ICEMG 2023-XXXXX

Design and Performance comparison of three and five-phase SynRM

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Abstract
The torque density of multiphase machines with a prime number of phases (five and seven) has been found to be superior compared to machines with other phase numbers. However, these machines need a unique stator design. Hence, either the manufacturing process of electric machine should be change or the three-phase machines should be upgraded to multiphase winding by rewinding techniques. Fortunately, there are some interesting rewinding techniques that have been proven suitable and viable. This article designs and investigates the performance of three and five-phase Synchronous reluctance motor and five-phase Synchronous reluctance motor rewided into a three-phase stator frame in such a way that they are comparable. The results of two-dimensional finite element method show that five-phase designed motor has superior advantages over the other designed motors in terms of average torque and torque ripple which are its drawbacks. It has a remarkable improvement in average torque and efficiency. It also has considerably lower torque ripple compared to other two machines.

Keywords: Electric machines, Rotating machines, Synchronous reluctance motor, five-phase motor, three-phase stator frame.

Introduction

In recent years, electric motors with high levels of efficiency that do not employ rare earth permanent magnets (RE PMs), or use a low percentage of them, have gained popularity due to high and unstable price of magnetic materials [1]. lately, synchronous reluctance motors (SynRMs) have drawn a lot of attention because of their distinguishing qualities when compared to all other electric machines, where the rotor of the machine without a winding, cage, or magnets [2]. This means they have a lower rotor loss, Thereby, their temperature rise is lower and they have a higher level of efficiency than, for instance, induction machines (IMs). They also feature a robust structure, have a limited rotor inertia and employ identical power electronic converters and control systems as IMs, which has a positive financial impact [3]. They are more beneficial than so many other electric machines due to these features, particularly for high-speed applications.

For many years, three-phase electric motors have been used in various industrial applications. However, in last few decades, multiphase electric machines (>3) have received an increase in interest from the scientific world as a viable substitute for 3-phase machines Due to their superior torque density, better reliability, and high capacity to tolerate faults [4]. Despite the fact that any phase order, with either composite or prime numbers, can be constructed for a multiphase stator winding on paper, the key technological barrier that restricts phase order choices is the correlated converter complexity. Consequently, Recent investigations have mostly concentrated on addressing the 5 and 6-phase instances. [5]-[7].

It is essential to acknowledge the fact that in many industrial areas, multiphase machines that their windings have a phase order which is a multiple of three, inclusive of 6-phase machines, are the most preferred choices because of the traditional and accepted 3-phase technology and, as a result, the easily available 3-phase converters, can still be kept up. However, the published works has shown that electrical machines which have a prime phase order, such as 5, 7, or 11-phase winding, are distinguished with a wide range of alluring benefits and distinctive features above other alternatives [8].

One of the main problems in commercializing the multiphase machines is that they require a stator cores that have unique designs, with stator slot number being an integer multiple of the phase order. They also need specific power converters. sadly, the majority of typical 3-phase stator frames cannot be rewind with another balanced winding of a prime phase order in a Straightforward manner. This is the reason why there hasn't been much interest in the utilization of multiphase machines with prime phase number in practical industrial areas. However, the procedures needed to rewind any common stator frame of 3-phase machine with a symmetrical n-phase winding, a prime phase order, and the same number of poles are outlined in an intriguing technique which is proposed in [8].

Five-phase SynRM has drawn lots of researchers' attention due to above mentioned characteristics that they have, compared to other electrical machines. In [8], a new rewinding method for rewinding the stator of any 3-phase motor to multiphase system was introduced. In [9], a new rewinding technique for rewinding a typical frame of 3-phase stator to a 5-phase stator was proposed and variety winding connections (star and combined star pentagon connection) were investigated in a SynRM motor and 5-phase SynRM with combination of star and pentagon connection showed a better average torque and lower torque ripple. In [10], a 5-phase stator was designed for a 3-phase SynRM while rotor was kept the same. The results showed that the motor with upgraded five-phase stator has higher average torque. In addition, its torque ripple is decreased compare to 3-phase SynRM. In [11], the impact of rotor flux barriers' number and the mixed stator winding configurations on the average and torque ripple of 5-phase SynRM was investigated and a considerable reduction of torque ripple was justified with the new winding configuration. [12], inquired into the various slot-pole combination of conventional 3-phase stator structure that can be utilized in building a multiphase machine with prime-phase order.

