Improving the Efficiency of Switched Reluctance Motors using a Step-Skewed Rotor

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(Manuscript received Aug. 8, 2014, revised March 21, 2015)

This paper discusses how to improve the efficiency of switched reluctance motors (SRMs) by means of a step-skewed rotor (SSR). The cross-sectional configuration of the tested SRM with SSR, including the size and shape of the salient poles, was nearly identical to that of a conventional SRM. The tested SRM was divided into three stacks, of which only one rotor was skewed. The skewed angle was designed to reduce both the torque ripple and the radial force. Experiments were carried out to confirm the effectiveness of efficiency improvement of the SRM with SSR: a maximum efficiency of more than 90% was achieved. Compared with the efficiency of a conventional SRM, the efficiency of the proposed SRM with SSR was greater by more than 10 percentage points.

Keywords: switched reluctance motors, step-skewed rotor

1. Introduction

The advantages of switched reluctance motors (SRMs) include the employment of no permanent magnets and a simple structure, as well as being robust, inexpensive, reliable and suitable for higher speed functions, such as for electric vehicle (EV) and hybrid EV (HEV) applications (1) (2). HEV and EV require motors with higher efficiency, higher power density, and lower cost. Developed SRMs for HEV and EV have realized almost the same level of efficiency as interior permanent magnet synchronous motors (3).

SRMs with larger pole numbers can attain a higher efficiency in a larger output power range (3-5). Most of SRMs for HEV and EV applications contain a large number of poles. SRMs with a smaller number of poles, however, have an advantage in higher speed applications for reason that such SRMs demands lower output frequency of the drive circuit than SRMs with a larger number of poles at the same rotational speed.

It is thus important to improve the efficiency of SRMs with a smaller numbers of poles. For such SRMs, the configuration and core materials are often changed to improve efficiency (6-7).

This paper discusses the effects of a step-skewed rotor (SSR) in SRMs. The tested SRM has 6 stator poles and 4 rotor poles. The cross-sectional configuration of the rotor including the motor size and shape of the salient poles of the SRM tested were almost identical to that of a conventional SRM. The tested SRM was divided into 3 stacks, and only one rotor was skewed. The skew angle was designed to reduce torque ripple and to distribute radial force.

In this paper, improvement in efficiency of the SRM with SSR is reported. Some experiments have been presented to confirm efficiency improvement, and the experimental results of the SRM with SSR are compared with those of a conventional SRM.

2. Switched Reluctance Motor with a Step-Skewed Rotor

SRMs consist of a salient stator with excitation windings and a salient rotor having neither windings nor magnets. The absence of windings and magnets in the rotor poles produces benefits such a simple structure, robustness, inexpensiveness, reliability, and suitability for higher speed applications.

2.1 Problems of Conventional SRMs

The cross-sectional view of a conventional laboratory 6/4 SRM is shown in Fig. 1. Rotor position $\theta = 0^\circ$ is defined as aligned, and is positive in the clockwise direction.

Current flows through the winding on the stator poles A and A’ rotating the rotor in the clockwise direction. Just before the aligned position, the current is turned off, and the next winding on the stator poles B and B’ is energized to pull...
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The attractive force generated when the winding is energized can be split into torque and radial force. The magnitude of the attractive force depends on $\theta$, the magnitude of motor current, and magnetic saturation level of the cores. Torque and radial force are not constant even if the attractive force is unvarying. The radial force, therefore, causes stator vibration, and the torque has a ripple component.

Figure 2 shows examples of current and torque waveforms of a conventional SRM with one-voltage-pulse control. Motor current is not invariable even though the winding voltage is constant from $\theta = -40^\circ$ to $\theta = -10^\circ$. As a result, the torque has a large ripple component. The torque decreases to a lower level around the aligned position, especially, as shown in Fig. 2(b). There, the SRM is in two-phase conduction mode. A rotor pole is in the aligned position. The attractive force is nearly equal to the radial force, and thus less torque is generated. However, the next rotor pole is in an unaligned position, and a smaller attractive force is consequently generated. The proposed SRM with SSR is effective in solving of lower torque generation around the aligned position as the next stack can compensate for the lack of torque.

