Novel Three Phase Flux Reversal Machine with Full Pitch Winding

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Abstract—This paper proposes a concept of fictitious ‘Electrical Gear’ in analyzing the flux pattern of Flux Reversal Machine (FRM). Concept of novel full pitch winding is presented for FRM. Finite Element Method (FEM) analysis of conventional concentrated stator pole winding FRM and proposed full pitch winding FRM are carried out to validate the concept. Generator performance of full pitch winding FRM is compared with conventional concentrated stator pole winding FRM. Full pitch winding arrangement increases the inductance of the machine which results in poor voltage regulation. Series capacitive compensation is provided to the machine for better voltage regulation. Output power of compensated full pitch winding FRM is approximately twice as that of the conventional concentrated stator pole winding FRM. Physical dimensions, electrical and magnetic loadings are kept same in both the machines.

Index Terms—Flux reversal machine, full pitch winding, doubly salient permanent magnet electrical machine, finite-element method (FEM) analysis.

I. INTRODUCTION

SINGLE phase FRM was first introduced in 1997 by R. P. Deodhar et al [1] for an automobile generator to replace the standard claw pole alternator. It has numerous advantages such as simple construction, low inertia, high power density and is suitable for high speed application due to permanent magnets on the stator pole. This single phase configuration was fully explored as a generator and not as a motor. Three phase FRM was introduced by C. Wang et al [2] in 1999. The design of the machine was optimized to (i) increase the peak to peak coil PM flux linkage variation, (ii) reduce the cogging torque and PM weight, (iii) restrain the self and mutual inductance. The basic machine configuration has an 8 salient pole rotor and 6 pole stator with concentrated windings. Permanent Magnets are mounted on stator pole. Fig. 1 shows the machine configuration.

FRM for low-speed servo drive application was introduced by Ion Boldea et al [3] in 2002. This low speed machine has 28 rotor poles and 12 stator poles with two permanent magnet pairs on each stator pole. This machine was designed for 128 rpm at 60 Hz. High torque density with less than 3% torque pulsation with vector control was achieved. In order to reduce the cogging torque, rotor teeth pairing method was proposed [4]. Attempts were made to reduce the leakage flux by providing flux barrier on the rotor poles at its edges [5]. Power density comparison of doubly salient permanent magnet electrical machines were made. FRM has higher power density in comparison with other machines in the same class [6].

In this paper, concept of fictitious ‘Electrical Gear’ and full pitch winding applicable to FRM is presented. 2-D FEM analysis [7] is carried out on the conventional concentrated stator pole winding FRM and proposed full pitch winding FRM. Optimized machine dimensions are obtained from C. Wang et al [2]. The important dimensions of FRM are given in Table I for ready reference.

Section II describes the flux pattern linking to the stator winding of the machine and from there the concept of fictitious ‘Electrical Gear’ and full pitch stator winding arrangement is discussed. Section III describes the 2-D FEM analysis results obtained for full pitch FRM and concentrated stator pole winding FRM. The results are compared with the results of paper [2]. Section IV describes the FEM analysis on load to find the voltage regulation of full pitch winding FRM. Effects on machine parameters due to full pitch winding and method used to improve the voltage regulation is also discussed. Section V compares the power density of full pitch winding FRM with PMSM and finally conclusions are drawn.
II. FLUX PATTERN LINKING TO THE STATOR WINDING AND FULL PITCH STATOR WINDING

Geometry of three phase flux reversal machine (as per Table I) is shown in Fig. 2. The flux plot of the machine at no load is shown in the same Fig. FRM machine has 6 stator poles and 8 pole variable reluctance rotor. The normal component of flux density at the middle of stator pole along the periphery of the machine is shown in Fig. 3. The observation of this normal component of flux density plot reveals that the machine has two pole flux pattern. In other words machine has two effective poles.

Phase flux linkage of FRM is sinusoidal and hence induced voltage is also sinusoidal [2]. Considering a linear load the phase current is sinusoidal. Normal component of armature reaction along the air gap at one instant of time is shown in Fig. 4. This flux pattern also reveals that machine has two poles. In general, machine has same number of stator poles and rotor poles.

The frequency and speed relationship for FRM [3] is given by

\[ f = \frac{n \times n_r}{60} \]

where, \( n \) = rotor speed in rpm.
\( n_r \) = Number of rotor teeth (poles).
\( f \) = frequency in Hz.

FRM machine has two effective poles, and hence in one cycle, flux pattern completes one revolution. Thus when rotor speed is \( n \) rpm, the flux pattern completes \( n \times n_r \) revolutions per minute. Hence flux pattern rotates \( n_r \) times the shaft speed. In conventional synchronous machine, flux pattern speed and rotor speed is same. Pictorial representation of FRM generator and permanent magnet synchronous generator is shown in Fig. 5. Both machine representation is for same speed and output frequency. Flux pattern in FRM rotating \( n_r \) times rotor speed is represented as a fictitious step-up gear and is called as ‘Electrical Gear’. Conventional synchronous machine should have \( 2 \times n_r \) poles for same output frequency.

