

*EVS25**Shenzhen, China, Nov 5-9, 2010***Application for Step-skewing of Rotor of IPM Motors Used in EV**Hongliang Ying¹, Zhouyun Zhang¹, Jun Gong¹, Surong Huang², Xuanming Ding¹¹ Technique center of Shanghai Edrive Co., Ltd, Shanghai, 200240, China² Department of Automation, Shanghai University, Shanghai, 200072, China

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Abstract

Technique of Step-skewing of rotor (SSR) is much efficient to reduce the harmonics of Back EMF, minimize cogging torque and torque ripple. In EV & HEV applications, it can conspicuously increase the torque control precision, decrease torque ripple, thus improve the vehicle comfort. This paper analyzed the no-load and load performance of motor with step-skewed rotor and another with slot-skewed stator. Through comparing the performance of each motor, this paper revealed the advantage of step-skew technique. The conclusion is verified by FEA and experiment. *Copyright form of EVS25.*

Keywords—Step-skewing, Skewed slot, IPM, EV, HEV

1. Introduction

Power density and efficiency of motors is the most important factors in EV&HEV application. Insert Permanent-magnet (IPM) synchronous machine supplied from power inverter takes advantages on high power density, high efficiency, high reliability, and low inertia, and has become one of the main options in high performance applications especially in EV&HEV. Technique of Step-skewing of rotor (SSR) is much efficient for reducing harmonics of Back EMF, minimizing cogging torque and torque ripple.

In EV & HEV applications, it can conspicuously increase the torque control precision, decrease torque ripple, thus improve vehicle comfort. And

SSR can avoids many negative influence of skewing of stator slot, such as difficulty for embedding stator coil, hardness for increasing fill factor and low heat-conduction effect than those of straight slot. Although SSR made rotor production more complicated, it saved lot of time on embedding wires, and is much fit for mass production.

To achieve SSR technology, traditional method suggests many steps for PM rotor, but the latest research indicates that two or three steps are more economical for vehicle application. Many researchers focused on its effect on reducing harmonics, cogging torque and torque ripple[1]~[3]. Paper [4] describes the influence of SSR on torque, and pointed out that the step-skew angle should be concerning to steps of rotor.

2. Step-skewed rotor & step-skew factor

Theoretically, there lies almost the same torque decrease affection between step-skew and skew-slot, with difference on the number of steps; figure 1 shows the principle of step-skewed rotor.

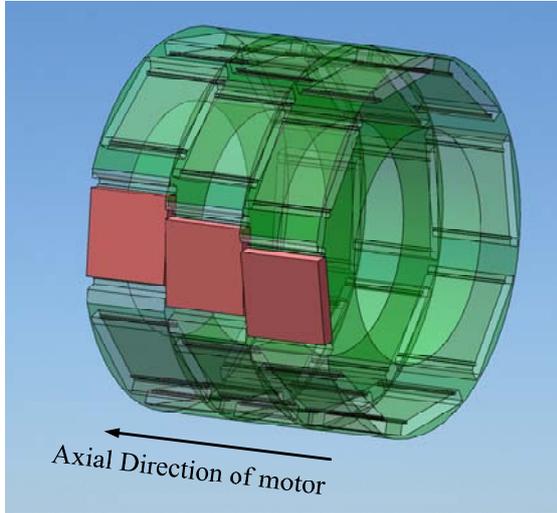


Fig. 1 Technique of SSR

2.1 Reduction of harmonics

As a result of skewed poles, harmonics of back EMF will be reduced. The step-skew factors of harmonics are:

$$k_{\text{skew_pole}_v} = \frac{\sin\left(\frac{n \cdot v \cdot \alpha}{2(n-1)}\right)}{n \cdot \sin\left(\frac{v \cdot \alpha}{2(n-1)}\right)} \quad (1)$$

In this equation, n is the number of step, v is the order number of harmonics, α is the step skew angle.