As far as the author is aware, in literature, the comparison of 3 and 5-phase SynRM and 5-phase SynRM rewinded into 3-phase stator structure has not been investigated. This particular case should be examined to determine the best available option. This document is structured as follows: First, 3 and 5-phase SynRM are designed in such way that are comparable to each other. Then, while stator dimension and copper volume are kept fixed, 3-phase designed stator frame is upgraded to 5-phase stator by a rewinding technique and finally, two-dimensional finite element simulation are carried out for the three designed machines and results are discussed.

Design of three and five phase SynRM

Synchronous reluctance motors are designed based on an existing induction motor with 5.5 kw peak power at 1500 rpm that is manufactured by ABB company. For 3-phase synchronous reluctance motor (SynRM 1), a motor with twenty-four slots and four pole is designed since they are widely used in the industry. Since slot number of 5-phase motor should be multiple of five, a twenty-five slot with four pole synchronous reluctance motor (SynRM 2) is designed so that it can be comparable with SynRM 1. For reduction of torque ripple, the method represented in [13] has been employed.

To have a fair comparison, in designing of the two motors, three features of them should be considered as equal; 1) the iron volume 2) the copper volume 3) the current density. In addition, rotor flux barriers dimensions are the same in the designed motors. Therefore, the number of conductors per slot of SynRM 2 (N_{c5}) is consumed by (1). N_{c3} is the number of conductors per slot of SynRM 1, S_3 and S_5 are the number of slots for SynRM 1 and SynRM 2, respectively. The main parameter of desired motors and precise specifications of SynRM 1 and SynRM 2 are shown in Table 1 and Table 2, respectively.

$$N_{c5} \cdot S_5 = N_{c3} \cdot S_3 \qquad (1)$$

According to the number of slots for each pole for each phase, in SynRM 1, integral slot distributed winding and in SynRM 2, fractional slot distributed winding is used. As it's illustrated in fig.1, The windings are implemented by the use of star of slot theory which is widely explained in [14]. Any existing stator winding might easily be constructed using this concept and for any possible slot/pole combination by drawing a certain number of phasors, which is identical to the number of stator slots. Each phasor is a representation of the fundamental emf component that is induced by the coil side that is placed in each corresponding slot.

Rewinding of SynRM 1

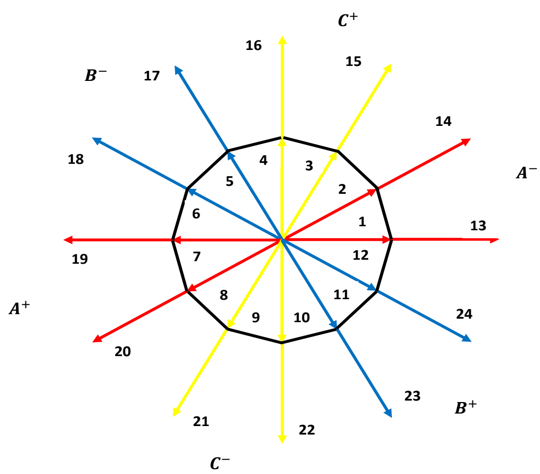
The suggested winding methods described throughout this paper are developed using the star of slot theory, the specifics of which were covered in [8] and [10]. In this method, the existing machine's stator comprises S-slots and its rotor has p-pole pairs. In order to have the 3-phase winding's magnetic axes for each phase lie on the star of slot phasors, the number of slots should be such that slot per pole per phase (q) would be an integer. To obtain the proper m-phase machine in a 3-phase existing stator frame, the magnetic axis of m-phase system, should be located between two phasors of star of slots.

