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.
The voltage equation of a phase can be written as:

\[ u = R \cdot i + \frac{d\psi}{dt}, \tag{1} \]

where \( u \) is the phase voltage; \( i \) is the phase current; \( R \) is the phase resistance; \( \psi \) is the phase flux linkage; \( t \) is the time.

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

\[ u = R \cdot i + L \cdot \frac{di}{dt}, \tag{2} \]

where \( L \) is the unvaried phase inductance. It should be noted that magnetic saturation is not considered in this equation.

The inductance can then be calculated as:

\[ L_{\theta=\theta_l} = \frac{1}{2 \cdot \pi \cdot f} \sqrt{\frac{U^2}{I^2} - R^2}, \tag{3} \]

where \( \theta \) is the rotor position; \( \theta_l \) 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 positions 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 longer 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 with the AC voltage source. 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.

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

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:

\[ m = \frac{d\psi}{di} \bigg|_{i=I_{dc}}. \tag{5} \]

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

\[ u = R \cdot i + m \cdot \frac{di}{dt}. \tag{6} \]

The locally linearized curve can be expressed as:

\[ \psi = m \cdot i + n. \tag{7} \]

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.

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>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phases</td>
<td>3</td>
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<tr>
<td>Pole combination</td>
<td>6/4</td>
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<tr>
<td>Stator outer radius</td>
<td>51 mm</td>
</tr>
<tr>
<td>Stator inner radius</td>
<td>20 mm</td>
</tr>
<tr>
<td>Stator yoke</td>
<td>15 mm</td>
</tr>
<tr>
<td>Stator pole arc</td>
<td>28°</td>
</tr>
<tr>
<td>Rotor outer radius</td>
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<tr>
<td>Rotor inner radius</td>
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<td>Rotor yoke</td>
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<tr>
<td>Rotor pole arc</td>
<td>32°</td>
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<tr>
<td>Stack length</td>
<td>50 mm</td>
</tr>
<tr>
<td>Turn number per pole</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 1 Parameters of the outer rotor SRM

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:

\[
   u_{dc} = R \cdot i_{dc},
\]

where \( i_{dc} = 3 \text{A}, 6 \text{A}, ..., 30 \text{A}; R = 2.56 \Omega \).

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.

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.

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

REFERENCES

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