Fabrication, Parameter Evaluation and Testing of a Permanent Magnet Synchronous Generator

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Abstract—This paper presents steps and procedure for the fabrication, parameter determination and testing of a 3-phase, 6 pole, 245V, 2kVA, surface mounted permanent magnet synchronous generator (PMSG) for possible use in pico-hydel system. A thorough design of the machine following conventional methods was initially carried out followed by fine-tuning of the dimensions and performance parameters through repeated iterations using excel-sheet based methods backed up by design verification using FEM-based standard softwares[7]. The electrical parameters were then evaluated using analytical methods and cross-checked using the FEM model. Thereafter the machine was fabricated at the works of a local machine manufacturer. Here also it had to go through multiple fabrication stages, particularly for the PM-rotor. A separately excited dc motor serves as the prime mover. Then the machine parameters have been experimentally determined. Finally the PMSG has been tested under partial load. The various stages starting from fabrication to partial load testing have been presented in this paper.

Index Terms—Permanent magnet synchronous generator, direct axis inductance, quadrature axis inductance, no load back emf.

I. INTRODUCTION

The permanent magnet synchronous generator (PMSG) or PM alternator is projected as a key equipment in renewable energy applications for generating power in case of wind generators, pico-hydel etc. in remote hilly/mountainous tracts where usual grid based electricity may not reach due to obvious difficulties. Very recent investigations based on user demand identify the need for a new technology named pico-hydel system for off-grid electrification (2 – 5kVA) in remote hilly regions near low volume but fast mountainous streams and waterfalls[8]. PMSG is proposed as one of the most suited technology in such applications. Its high efficiency and maintenance free operation out-competes the conventional generators (Induction Machine) used for these type of application. But the major disadvantages of PMSG are the high cost of the permanent magnets and possibility of demagnetisation of permanent magnets under certain fault conditions. Thus the design of the PMSG should be optimised to have minimum volume of permanent magnets together with reduced size and weight for the complete machine. The design should also ensure the protection of permanent magnet against demagnetisation effect of armature current. In other words the demagnetising component of the armature current(d-axis current)should always remains zero(even during the transients ideally to prevent magnet demagnetisation), which points to the need for having closed-loop control with a load side inverter operation. Hence, the present design considers that the PMSG will be run under appropriate control to deliver power from machine to grid at internal unity power factor (pf).

It may be worthwhile to mention that this work was taken up, under a funded research initiative, with a view to develop an indigenous design approach for PMSG based generation technology. PMSGs are not commercially available from Indian manufacturers. To add to the problem, permanent magnets having high energy densities are not available indigenously. For the present work the magnets, are being procured at very high costs from foreign sources.

II. PMSG DESIGN

In the present work PMSG design has been started with an available stator lamination (of an Induction Machine of comparable power rating). This has been done in order to reduce tooling and fabrication costs and manufacturing time. The mechanical drawing of the generator assembly is shown in Fig.1. The available dimensions of the lamination used and other pertinent data are given in Table1. The 2D cross sectional view of the machine with the relevant dimensions in mm is shown in Fig.2.
<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator OD</td>
<td>158.2 mm</td>
</tr>
<tr>
<td>Stator ID, D</td>
<td>95 mm</td>
</tr>
<tr>
<td>Tooth Width(parallel teeth)</td>
<td>4 mm</td>
</tr>
<tr>
<td>Slot Depth</td>
<td>17 mm</td>
</tr>
<tr>
<td>Number of Slots</td>
<td>36</td>
</tr>
<tr>
<td>rated power</td>
<td>2 kW</td>
</tr>
<tr>
<td>Number of poles, P</td>
<td>6</td>
</tr>
<tr>
<td>Air gap length, ( l_g )</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Rated speed</td>
<td>1000 r.p.m</td>
</tr>
</tbody>
</table>

**TABLE I**

**TARGETED SPECIFICATIONS OF PMSM**

The design is fine tuned with the help of standard finite element method (FEM) based software. The detailed design and FEM analysis are given in [6]

**III. FABRICATION OF 2kVA PMSG**

Fig.3 shows the fabricated generator. The stator is housed in a standard induction machine cast iron shell for its easy availability and lower cost. Presently aluminum or antimony based housing is being considered for another prototype.

During fabrication of rotor body, the material selected was stainless steel. Stainless steel comes in the form of solid structure. On this solid rotor body as shown in Fig.4, for holding the magnets, a channel is cut. Magnets are inserted in these channels and are restricted from flying off by mechanically overlapping lips of the channel.