Table 1: The main specification of designed motors

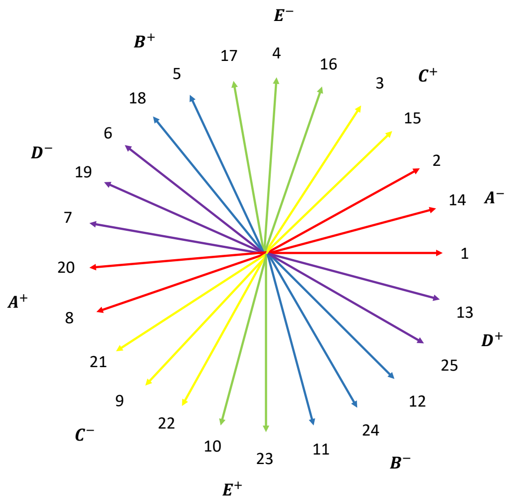
Specifications/Parameter	Value	unit
Rated output power (P_{out})	5.5	kw
Rated Frequency (f)	50	Hz
Rated speed (n_s)	1500	rpm
Rated torque (T_m)	35	N.m
Winding configuration	wye-connection	-
Slot fill factor	40	%
Copper diameter	1.829	mm
Rated current	10.85	A
Outer stator diameter (D_o)	223	mm
Outer rotor diameter (D_i)	124.45	mm
Stack length (L_{stk})	106.5	mm
Airgap (g)	0.5	mm
Stator, rotor steel	M350-50A	-
Rotor shaft diameter	38	mm
Number of flux barrier in each pole	3	-
Angular span of flux barriers ($\alpha_1,\alpha_2,\alpha_3,\beta$)	($5^\circ,15^\circ,25^\circ,10^\circ$)	deg

Table 2: precise specifications of SynRM 1 and SynRM 2

Specifications	SynRM 1	SynRM 2	unit
Number of phases	3	5	-
Number of slots/poles	24/4	25/4	-
Slot/pole/phase	1	1.25	-
Coil turns number	33	32	mm
Coil pitch	6	6	-
DC link Voltage	600	248	Volt



(a)



(b)

Fig. 1: star of slots of (a) SynRM 1 (b) SynRM 2

Then number of conductors in every two slots is calculated in such that phasor of coresponding phase of new m-phase system is obtained. The new m-phase winding's displacement angles are specified in the angular vector H_n as in (2). The angles of two adjacent star of slot phasor ln accordance with each phase of the new m-phase machine (g_1 and g_2) can be expressed as (3) and (4). In (2), ζ_m is the displacement angle of the magnetic axis of phase m and the values of m for m-phase machine would be $m=1:5$. In (3) and (4), λ_{1m} and λ_{2m} are the angle of the first and the second adjacent star of slot phasor to phase m, respectively.

$$H_n=[\zeta_1 \quad \zeta_2 \quad \cdots \quad \cdots \quad \zeta_m] \tag{2}$$

$$g_1=[\lambda_{11} \quad \lambda_{12} \quad \cdots \quad \cdots \quad \lambda_{1m}] \tag{3}$$

$$g_2=[\lambda_{21} \quad \lambda_{22} \quad \cdots \quad \cdots \quad \lambda_{2m}] \tag{4}$$

If we consider N_{ph} as the number of turn per phase in the new m-phase machine, the number of conductors in adjoining star of slot phasors to phase i are derived as follows:

$$\begin{bmatrix} N_{phi} \\ 0 \end{bmatrix}=\begin{bmatrix} \cos(\zeta_i-\lambda_{1i}) & \cos(\zeta_i-\lambda_{2i}) \\ \sin(\zeta_i-\lambda_{1i}) & \sin(\zeta_i-\lambda_{2i}) \end{bmatrix}\begin{bmatrix} N_{1i} \\ N_{2i} \end{bmatrix} \tag{5}$$

Star of slot of SynRM 1 is derived in previous section. The magnetic axis for each phase is not perpendicular to the star of slot phasors when the star-connected five-phase winding is applied, as seen in Fig. 2. Using equation (2-5), first, the angle of any phasor of five-phase machine is derived and expressed in (6-9) and then the number of turns in any slots are calculated and shown in Table 3.

$$T=[A \quad E \quad D \quad C \quad B] \tag{6}$$

$$H_n=[0^\circ \quad 72^\circ \quad 144^\circ \quad 36^\circ \quad 108^\circ] \tag{7}$$

$$g_1=[0^\circ \quad 60^\circ \quad 120^\circ \quad 30^\circ \quad 90^\circ] \tag{8}$$

$$g_2=[0^\circ \quad 90^\circ \quad 150^\circ \quad 60^\circ \quad 120^\circ] \tag{9}$$