2.2 Reduction of torque

From reference [4], PM torque reduction factor and reluctant torque reduction factor of step-skewed motor are:

$$k_{T_{\text{skew_pole_PM}}} = \frac{\sin\left(\frac{n \cdot \alpha}{2(n-1)}\right)}{n \cdot \sin\left(\frac{\alpha}{2(n-1)}\right)} \quad (2)$$

$$k_{T_{\text{skew_pole_RE}}} = \frac{\sin\left(\frac{n \cdot \alpha}{n-1}\right)}{n \cdot \sin\left(\frac{\alpha}{n-1}\right)} = k_{T_{\text{skew_pole_PM}}} \cos \frac{\alpha}{2} \quad (3)$$

Formula (2) equals to the step-skew factor of fundamental frequency. If n is infinitely great, these factors equaled to factors of slot-skewing.

Then the torque can be described in formula (4):

$$T = \frac{3}{2} pn [\psi_m I_s k_{T_{\text{skew_pole_PM}}} \sin \beta + \frac{1}{2} I_s^2 (L_d - L_q) k_{T_{\text{skew_pole_RE}}} \sin 2\beta] \quad (4)$$

In this equation, p is the number of pole pair, ψ_m is the magnetic flux per pole of single step, I_s is the stator current amplitude.

It can be concluded from these equations, PM and reluctant torque components will be reduced by using step-skewed rotor, especially the reluctant torque component (see in equation 3). So choosing the proper step number and step skew angle is very important to the motor. It will decide the power density of motor.

3. Performance comparison of step-skewed motor and slot-skewed motor

A prototype with 2-step-rotor was made in way of ref. [4].

In comparison, a prototype with skewed stator was also made, using the same stator and rotor sheet. For convenience, turns, resistance of winding, and the length of stator were all the same. Prototypes and experimental bench are showed in Fig. 2.

3.1 No-load performance

Tab I lists out step-skew and skew-slot factors of main harmonics. It can be seen that step-skewed motor also has the similar effect on reduction of harmonics.



Fig. 2 Prototype and experimental bench

Tab I Harmonic Reduction Constant of Two Motors

Order	1	5	7	11	23
Motors					
Step-skewed	0.991	0.793	0.609	0.131	-0.991
Slot-skewed	0.989	0.738	0.527	0.090	-0.043

Fig. 3 shows the simulated line back EMF of two prototypes and one assumed un-skewed motor by FEA. We can see two similar back EMF.

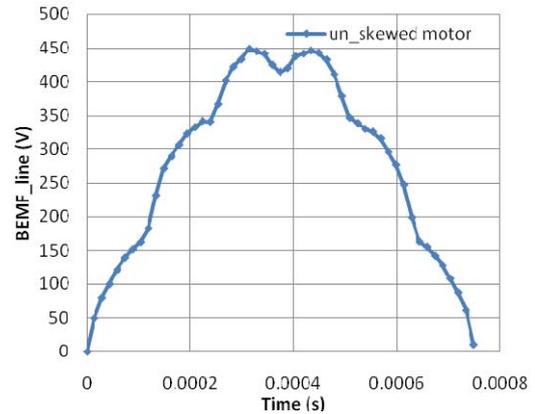
Through Fourier analysis, harmonics of three motors can be seen in Fig. 4. The assumed un-skewed motor has main harmonics at order 5,7, 11 and 23. The step-skewed motor has cut the magnitude of 5th,7th and 11th harmonic, but with little effect on 23th harmonic. The slot-skewed motor has reduced all these four harmonics.

In EV & HEV application, the back EMF of step-skewed motor showed in Fig.3-(b) is far beyond the level of acceptable. Fig.5 is the experimental curves of two prototypes. Little difference between the two curves can be seen in the two figs.

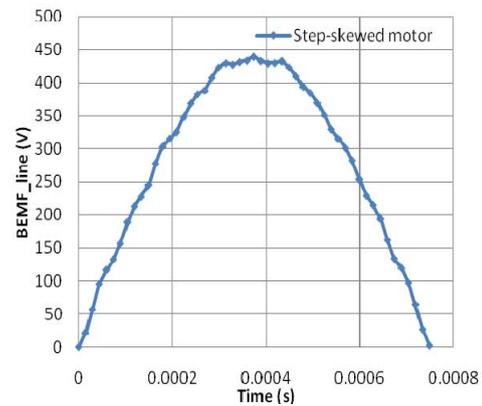
So, step-skewed motor has almost the same no-load performance to slot-skewed motor.