2.2 Design of Skew Angle for the SRM with SSR

The proposed SRM with SSR has 6 stator poles and 4 rotor poles. The rotor of the SRM with SSR is divided into some stacks which are skewed. The number of stacks $k$ and the skew angle $\theta_{skew}$ of the rotor are designed to reduce torque ripple and to distribute radial force as follows.

As shown in Fig. 2(b), the conventional SRM has a large torque ripple. Since the ripple has periodicity, the torque can be expressed as follows.

$$T_q = T_{qDC} + \sum_{n=1}^{\infty} T_{qn} \sin(\omega_n t + \phi_n), \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 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Fig. 4. Salient poles and windings in the stator of the SRM with SSR

Fig. 5. Salient poles in the rotor of the SRM with SSR

Fig. 6. Cross-sectional view $k = 2$ and $\theta_{skew} = 15^\circ$

Fig. 7. Radial force direction at $k = 2$ and $\theta_{skew} = -15^\circ$

Fig. 8. Cross-sectional view at $k = 3$ and $\theta_{skew} = 10^\circ$

Fig. 9. Waveforms of total torque and phase currents of each stack at $k = 3$ and $\theta_{skew} = 10^\circ$

The phase shift of the torque ripple as the appropriate magnetized rotor position for each rotor stack is shifted by $\theta_{skew}$. Assuming that each rotor stack is magnetized at each proper rotor position and the generated torque possesses the same waveforms, the sum of the fundamental ripple component in each rotor stack, $T_{q1sum}$, can be obtained from next equation,

$$T_{q1sum} = T_q1 \sum_{m=1}^{k} \sin \left( \omega_1 t + \phi_1 + 2\pi (m-1) \frac{\theta_{skew}}{\theta_1} \right),$$

where, $k$ is the number of rotor stacks. The $\theta_{skew}$ required for $T_{q1sum}$ to be zero theoretically can be calculated from (5).

$$\theta_{skew} = \begin{cases} \frac{\pi}{6} \frac{1}{k} [\text{rad.}] = 30 \frac{1}{k} [\text{deg.}] \\ \frac{\pi k - 1}{6} \frac{1}{k} [\text{rad.}] = 30 \frac{k-1}{k} [\text{deg.}] \end{cases}$$

The minimum number of $k$ is two, and the $\theta_{skew}$ is calculated as $15^\circ$ at $k = 2$ from (6). In case of $k = 2$ in Fig. 6, the radial force for positive rotating in the clockwise direction has an imbalanced distribution, as shown in Fig. 7. Except for the case of $k = 2$, the smaller number of the stacks is three. In case of $k = 3$, $\theta_{skew}$ is calculated as being $10^\circ$ and $20^\circ$ from (6).

The cross-sectional view of each stack for the SRM with SSR at $k = 3$ and $\theta_{skew} = 10^\circ$ are shown in Fig. 8. The simulated total torque and motor current waveforms are shown in Fig. 9. Compared with the torque ripple for the conventional SRM in Fig. 2(b), that for the SRM with SSR is reduced as shown in Fig. 9. Motor current as shown in Fig. 9, however, often concurrently flows through the same phase winding of each stack. Radial force in such a period is generated in the...
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Figure 10. Radial force direction at $k = 3$ and $\theta_{\text{skew}} = 10^\circ$

Fig. 11. Cross-sectional view at $k = 3$ and $\theta_{\text{skew}} = 20^\circ$

same direction, as shown in Fig. 10.

Figure 11 illustrates the cross-sectional view of each stack for the SRM with SSR at $k = 3$ and $\theta_{\text{skew}} = 20^\circ$. In this case, the rotor poles of each stack arrive at the aligned position at different times, and torque ripple reduction can thus be achieved as shown in Fig. 12. Motor current flows through the different phase windings of each stack, and radial force is distributed as shown in Fig. 13.

Furthermore, compared with the torque of the conventional SRM in Fig. 2(b), smaller torque is required for each stack of the SRM with SSR in Fig. 12(a) under the same output torque condition because the generated total torque of the SRM with SSR is the sum of the torque of each stack. The magnetic flux in the air gaps between the energized stator poles and the nearby rotor poles of a stack in the SRM with SSR is, therefore, smaller than that of the conventional SRM. Smaller magnetic flux decreases the radial force. Both of the reduction and the distribution of the radial force decrease the vibration of the SRM with SSR.

