thus, load torque should be properly tuned.

Simulation results and discussion. Simulation of the proposed dynamic measurement using an outer rotor SRM is carried out in MATLAB/Simulink environment. The parameters of the motor are listed in Table 1.

Table 1

Parameters of the outer rotor SRM

Parameter	Value
Number of phases	3
Pole combination	6/4
Stator outer radius	51 mm
Stator inner radius	20 mm
Stator yoke	15 mm
Stator pole arc	28°
Rotor outer radius	95 mm
Rotor inner radius	52 mm
Rotor yoke	15 mm
Rotor pole arc	32°
Stack length	50 mm
Turn number per pole	150

Two voltage sources in series connection supply power to the phase winding to run the motor. The AC voltage is kept at 1 V (magnitude) and 10 kHz, while the DC voltage is manually changed based on the need of equilibrium point. In order to know the magnetic characteristics under different current conditions, a 3 A linear step length is used. The required DC voltage u_{dc} is given by:

$$u_{dc} = R \cdot i_{dc}, \qquad (7)$$

where i_{dc} = 3 A, 6 A, ..., 30 A; R = 2.56 Ω.

In order to verify the accuracy of the proposed dynamic measurement, finite element method (FEM) is adopted beforehand to obtain accurate flux linkage characteristics, and used to compare with the proposed method in simulation. The dynamic inductance calculated by FEM is represented by solid lines, while the one estimated from the proposed method is denoted by stars, as shown in Fig. 4.

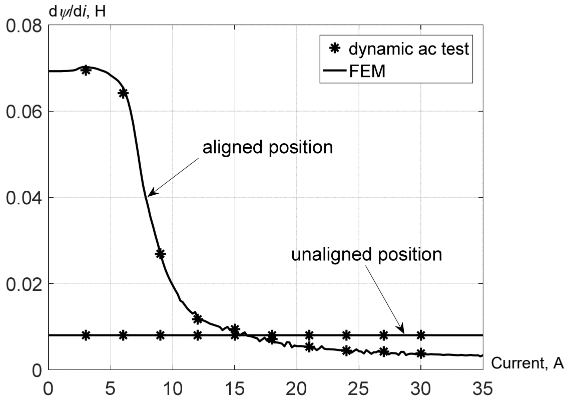

Fig. 4. Slope of flux linkage vs current curve at aligned and unaligned position obtained from the proposed dynamic AC measurement and FEM

Two typical positions, namely aligned position and unaligned position are presented in the figure. The characteristics at other rotor positions can also be obtained through the same process. The magnetic saturation point is at around 6 A. It can be found that the results given by the proposed method are in good agreement with that of FEM, no matter whether magnetic circuit is unsaturated or saturated, and no matter what the rotor position is. It should be noted that the large dynamic inductance change found in Fig. 4 is due to the outer rotor structure, which is uncommon in a conventional motor with an external stator.

In Fig. 5, the waveforms of phase voltage, phase current and rotor position are shown. The DC voltage is chosen as 61.4 V, thus the equilibrium current is 24 A, and it is well beyond the saturated current. The FFT result at aligned position is shown in Fig. 6, it can be found that the magnitude of the AC current caused by the AC voltage is 3.63 mA. By using (3), the estimated slope m of flux linkage curve is 4.40 mH, while the result obtained from FEM is 4.42 mH, of which the difference is less than 1 %. The simulation results show good accuracy when using the proposed measurement in both unsaturated region and saturated region.

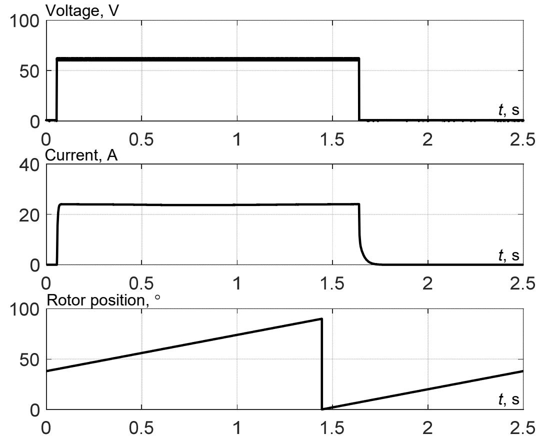

Fig. 5. Simulation waveforms when the current at equilibrium point is 24 A

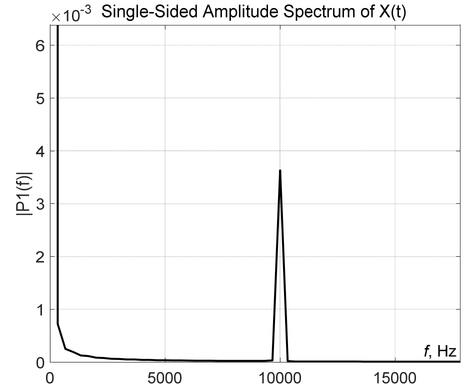

Fig. 6. FFT result at aligned position when the current at equilibrium point is 24 A

Conclusions. This paper proposes a dynamic measurement method of magnetic characteristics for SRM under both unsaturated and saturated conditions. The conventional lock-rotor test is not practical to implement if the specific apparatus used to lock the rotor is not available. Besides, the saturation effect is falsely ignored in the static AC test. The proposed method handles the nonlinear characteristics of SRM by introducing a DC offset in the high frequency AC voltage, and equivalent circuit at equilibrium point is given by performing local linearization. By simply changing the DC offset, the proposed method can cover regions from magnetic unsaturation to saturation. The superposition theorem in electrical circuits is used to obtain the slope of flux linkage curves. Compared with the conventional static AC measurement, the proposed method does not require to lock the rotor. Besides, saturation effect is properly addressed. Simulation results show that the proposed dynamic measurement is effective in obtaining the magnetic characteristics of SRM.

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Conflict of interest. The authors declare that they have no conflicts of interest.

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