Since, stainless steel has a low magnetic permeability and as shown in the above figure there are partial overlap of the channel lips on the magnet edges (to prevent flying off), the no load back emf comes as shown in Fig.5 which does not match in shape and magnitude with predicted waveforms based on FEM simulation as shown in Fig.6. So due to under performance of the machine, the machines was taken back to the works of the manufacturer. There, the rotor body was refabricated with same material as in stator core, i.e. M36 silicon steel material which is having a much better magnetic property. At the same time unlike previous structure, no channel is made to hold magnets. Since nickel coated NdFeB magnet is used, no glue like araldite is put on the magnet surface for tightly holding the magnet on the rotor body. Instead after putting the magnet on the rotor body, a PVC
tape sleeve is jacketed on the magnet to prevent flying off of
the magnets due to centrifugal force. The new rotor is shown
in Fig.7. The shaft is made of EN24 material manufactured
by forging process (hardened and tempered) Fig.8 shows the
stator part of the machine. The stator body is applied with
a thin layer of locitite640 and shrink fitted into the housing.
The alternator was then found to be robust in construction
suitable for rough usage. Tight machining tolerances, precision
balancing and thorough testing guarantee a long service life.
The alternator was then protected against the ingress of solid
foreign bodies and water in accordance with IS:4691-1985.
The degree of protection provided is IP-55.

IV. PERFORMANCE CALCULATIONS AND PARAMETER
dETERMINATION OF THE PMSG

If armature current can be maintained in phase with generated
emf (which is the case in case of field oriented control),
then the permanent magnet on the rotor will not be subjected
to any demagnetising component of armature current (negative
d-axis current). The phasor diagram in Fig.9 demonstrates the
same.

A. Phasor Diagram at Rated Conditions

From Fig.8 it can be written

\[
V_t = -X_q I_q + j(E - R I_q) \tag{1}
\]

\[
V_t = -314 * .0173 * 4.8 + j(141.5 - 4.8 * 1.4) = -26.1 + j134.78 = 137.3 \angle 79^\circ \tag{2}
\]

Since \( \delta = 11^\circ \), terminal power factor = \( \cos(11^\circ) \) = 0.98 and
power output \( (P_o) \) is

\[
3 * Re(VI^*) = 3 * Re[141.5 * 4.8 \angle (11)] = 2000W \tag{3}
\]

The line to line terminal voltage at rated load will be 237.8V.
From FEM calculation at rated speed (Fig.5), the computed
line to line terminal voltage is around 245V.

B. Performance prediction of the PMSG

Fig.10 shows \( P_o \) vs. \( \eta \) curve of the designed PMSG. At
rated load and speed, the efficiency of the alternator is close
to 90%. Compared to conventional generator, it can be claimed
that this machine has got higher power-weight ratio (TABLE III),
higher efficiency and operation (virtually) without any
maintenance. The performance of the machine is calculated
assuming operation in still air with ambient temperatures up
to 30\(^\circ\) C (laboratory environment) and winding temperature
rise of 110\(^\circ\) C over ambient. The machine parameters are
determined using established procedure [1] and are given in
TABLE II.

<table>
<thead>
<tr>
<th>Maximum Continuous Power</th>
<th>1840 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency at rated load and speed</td>
<td>89 %</td>
</tr>
<tr>
<td>No. of Poles</td>
<td>6</td>
</tr>
<tr>
<td>No. of Phases</td>
<td>3</td>
</tr>
<tr>
<td>Winding Connection</td>
<td>star</td>
</tr>
<tr>
<td>Temperature Rise</td>
<td>0.613 degC/W</td>
</tr>
<tr>
<td>Maximum winding temperature</td>
<td>155 degC</td>
</tr>
<tr>
<td>Weight</td>
<td>15 kg</td>
</tr>
<tr>
<td>Load current</td>
<td>5.7A</td>
</tr>
<tr>
<td>No load bemf(l-l)</td>
<td>245 V</td>
</tr>
<tr>
<td>Phase resistance</td>
<td>1.7 ohm</td>
</tr>
<tr>
<td>Ld,Lq</td>
<td>17 mH</td>
</tr>
</tbody>
</table>

TABLE II

PERFORMANCE DATA AND MACHINE PARAMETERS

V. EVALUATION OF PARAMETERS FOR THE Prototype

The PMSG parameters are evaluated following standard
procedures. The same is given below. Thereafter the parameters
have been experimentally determined through tests. All these
have also been detailed in subsequent sections. The tested
parameters are found to be in excellent agreement with the
predicted values.
A. Experimental determination of emf constant

The fabricated PMSG is coupled with a separately excited dc motor as prime mover. The dc motor is run at 1000rpm and generated emf is measured at the terminals of the PMSG (waveform shown in Fig.11). The oscilloscope plot is captured with the help of isolated voltage probe whose attenuation is 500X and oscilloscope channel has an attenuation of 10X. It has been observed that the maximum value of phase back emf at this speed is 200V. Phase back-emf is little flattened and sagged at the top. This is expected as the stator could not be skewed up to full pitch at the vendor’s place.