From above consideration, the number of rotor stacks $k$ and the skewed angle $\theta_{\text{skew}}$ were designed as three and $20^\circ$, respectively.

2.3 Configuration and Rotation Principle of the SRM with SSR

The specifications of the SRM with SSR in Fig. 3 and the conventional SRM are listed in Table 1. Stator and rotor size of the tested SRM with SSR was designed to be almost the same as that of the conventional SRM presented in Fig. 1. The cross sectional areas of two machines are the same. The magnetization characteristics of the iron core of the tested SRM with SSR were also almost identical to that of the conventional SRM. In comparison of dc magnetization characteristic of core material for the conventional SRM (50RM400) with that for the SRM with SSR (35H360) in detail, magnetic flux density of 50RM400 is about 2% higher than that of 35H360 from 1 A to 40 A of motor current. The difference is small negligibly.

Current through the windings in each stack is dependent on the rotor position of each stack. Assuming that the rotor position of each stack is as shown in Fig. 11, current for stack 1 flows through windings on $v_{11}$ and $v_{12}$ because of their series connection as shown in Figs. 4(b) and (c). Similarly, current for stack 2 flows through windings on $u_{21}$ and $u_{22}$, and current for stack 3 flows through windings on $w_{31}$ and $w_{32}$. As a result, the rotor rotates in the clockwise direction. In this situation, the radial force is distributed in three directions as shown in Fig. 13.

2.4 Characteristics of the SRM with SSR

Comparison of characteristics between an SRM with SSR and a conventional SRM are shown in Figs. 14 and 15. The characteristics were obtained by 2D finite elements analysis (FEA).
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The reasons are follows.

3D FEA was carried out as a first step to confirm flux linkage between adjacent stacks. The flux linkage between stacks was found to be very small, and so the effect of mutual inductance could be ignored. The 3D FEA requires much time for calculation to obtain the useful features of the SRM with SSR, and these characteristics can be obtained in a shorter calculation time via superposition of the results obtained using 2D FEA for each stack.

Figure 14(a) shows the characteristics of a phase winding inductance of the conventional SRM with respect to motor current, and Fig. 14(b) shows those for a stack in the SRM with SSR. The motor current range was set to 2–10 A. The features are similar in shape, but each value for the SRM with SSR is about one-third smaller than that for the conventional SRM because of the stack length of the SRM with SSR also being about one-third shorter than that for the conventional SRM, as listed in Table 1.

Figure 15(a) shows the torque characteristics of the conventional SRM, and Fig. 15(b) shows that for a stack in the SRM with SSR. The form of the torque characteristics is also similar, and the magnitude for a stack in the SRM with SSR is about one-third smaller than that for the conventional SRM because of the stack length of the SRM with SSR also being about one-third shorter than that for the conventional SRM, as listed in Table 1.

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SRM with SSR, one drive circuit every stack is required as shown in Fig. 17. The rated voltage of the switching devices in the circuit for the SRM with SSR can be lower than that for the conventional SRM because smaller winding inductance in Fig. 14(b) can make dc source voltage $E$ lower. The copper loss $P_{\text{cop-SSR}}$ of the SRM with SSR can be calculated from motor current in each stack and winding resistance as follows,

$$P_{\text{cop-SSR}} = \frac{1}{T} \int_0^T R_{\text{SSR}} \sum_{k=1}^3 \left( i_u(k)^2 + i_v(k)^2 + i_w(k)^2 \right) dt$$

$$= R_{\text{SSR}} \sum_{k=1}^3 \left( i_{u\text{RMS}}(k)^2 + i_{v\text{RMS}}(k)^2 + i_{w\text{RMS}}(k)^2 \right),$$

where, $k$ is the stack number, $R_{\text{SSR}}$ is the winding resistance, $i_u(k), i_v(k),$ and $i_w(k)$ are phase-u, -v, and -w current of stack $k$, respectively, $i_{u\text{RMS}}(k), i_{v\text{RMS}}(k),$ and $i_{w\text{RMS}}(k)$ are rms values of $i_u(k), i_v(k),$ and $i_w(k)$, respectively, and $T$ is a period for average.