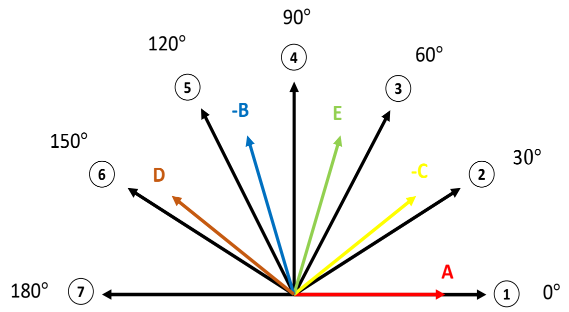


Fig. 3: phasors of star of slots for SynRM 1 and five-phase system

Table 3: Rewinding configuration for SynRM 1

Phase (j)		A	E	D	C	B	
Slot (i)		1	2	3	4	5	6
N_{ij}/N_{ph}	U	1 ⊗	0.81 ⊙	0.61 ⊗	0.41 ⊙	0.21 ⊗	0.81 ⊗
	L			0.21 ⊙	0.41 ⊗	0.61 ⊙	
N_{ci}/N_{ph}		1	0.81	0.82	0.82	0.82	0.81

As it can be seen in Table 3, The winding approach does not produce a satisfactory distinction between the highest and lowest filling factor between stator slots. Applying the conductor distribution strategy between adjacent slots can decrease the filling factors' percentage difference. This is done by distributing percentage of conductors of the slot that has the highest fill factor (in this case phase A in slot 1) equally between two adjacent slots. The amount of this sharing is determined based on the slot that has the second highest fill factor. In this technique, The overall number of turns for phase A will remain the same. For preserving the EMF magnitude of phase A, the number of conductors in adjoinig slots that are displaced by the angle σ (the angle between two slot phasors) is obtained from (6) and the result is shown in Table 4.

$$\Delta N_a=\left(\frac{1-0.8}{2}\right)\frac{N_{ph}}{\cos\sigma}=(0.1)\frac{N_{ph}}{\cos(20^\circ)}\simeq 0.1N_{ph} \tag{10}$$

The last stage in this design is to choose an appropriate Number of turns per phase per pole, N_{ph}, for a new m-phase winding. Maintaining the same copper volume of the current three-phase winding is the study's applied criteria.

Table 4: Implementation of conductor distribution technique in Rewinding configuration for SynRM 1

Phase (j)		A	E	D	C	B	
Slot (i)		1	2	3	4	5	6
$\frac{N_{ij}}{N_{ph}}$	U	0.8 ⊗	0.81 ⊙	0.61 ⊗	0.41 ⊙	0.21 ⊗	0.1 ⊙
	L		0.1 ⊗	0.21 ⊙	0.41 ⊗	0.61 ⊙	0.81 ⊗
N_{ci}/N_{ph}		0.8	0.91	0.82	0.82	0.82	0.91

For this purpose, the amount of copper in each pole of Rewinded SynRM 1 is equalized with the amount of copper in SynRM 1. If N_c^3 and a_c^3 are assumed number of turns in each slot and corresponding cross section area of SynRM 1, respectively, N_{ph} can be derived from (7).

$$\sum_{i=1}^{S} N_{ci} \cdot a_c^n = S \cdot N_c^3 \cdot a_c^3 \tag{11}$$

Where N_{ci} and a_c^n are number of conductors in each slot and cross-section area of m-phase winding. By applying (7), hence;

$$N_{ph} \times (0.8 + 3 \times 0.82 + 2 \times 0.91) = 6 \cdot N_{ci}^3 \tag{12}$$

Considering same conductor size $(a_c^n = a_c^3)$, therefore $N_{ph} = 1.8 N_c^3 = 1.8 \times 66 \simeq 78$. The exact number of turns in each slot in rewinded SynRM 1 and the ratio between number of turns per each slot in rewinded SynRM 1 and number of turns per each slot in SynRM 1 are shown in Table 5.

Table 5: calculated number of conductors in each slot

Phase (j)		A	E	D	C	B	
Slot (i)		1	2	3	4	5	6
$\frac{N_{ij}}{N_{ph}}$	U	62 ⊗	62 ⊙	47 ⊗	31 ⊙	16 ⊗	8 ⊙
	L		8 ⊗	16 ⊙	31 ⊗	47 ⊙	62 ⊗
N_{ci}		62	70	63	62	63	70
N_{ci}/N_c^3		0.9545	1.0758	0.9697	0.9697	0.9697	1.0758

Results and discussions

In this section, 2-dimensional (2-D) FEM transient simulations are used to evaluate the performance of the SynRMs that are designed in former sections and results are analyzed. SynRM 1 is 3-phase motor and SynRM 2 is 5-phase motor and SynRM 3 is 5-phase rewinded motor in the stator frame of SynRM 1.