3.2 Load performance

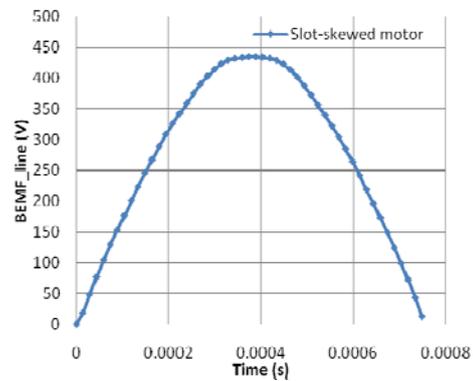
Tab II listed out the torque reduction constants of two kinds motors. Obviously, constants of step-skewed motor are even bigger. As a result of it, step-skewing technique remains more torque than slot-skewing technique. The power density of motor is harmed a little.



a) un-skewed motor

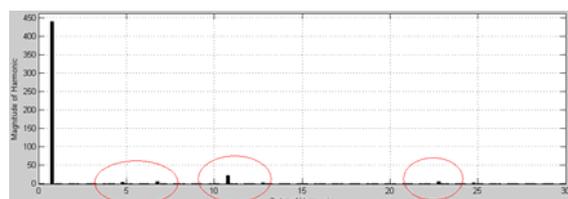


b) step-skewed motor



c) slot-skewed motor

Fig. 3 Simulation no-load Back EMF



a) un-skewed motor

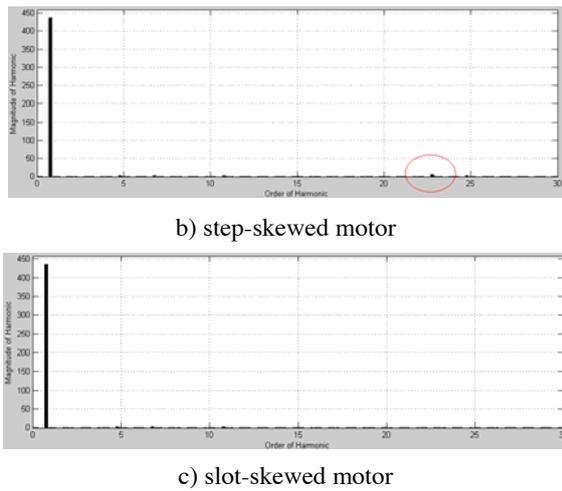


Fig. 4 Fourier analysis result of BEMF

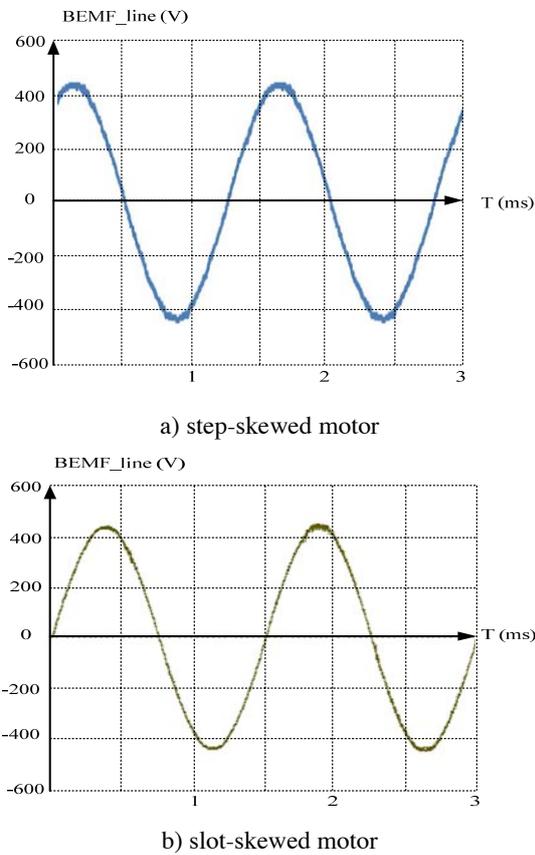


Fig. 5 Experimental no-load BEMF(10000r/min)