Supposing that all current is the same waveforms, the rms value of current satisfies the following equation,

$$i_{\text{RMS-SSR}} = i_{u\text{RMS}}(k) = i_{v\text{RMS}}(k) = i_{w\text{RMS}}(k).$$

Equation (7) can be, therefore, changed as follows,

$$P_{\text{cop-SSR}} = 9i_{\text{RMS-SSR}}(k)^2 R_{\text{SSR}}.$$  (9)

The copper loss of the conventional SRM $P_{\text{cop-conv}}$ is expressed as follows,

$$P_{\text{cop-conv}} = \frac{1}{T} \int_0^T R_{\text{conv}} \left( i_u^2 + i_v^2 + i_w^2 \right) dt$$

$$= R_{\text{conv}} \left( i_{u\text{RMS}}^2 + i_{v\text{RMS}}^2 + i_{w\text{RMS}}^2 \right),$$

where, $R_{\text{conv}}$ is the winding resistance of the conventional SRM, $i_u, i_v,$ and $i_w$ are instantaneous values of the current of phase-u, -v, and -w, respectively, and $i_{u\text{RMS}}, i_{v\text{RMS}},$ and $i_{w\text{RMS}}$ are rms values of $i_u, i_v,$ and $i_w$, respectively. If waveforms of $iu, iv$ and $iw$ are the same, next equation can be obtained from Eq. (10)

$$P_{\text{cop-conv}} = 3i_{\text{RMS-conv}}^2 R_{\text{conv}}.$$  (11)

where, $i_{\text{RMS-conv}}(k)$ is rms values of phase current.

3. Experimental Results

The experiments were carried out in order to confirm efficiency improvement in the SRM with SSR. Figure 17 shows the experimental setup for the SRM with SSR.

Motor current was controlled by one-voltage-pulse control and flat-topped current control for the conventional SRM. For the SRM with SSR, motor current was controlled by only one-voltage-pulse control. The one-voltage-pulse control is the simplest current control for SRMs with only turn-on angle $\theta_{\text{on}}$ and turn-off angle $\theta_{\text{off}}$. The $\theta_{\text{on}}$ and $\theta_{\text{off}}$ were fixed in the experiments as listed in Table 2, and the source voltage was adjusted to match load conditions. In the flat-topped current control, current was kept constant from $\theta_{\text{on}}$ to $\theta_{\text{off}}$ with hysteretic current regulator.

Figure 18 presents the phase voltage and phase current waveforms of stack 1 in the SRM with SSR at 1500 rpm and torque reference $T^* = 2$ [Nm] with one-voltage-pulse-control.

![Fig. 18. Waveforms of phase current in stack 1 of the SRM with SSR at 1500 rpm and $T^* = 2$ Nm](image)

Table 2. Experimental conditions

| Turn-on position $\theta_{\text{on}}$ | $-40^\circ$ |
| Turn-off position $\theta_{\text{off}}$ | $-10^\circ$ |
| Sampling period for control | 30$msec$ |
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The source voltage $E$ was adjusted to be 45 V to match the load condition. The average current value for all phase current, the output torque, and the efficiency are obtained as 3.26 A, 2.0 Nm, and 88.4%, respectively. From Fig. 18, it can be confirmed that the SRM with SSR was properly operated.

Figures 19 and 20 show the phase voltage and current waveform of the conventional SRM with one-voltage-pulse control at $E = 120$ [V] and with flat-topped current control at $E = 150$ [V], respectively. The winding inductance of the conventional SRM was larger than that for the SRM with SSR, as shown in Fig. 14. In contrast to the case for the SRM with SSR, a higher source voltage $E$ of the conventional SRM was, therefore, needed to operate under the same load condition. The average current value, the output torque, and the efficiency are obtained as 3.73 A, 2.0 Nm, and 75.6%, respectively, from the results of the conventional SRM with the one-voltage-pulse control at 1500 rpm, and 3.67 A, 1.93 Nm, and 73.0%, respectively, from the results of the conventional SRM with the flat-topped current control at 1500 rpm. The cause of variable current peak in Figs. 18 and 19 is the sampling period for control, 30 $\mu$s, as listed in Table 2, and the period was limited by the DSP system in Fig. 17.

