Operation Melioration in Permanent Magnet Machine by using Dual Stator Design

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Abstract—Miniature permanent magnet (PM) brushless motors used in Industrial power tool application require high torque and efficiency. Further, the size constraints imposed by the hand-held tool requires the use of high torque density motor. Therefore, by utilizing the stator slot area to achieve the required number of amperes turns is important while considering the low-cost motor solution. Existing single-piece stator lamination design has poor conductor fill factor in the slots due to manual insertion of the coils in the narrow slot opening. Hence to solve the poor slot fill factor (SFF) and to simplify the winding process, the stator lamination is split into two-parts and the pre-wound coils are placed outwards in the open slots. This results in increased SFF and result into 22% improvement on motor regulation. The FEA based simulation is carried out and simulated motor performance is validated with experimental results. In addition, the challenges during the prototype motor build is discussed.

Keywords— PM synchronous motor, cogging torque reduction, Laminations, Full pitch winding

I. INTRODUCTION

Traditional slotted permanent magnet synchronous motors (PMSM) uses two-layer full pitch winding and the designed slot opening is narrow considering the performance requirements such as sinusoidal back-emf shape and low detent/cogging torque. Also, due to the manual winding insertion and subsequent use of retaining wedges, the poor slot fill factor (SFF) is encountered. This results in increase in winding resistance for the same motor torque constant. Further this traditional way of filling the conductor in the stator slots increases the production hours and highly dependent on the skilled workmanship.

Few research works are carried out in this topic and presented in the literature. Ref. [1] details the concentratedly wound coils on a plurality of teeth of a stator core. It is shown that a high space factor of coils in slots in a stator core and stable output characteristics using the core segments are possible. The multipart stator or open slotted outwards design is presented in [2]. This design permits the loading of the form-wound coils from the outside. The stator modules consist of soft magnetic composite (SMC) material is presented in [3]. By making the use of a concentrated winding configuration, the stator structure is simplified with the benefit of less end-winding losses [3]. The segmented stator design is presented in [4]. It is presented that the higher fill factor could be achieved due to modularity of the structure. In all the work presented in the literature uses concentrated winding configuration to improve the performance of the motor. In this paper, it is shown that the motor performance would be improved with full pitch winding configuration using two-piece stator core design.

The paper is presented with the design requirements and adoption of two-piece stator design followed by the simulation and experimental validation.

II. SLOTTED PMSM DESIGN REQUIREMENTS

Fig.1 shows the cross-sectional view of the existing single-piece stator for 4-pole PMSM. The stator consists of laminated stator stack and the rotor consists of tile magnets placed on the magnet holder. The magnetic field pattern at no load is presented in Fig.2. In the existing design, to reduce the detent/cogging torque, the stator laminations are skewed by one slot pitch which is 30° mechanical degrees for 12-slot, 4-pole PM motor configuration. This skewing technique reduces the detent to very low value but at the same time the motor back-emf constant (V/rpm) also reduces by about 6 to 8%. In addition, the skewing process is complicated and this increases the manufacturing cost.
Table I details the specifications of existing 12-slot, 4-pole PMSM motor. The overall diameter of the motor is 30mm and the number of slots are 12 and 4-pole design is chosen based on the customers working points in the pulse tools application. The selected magnet grade is 34.5MGOe with Br of 1.2T considering the saturation limit of the magnetic circuit. The number of the coils per phase is four and are connected in series. The phases are connected in star. The existing bare copper fill factor is 28.5%. The overall length of the motor is ~144mm. In case of industrial hand tool application, the dielectric strength of the insulation is tested at 1300V (AC), 5mA (max). Thus, considering the slot insulation requirement, the fill factor is calculated.

### TABLE I. SPECIFICATIONS OF THE MOTOR

<table>
<thead>
<tr>
<th>Specification</th>
<th>Values</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Outer diameter</td>
<td>30</td>
<td>mm</td>
</tr>
<tr>
<td>Overall motor length</td>
<td>144</td>
<td>mm</td>
</tr>
<tr>
<td>Continuous stall torque</td>
<td>352.4</td>
<td>mN-m</td>
</tr>
<tr>
<td>Continuous stall current</td>
<td>4</td>
<td>A</td>
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**III. TWO-PIECE STATOR DESIGN**

The proposed the two-piece design shown in Fig.3, has an advantages of reduced detent torque without compromising on the generated back-emf of the motor. This is because the slots are fully closed in the vicinity of the airgap and therefore the change in reluctance seen by the rotor is lesser as compared to existing design without skewing the stator slots.