![Fig. 11. Generated line to line emf at 1000 rpm](image)

B. Weight and Power Density of the Prototype and Comparison with 2kVA Induction Machine

The fabricated generator is measured to have a total weight of 31kg of which Mild Steel (MS) housing is 19kg. It is expected that an aluminium-antimony based housing can reduce the total weight of the machine by 40% and subsequently thermal resistance of the machine will decrease yielding higher output power. Table3 shows a comparison of weight and energy density of the 2kVA PMSG and an available Induction Machine (IM) with same power rating.

<table>
<thead>
<tr>
<th>Items</th>
<th>PMSG</th>
<th>IM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Weight</td>
<td>12kg</td>
<td>25kg</td>
</tr>
<tr>
<td>Total Weight (including Housing)</td>
<td>31kg</td>
<td>42kg</td>
</tr>
<tr>
<td>Effective Power Density</td>
<td>166.6W/kg</td>
<td>88W/kg</td>
</tr>
<tr>
<td>Net Power Density</td>
<td>64W/kg</td>
<td>47.6W/kg</td>
</tr>
<tr>
<td>Effective Torque Density</td>
<td>1.584N-m/kg</td>
<td>0.54N-m/kg</td>
</tr>
<tr>
<td>Net torque Density</td>
<td>0.613N-m/kg</td>
<td>0.54N-m/kg</td>
</tr>
</tbody>
</table>

TABLE III

**Comparison between 2kVA PMSG and Induction Machine**

C. Validation of DC Resistance Parameter

The RY terminals of the machine is fed with a dc voltage of 9.1V and the current through the winding is measured as 2.5A. The terminal to terminal dc resistance came out as 3.64Ω. The dc phase resistance is 1.82Ω and due to skin effect at 50Hz the ac phase resistance is calculated as 2Ω.

D. Validation of Ld and Lq Parameters

To find out the direct axis inductance (Ld) and quadrature axis inductance (Lq), the following steps are followed[1].

- R phase is aligned to d-axis by applying 5V DC voltage across BY terminals
- B phase is aligned to d-axis by applying 5V DC voltage across RY terminals

Leakage inductance ($L_l$), d-axis inductance ($L_d$) and q-axis inductance ($L_q$) are calculated by measuring phase voltages, induced voltages and phase currents for above conditions. The measured values are: $L_d = 18.86$mH and $L_q = 18.86$mH.

E. No load generated EMF test

The generator is run at different speed with the help of coupled dc shunt motor. The dc machine speed is varied and the line voltages of the PMSG are recorded. Fig.12 shows plot of generated (both simulation and experiment) emf at different speeds.

![Fig. 12. Experimental and Simulated generated EMF Vs. speed](image)

Table IV shows comparison of simulated parameters and measured parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Simulation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per phase resistance</td>
<td>1.6 Ω</td>
<td>1.82 Ω</td>
</tr>
<tr>
<td>$L_d$</td>
<td>17mH</td>
<td>18.86mH</td>
</tr>
<tr>
<td>$L_q$</td>
<td>17mH</td>
<td>18.86mH</td>
</tr>
<tr>
<td>No-load back emf</td>
<td>247V</td>
<td>247V</td>
</tr>
</tbody>
</table>

TABLE IV

**Comparison between simulated and measured parameters**

VI. PARTIAL LOAD TEST OF THE GENERATOR

A 1.5kW dc shunt motor is coupled with the generator to conduct different tests on the PMSG. The available dc motor in the laboratory could deliver a maximum load of 868W on the PMSG. A bigger dc motor is being planned for full load testing. A three phase variable resistive load when connected at the terminals of the generator, the dc motor is run at different speeds and a load current of 1.5A is kept constant by adjusting the load box settings. Fig.13 shows power delivered by the generator at different speeds.

![Fig. 13. Output power Vs. speed](image)
VII. CONCLUSIONS

In this paper a 2kW surface mounted PMSG has been fabricated with an available induction machine’s stator lamination. Keeping in mind the cost of the product, materials have been selected judiciously and machine design is worked out in a simple manner like integral slot winding, effort has been made to reduce cogging torque by skewing stator etc. The machine is fabricated with the machines and tools which are typically available in a small machine shop. The experimental determination of the parameters and partial load test show excellent co-relation between calculations and experiments.

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[8] en.wikipedia.org/wiki/Picohydro