FRM has 6 slots and two pole flux pattern, hence electrical angle per slot is \( 60^\circ \). Conventional concentrated stator pole

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air gap in mm</td>
<td>( g )</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Magnet thickness in mm</td>
<td>( h_{pm} )</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Rotor pole span angle</td>
<td>( \beta_r )</td>
<td>16.2°</td>
</tr>
<tr>
<td>4</td>
<td>Stator pole span angle</td>
<td>( \beta_s )</td>
<td>42.6°</td>
</tr>
<tr>
<td>5</td>
<td>Stator pole span in mm</td>
<td>( \tau_{ps} )</td>
<td>27.8</td>
</tr>
<tr>
<td>6</td>
<td>Rotor pole span in mm</td>
<td>( \tau_{pr} )</td>
<td>10.3</td>
</tr>
<tr>
<td>7</td>
<td>Stator pole height in mm</td>
<td>( h_{ps} )</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>Rotor pole height in mm</td>
<td>( h_{pr} )</td>
<td>18</td>
</tr>
<tr>
<td>9</td>
<td>Outer diameter of rotor in mm</td>
<td>( D_r )</td>
<td>72</td>
</tr>
<tr>
<td>10</td>
<td>Outer diameter of stator in mm</td>
<td>( D_o )</td>
<td>129</td>
</tr>
<tr>
<td>11</td>
<td>Number of turns /phase</td>
<td>( N_{ph} )</td>
<td>52</td>
</tr>
<tr>
<td>12</td>
<td>Stack length of machine in mm</td>
<td>( l_{ak} )</td>
<td>86</td>
</tr>
</tbody>
</table>
winding has a coil span of 60°. Fundamental pitch factor of the stator winding is 0.5. As electrical angle between the slots is 60°, full pitch winding is possible. The arrangement of full pitch winding is shown in Fig. 6, which results in unity pitch factor.

III. FEM ANALYSIS OF FULL PITCH WINDING FRM AT NO LOAD

FRM machine design data is obtained from [2] and given in the Table I for ready reference. Physical dimensions of the machine and number of turns are kept same in full pitch winding FRM and conventional concentrated stator pole winding FRM. Only the winding arrangement is changed. FEM analysis is carried out to find the phase flux linkage variation of both the machines with rotor position. Phase flux linkage variation of both the machines without skewed rotor is shown in Fig. 7. This variation is shown for one rotor pole pitch (i.e., mechanical 45°). Fig. 7 clearly shows that full pitch winding FRM stator flux linkage is approximately twice as that of the flux linkage of conventional concentrated stator pole winding FRM.

Simulations are carried out at different speeds on both machines to determine the induced voltage on no-load. Induced voltage at different speed for both machines without skewed rotor is shown in Fig. 8. The simulated result shows that no load induced voltage in full pitch winding FRM is approximately twice as that of the voltage induced in the conventional concentrated stator pole winding FRM. No-load phase voltage waveforms of both configurations at 8000 rpm are shown in Fig. 9.

Stator phase inductance is calculated using FEM as per procedure given in [2]. First magnet flux linking the stator winding is obtained and then positive mmf to the winding, total flux linkage to the winding is obtained. The self inductance is obtained by subtracting the PM flux linkage from total flux linkage. The same procedure is used to determine the self inductance when negative stator mmf is applied. The

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Fig. 5. Generator representation of FRM and PMSM

Fig. 6. Full pitch winding arrangement

Fig. 7. Phase flux linkage of full pitch winding FRM and concentrated stator pole winding FRM

Fig. 8. No load phase voltages of full pitch winding FRM and conventional concentrated stator pole winding FRM
average of these two self inductances represents the actual value of self inductance. The stator phase inductance variation for both machines with rotor position is shown in Fig. 10. Self inductance variation of full pitch winding FRM is 2.42 mH to 2.52 mH, whereas this variation for conventional concentrated stator pole winding FRM is 0.78 mH to 1.1 mH. Full pitch winding arrangement increases the self inductance of winding by 2.5 to 3 times depending upon the saturation in the machine. If saturation is neglected, then self inductance increases by 3 times, whereas variation of self inductance with rotor position is very small in both cases.

Under normal operating conditions some parts of magnetic circuit gets saturated in the full pitch winding FRM. Mutual inductance variation is 0.54 mH to 0.91 mH. Under unsaturated condition, this variation is from 0.835 mH to 0.93 mH. Mutual inductance of full pitch winding FRM is approximately 0.33 times that of its self inductance. Mutual inductance variation with rotor position is shown in Fig. 11.

IV. FEM ANALYSIS OF FULL PITCH WINDING FRM AT STEADY STATE ON LOAD

FEM simulation is carried at different load condition to determine the voltage regulation of machine at 2000 rpm for both types of winding configuration. Terminal voltage variation with load current is shown in Fig. 12. It is seen that regulation of full pitch winding FRM is poor as compared to concentrated stator pole winding FRM.