To improve the SFF of the existing design, the stator lamination part is splits into two. This allows the loading of the pre-wound stator winding from outside stator bore instead of inserting the coil from the inner stator bore for the existing design.

The pre-wound coils allow the higher fill factor of 41%. Higher SFF allows the more number turns per coil of the same thickness or with the thicker conductor with same number of turns. This results in improved motor regulation (i.e.,) R/k2.

Fig. 4 shows the magnetic field pattern of the two-piece stator design. It can be observed that the localized magnetic saturation is taken place in the short-circuited lamination core (segmented core) path.

The magnetic short circuit paths dimension is optimized using Finite element method (FEM) based analysis. The width of the short-circuited paths is optimized based on the required sinusoidal back-emf shape and the optimized value is about 0.3mm.
IV. MANUFACTURING CHALLENGES OF TWO-PIECE STATOR DESIGN

During the prototype validation stage there are different assembly process is considered. Firstly, the coil is wound on the winding machine for the required number of turns. The selected magnet wire is 27AWG having two parallel paths. The wound coils are tied up to make sure the easy placement in the stator slots. The end-winding length is calculated such that the coil is placed in the slot without rubbing the winding insulation against the lamination edges.

The laminations are stacked to the required height using laser welding process. The stator slots are insulated especially at the edges of the lamination stack. Once the coils are placed in the slots, the outer lamination tube is inserted on to it. The tolerance of these parts is considered such that there is transition fit between the segmented core and outer tube. Both are parts having same length and their location is based on the step provided in the stator outer tube. Also, the gluing is applied between the sides of the segmented core and the stator tube laminations. The gluing strength is checked using the push off test.

V. MOTOR PERFORMANCE VALIDATION

During the development of the stator parts, the dimensional and geometrical tolerances related the stator outer tube ID and the segmented core OD were kept tight to make sure that the transition fitment is achieved. Further, FEA based simulation study is carried out to understand the effect of the B in the air-gap. It is seen that the reduction in B is negligible. Prototype motor is shown in Fig. 5.

Initial testing of the prototype motor such as hi-pot test, winding resistance and inductance measurement were carried out. Further phase back-emf is measured. It can be seen from the Fig.7, when any phase is measured with respect to ground, the waveform is sinusoidally coupled with third-order harmonics [5]. The measured peak-peak back-emf at ~500 rpm is 7.2V and this is compared with the simulated back-emf at 500 rpm and the value is about 7.1V as shown in Fig. 6. Simulated values are closely matching with the experimental results. Further, the over-load capability of the motor is also tested and compared with the standard motor.

Fig. 5. Simulated phase Back-emf waveform

Fig. 6. Simulated phase Back-emf waveform

Fig. 7. Measured phase back-emf (Scale X-axis: 10ms/div, Y-axis 1V/div)

Fig. 8. Simulated cogging torque comparing the standard single-piece stator design and the proposed two-piece stator design

Fig.8. compares the simulated cogging torque with rotor position. It can be seen that the cogging torque is reduced with the two-piece design as explained earlier. This allows simplified stator design without skewing the stator laminations. Further, the load test result is shown below in Fig. 9. Table II shows the comparison between the standard and proposed two-piece stator design.
VI. CONCLUSION

The performance of the PMSM is improved by adopting the two-piece stator design. Also, the manufacturing process is simplified and results in increase in number of ampere turns for the same frame size. This results in improved motor regulation of about 22% as compared to the conventional single-piece stator design. Further, the stator winding is protected without the use of slot wedges and slot insulation process is simplified because of the outwards open slot arrangement.

Also, issues related to the motor build with the two-piece design is presented. In the present work, the two-pieces were joined by using the gluing process and this process would hold the two -pieces against the slippage torque. Future work includes the locking arrangement between the stator pieces so that the relative motion between the two-stator pieces to be completely nullified.

REFERENCES