Tab II Torque Reduction Constants of Two Motors

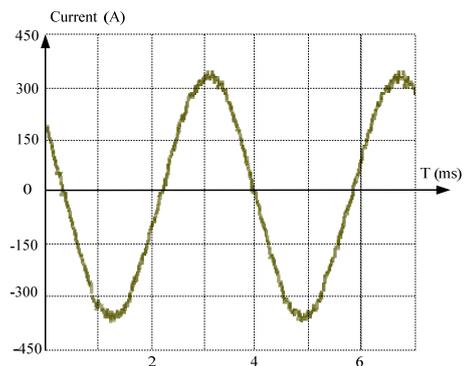
Motors	T component	
	Permanent	Reluctant
Step-skewing Motor	0.991	0.966
Slot-skewed Motor	0.980	0.955

Two similar current waves of motor is showed in Fig6. Through Fourier analysis of two waves (seen in Fig.7), we can see that harmonics of current are mainly eliminated. Tab III compares the nominal performance of two prototypes. The average torque, phase current, output power and efficiency of step-skewed motor are all a little better than slot-skewed motor.

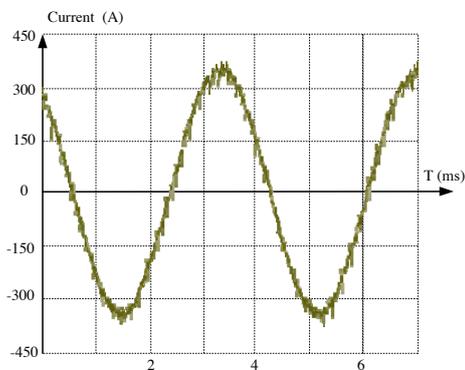
It can be concluded that step-skewed motor has almost equal performance to slot-skewed motor.

Tab III Nominal Performance Comparison

Motors Performance	Step-skewed Motor	Slot-skewed Motor
T_{av} (Nm)	93.8	92.8
I (A)	251.0	251.6
P_{out} (kW)	39.34	38.92
η (%)	94.02	93.96

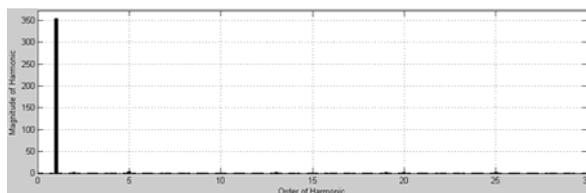


a) step-skewed motor

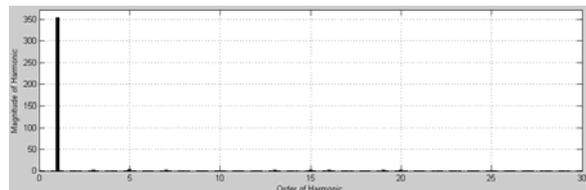


b) slot-skewed motor

Fig. 6 Experimental phase current



a) step-skewed motor



b) slot-skewed motor

Fig 7 Fourier analysis result of phase current

4. Conclusion

Technique of SSR is an efficient way to improve the performance of motor as technique of skewing slot. Although its effect on reduction of harmonics is weaker than slot-skewing, it avoids many negative influence of slot-skewing. Meanwhile, technique of SSR saved lot of time on embedding wires. So it made mass-production of motor more economical.

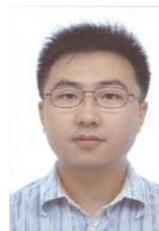
Step-skewed motors with few-step-rotor can achieve good effect on reducing harmonics and have almost equivalent performance to slot-skewed motors. It will be an important trend on mass production of IPM traction motors for EV&HEV.

5. Reference

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