Fig. 4 demonstrate the SynRMs' average torque which are at rated speed versus various current angles. It has been found that SynRM 2 has the highest average torque and SynRM 3 has the lowest of all. It's shown that optimum current angle of SynRM 1, 2 and 3, are 68, 66 and 68 degrees, respectively. Fig. 5 displays instantaneous torque at rated condition (1500 rpm and 10.48 A) and at optimum current angle. Compare to SynRM 1 and 3, The improvement of average torque and torque ripple in SynRM 2 is significant. Relative to SynRM 1 and 3, SynRM 2 has 2.08% and 2.65% higher average torque and has 14.9% and 30.36% lower Torque ripple, respectively. These improvements in average torque and torque ripple are due to winding factor, different winding type and MMF magnitude. This is also evident in the three machines' flux density distributions and flux density in the airgap which are shown in fig. 6 and 7.

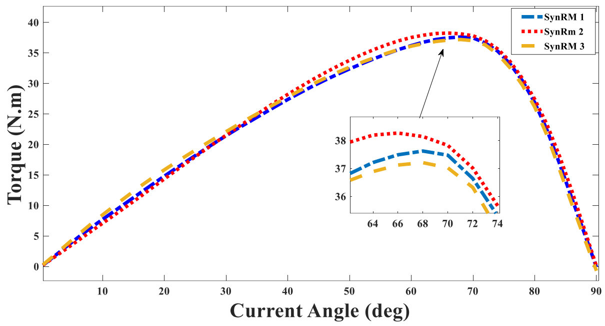


Fig. 4: Torque versus current angle of three designed machine

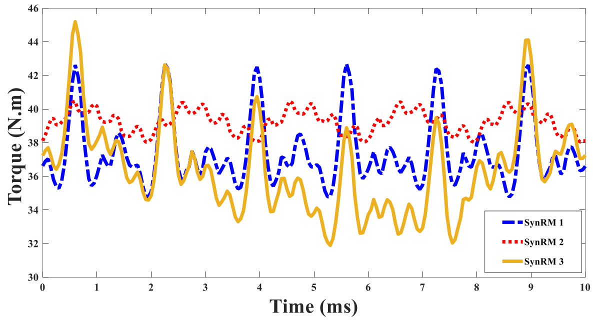


Fig. 5: instantaneous torque at optimum current angle

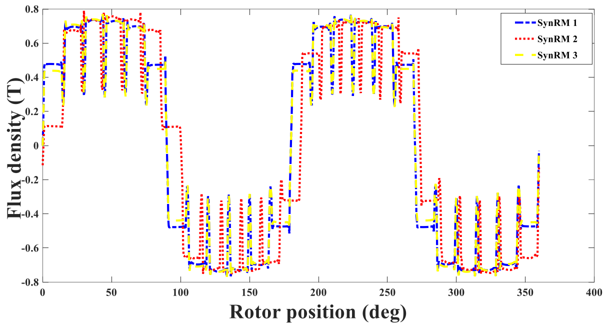
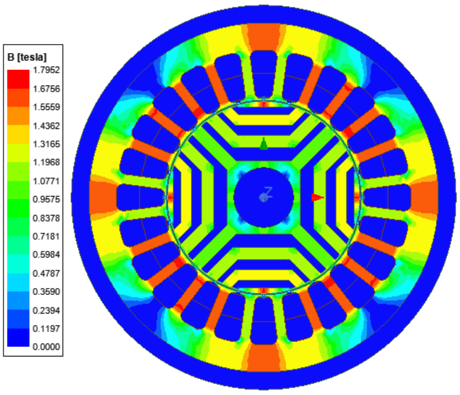