Regulation of full pitch FRM can be improved by using series capacitive compensation [9]. The arrangement for capacitive compensation is shown in the Fig. 14. The value of capacitor is given by [8].

\[ C = \frac{1}{\omega^2 \times L_s} \] (2)

where, \( \omega \) = Induced EMF frequency in rad/sec.

\( L_s \) = synchronous inductance of the machine in Henry.
Load characteristics of full pitch winding FRM

![Graph showing load characteristics of FRM](image)

**Fig. 13.** Terminal voltage variation with resistive load for full pitch winding FRM.

**Fig. 15.** Flux distribution in FRM and PMSM for same output voltage and frequency at common shaft speed.

Load current in Amps

<table>
<thead>
<tr>
<th>Load voltage (V)</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load current (A)</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>

where, $I_s$ = stack length of the machine in meter.

$\tau$ = pole pitch distance in meter.

$N_{ph}$ = number of turns per phase.

$\tau = 0.113097$ m for full pitch FRM. (Full pitch FRM has effective 2 poles.)

Using the above equation $Bm_1(max)$ in FPF RM is 0.127 Wb/m², whereas $Bm_1(max)$ in PMSM is 1.0186 Wb/m².

Flux density distribution is assumed to be sinusoidal as flux linkage is sinusoidal. Calculated flux density distribution along the air gap for both machines is shown in the Fig. 15.

Flux density distribution pattern of FRM rotates at $n \times \tau$ rpm, whereas flux density distribution pattern of PMSM rotates at $n$ rpm for a common shaft speed of $n$ rpm. Both flux pattern generates same output voltage and frequency. Hence equivalent conventional PMSM should have a flux density of 1.0186 Wb/m² for the same output power as full pitch winding FRM. Maximum possible air gap flux

**V. POWER DENSITY OF FULL PITCH FRM**

The flux linkage in full pitch winding FRM is shown in the Fig. 7. From this Fig. it can be observed that maximum phase flux linkage is 0.041 Wb. The relationship between maximum flux linkage $\psi_1(max)$ and maximum flux density $Bm_1(max)$ is given by [11].

$$\psi_1(max) = \frac{Bm_1(max) \times I_s \times \tau \times 2 \times N_{ph}}{\pi}$$  \hspace{1cm} (3)

where, $I_s$ = stack length of the machine in meter.

$\tau$ = pole pitch distance in meter.

$N_{ph}$ = number of turns per phase.

$\tau = 0.014137$ m for equivalent PMSM. (Equivalent PMSM has 16 poles.)

Using the above equation $Bm_1(max)$ in FPF RM is 0.127 Wb/m², whereas $Bm_1(max)$ in PMSM is 1.0186 Wb/m².

Flux density distribution is assumed to be sinusoidal as flux linkage is sinusoidal. Calculated flux density distribution along the air gap for both machines is shown in the Fig. 15.

Flux density distribution pattern of FRM rotates at $n \times \tau$ rpm, whereas flux density distribution pattern of PMSM rotates at $n$ rpm for a common shaft speed of $n$ rpm. Both flux pattern generates same output voltage and frequency. Hence equivalent conventional PMSM should have a flux density of 1.0186 Wb/m² for the same output power as full pitch winding FRM. Maximum possible air gap flux
density in PMSM is $0.9 \, \text{Wb/m}^2$ [10]. Hence full pitch FRM (equivalent PMSM) has 13.17% higher power density than conventional PMSM in low speed, low power range.

VI. FRM CONFIGURATIONS AND FULL PITCH WINDING

FRM machine configurations for low speed are presented by Ion and et.al. [3]. The configurations are

- low speed FRM with pole PMs on stator.
- low speed FRM with inset-PMs on stator.

These configurations have 12 stator poles (slots) and flux pattern of 4 poles. Full pitch winding arrangement is also possible for both configurations. Full pitch winding arrangement for low speed FRM machine with 16 rotor poles and 12 stator poles with 2 PM pole pieces per stator pole is shown in Fig. 16. End turn length will be less in higher pole machine which decreases the end turn leakage inductance and copper loss. Hence full pitch winding concept is applicable to all FRM configurations.

VII. CONCLUSION

Full pitch winding concept for FRM is introduced. Output power of compensated full pitch winding FRM is approximately twice as that of conventional concentrated stator pole winding FRM. Full pitch winding FRM is fully analyzed and simulated with flux-2D FEM software [7]. Full pitch winding arrangement increases the self inductance of machine by 2.5 to 3 times depending upon saturation in the machine which results in poor voltage regulation. Series capacitive compensation is provided to improve the regulation of full pitch winding FRM. Fictitious ‘Electrical Gear’ concept is introduced which makes it possible to compare the power density of full pitch winding FRM with PMSM. It is found that power density of compensated full pitch winding FRM is 13.75% higher than conventional PMSM. Full pitch winding FRM is a competitive candidate for low speed, low power generator and motor applications.

VIII. ACKNOWLEDGMENT

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REFERENCES