The efficiency of the SRM with SSR for rotor speed with respect to the reference torque $T^*$ is shown in Fig. 21. All phase voltages across motor terminals and all motor currents through motor windings of all stacks, average torque $T_{\text{ave}}$, and average rotational speed $\omega_{\text{ave}}$ were measured for the efficiency calculation. The efficiency $\eta$ is obtained from the following equations.

$$\eta = \frac{P_{\text{in}}}{P_{\text{out}}} = \frac{\omega_{\text{ave}} T_{\text{ave}}}{\frac{1}{T} \int_{0}^{T} \left( \sum_{k=1}^{3} (v_{uk} i_{uk} + v_{vk} i_{vk} + v_{wk} i_{wk}) \right) \, dt}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 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Fig. 23. Comparison of the loss segregation between the conventional SRM and the SRM with SSR at $T^* = 2\,\text{Nm}$ with one-voltage-pulse control

Table 3. The RMS current and the copper losses

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Conventional SRM</th>
<th>SRM with SSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>3.6A</td>
<td>3.2A</td>
</tr>
<tr>
<td>1000</td>
<td>3.7A</td>
<td>3.1A</td>
</tr>
<tr>
<td>1500</td>
<td>3.7A</td>
<td>3.3A</td>
</tr>
</tbody>
</table>

The copper loss of the SRM with SSR is about 1.5 times larger than that of the conventional SRM. The $P_{\text{other}}$ of the SRM with SSR is, however, much smaller than that of the conventional SRM.

One of the reasons is the difference of magnetic flux density in the stator and rotor yoke. Figures 24 and 25 show the calculation results of the magnetic flux density distributions on the surface of the rotor in the conventional SRM and the SRM with SSR, respectively, by 3D FEA. Ansoft Maxwell 14.0.0 was used for the calculation. The calculation is the static electromagnetic analysis.

The magnetic flux density distributions were calculated every 10 degrees from $\theta = -30^\circ$ to $\theta = 0^\circ$. The rotor position $\theta$ of the SRM with SSR is defined as the position of the lower stack. The magnetic flux density levels in both figures are shown by the same colors from blue at 0.1 T to red at over 2.0 T. In Fig. 24, only phase-u current $i_u$ is set to 10 A as a constant value, and other phase currents are zero. In Fig. 25, the phase current in the lower stack is the same condition of the conventional SRM. The phase currents in the upper and the middle stacks are also set to 10 A and commutated to keep generating positive torque.

Although the conventional SRM generates almost a uniform magnetic flux density distribution in the rotor yoke as shown in Fig. 24, each stack of the SRM with SSR generates difference level of the magnetic flux density in the rotor yoke, and at least one stack generates lower magnetic flux density in the rotor yoke than that of the conventional SRM as shown in Fig. 25 except $\theta = 30^\circ$. Lower magnetic flux density in the rotor yoke generates lower losses in the rotor of the SRM with SSR. The magnetic flux density distributions in the stator yoke of both SRMs are the same situation.

4. Conclusions

This paper reports on the improvement of efficiency in the SRM with SSR. The cross-sectional configuration of the rotor including motor size and shape of the salient poles of the SRM tested were almost the same as those of a conventional SRM. The designed SRM was divided into 3 stacks, and only one rotor was skewed. The skewed angle was designed to be 20 degrees to reduce both torque ripple and radial force.

The experiments were carried out in order to confirm efficiency improvement in the SRM with SSR. Maximum efficiency of more than 90% was achieved. Compared with the conventional SRM, the efficiency of the proposed SRM with SSR was improved by more than 10 percentage points.

Winding inductance of a stack and back electromotive force (EMF) coefficient in the proposed SRM with SSR were about one-third smaller than in a conventional SRM. Thus, the proposed SRM with parameters of lesser magnitude can contribute to an expanded drive condition because of the smaller back EMF at higher speed. Especially, application for...
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instantaneous current control, such as the reduction of torque ripple and eddy current loss (8(9)), with the proposed SRM can be realized with lesser current distortion at a higher speed range. It is, therefore, possible to construct more sensitive speed and position control systems with the proposed SRM employing an SSR.

This research was supported by a Research and Development Program for Innovative Energy Efficiency Technology from the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

References


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