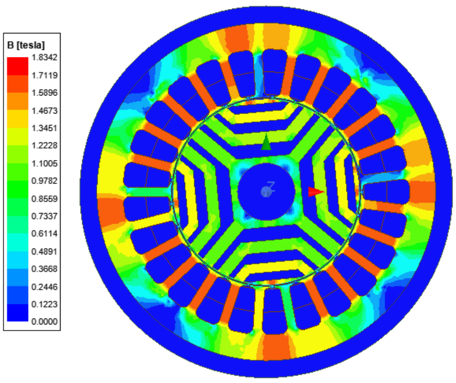
Fig. 6: Flux density distribution in airgap of three designed machines

Table 6: Designed machines' outputs at rated conditions and at the optimum current angle and rated condition

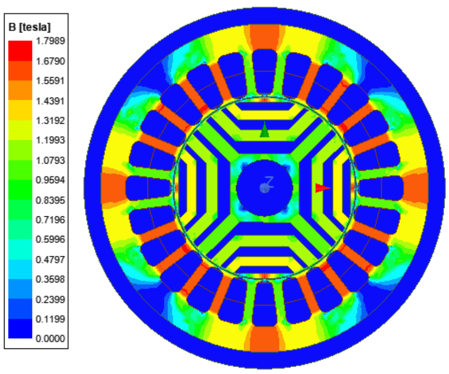
Outputs	SynRM 1	SynRM 2	SynRM 3
Average torque (N.m)	37.42	38.24	37.2
Torque ripple (%)	21.1	6.2	36.56
Efficiency (%)	89.48	89.95	89.33
Power factor	0.681	0.6647	0.6845



(a)



(b)



(c)

Fig. 7: Flux density distribution in (a) SynRM1 (b) SynRM 2 (c) SynRM 3

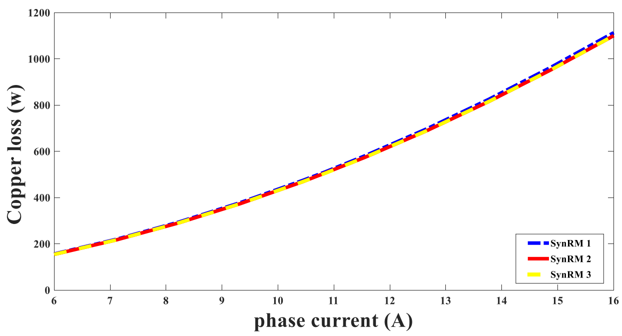


Fig. 8: Copper loss at different phase current of three designed machines

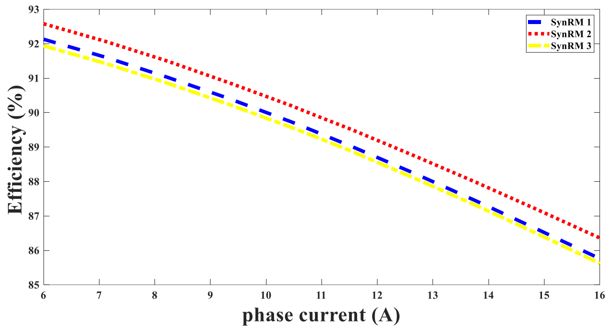


Fig. 9: Efficiency at different phase current of three designed machines

Fig. 8(a) demonstrate that the overall losses for the three machines are very similar. The reason for this is that the three machines all have the equivalent current density and copper volume. As a result, the major cause of loss in in any electrical machines, which is copper loss, will be equal in three machines. Moreover, the iron loss in these three designed machines is equal because they have the same amount of iron volume. Hence, as it's illustrated in fig. 8(b) and Table 6, since the total loss of these machines are fixed and improvement in average torque in 5-phase SynRM, at rated condition, efficiency is considerably boosted from 89.48 and 89.33 in SynRM 1 and 2, respectively, to 89.95 in SynRM 3. It's also can be seen from table 6 that SynRM 2 has the lowest power factor which is due to lower optimum current angle compared to other machines.

conclusion

This essay evaluated the performance comparison between 3 and 5-phase synchronous reluctance and 5-phase synchronous reluctance rewinded in the 3-phase stator frame with 2-D FEM transient simulation. The iron volume, current density, copper volumes were kept fixed and the same rotor were used in the designed machines. It's shown that 5-phase synchronous reluctance has higher average torque and efficiency. In addition, 5-phase SynRM had 14.9% and 30.36% lower Torque ripple compared to 3-phase synchronous reluctance and five-phase synchronous reluctance rewinded in a 3-phase stator frame, respectively.

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