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Computer-Aided Design of a Permanent Magnet Synchronous Motor (PMSM)

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Abstract:- This paper briefly describes a finite-element based method used to design a permanent magnet synchronous motor PMSM for variable-speed drive applications. The stator of the PMSM is identical to that of any three phase AC machine, so the stator frame of an induction machine was used for the design. Thus the stator dimensions and current rating are fixed thereby reducing the design to the optimisation of the magnetic loading of the motor. A key requirement is to obtain a machine capable of producing sinusoidal back emf and thus suitable for smooth torque generation when supplied with sinusoidal currents.

Keywords:- *Component; Formatting; Style; Styling; Insert.*

I. INTRODUCTION

The design of a permanent-magnet synchronous motor PMSM is best carried out with the help of magnetic field analysis as suggested by a number of authors: [8]–[11]. The traditional method of design which relies purely on empirical formulae and certain rules of thumb, is unable to cope with the need for accurate computation of field values in a machine with complex cross-sectional area and having heterogeneous nature. Furthermore the presence of materials with complex geometries and nonlinear properties means that the simple linearised models, that mostly neglect saturation, employed in the traditional method are not acceptable in this case. Thus in order to evaluate accurately the effects of design changes aimed at achieving desirable performance-specifications, it is necessary to perform detailed magnetic analysis. As a result of such analysis, performance characteristics, winding inductance, flux plots, localised flux densities etc., are easily obtained. Another reason for the shift to design by analysis is the need to optimise the overall drive rather than the electric motor alone, especially in cases where operation is in variable-speed mode that usually involves costly power conditioning.

II. MAGNET PLACEMENTS

A. Internal-Magnet Rotors

The degree of complexity in the design and construction of the permanent-magnet synchronous motor varies with the shape, size and location of the permanent magnets. Designs differ by the location of the magnets, internal, surface or inset, and by the orientation of the magnet axes; radial or circumferential. Figure 1 shows various types PM rotor configurations and how the permanent magnets are placed with respect to the rotor. The choice of rotor topology is very important as it directly affects such factors as magnetic flux distribution in the machine, the homogeneity of the rotor, the windage loss, etc. From the construction point of view, the most complicated case is when the magnets are embedded in the rotor to produce as narrow airgap as possible and thus ensure flux weakening capability. Another reason for burying the magnets in the rotor is that it enhances robustness, and offers protection for the magnets from exposure to the airgap. This makes the internal-magnet construction (figure 1a,b), suitable for operation at high speeds. Furthermore, the circumferentially-oriented magnet-axes design of Figure 1b is used for flux concentration especially in motors that utilise low-energy magnets. A draw-back for this type of construction however is that the shaft has to be made from nonmagnetic materials so as to avoid magnetic short-circuiting of the magnets.

The internal-magnet machines possess magnetic saliency and, due to their relatively short airgap lengths in the q-axes, display noticeable armature reaction effects, which have to be taken into account when choosing the optimum operating point. [2], [7], [8] The situation is almost identical in motors that have inset magnets with narrow gaps as they too are characterised by magnetic saliency and appreciable armature reaction.

The application of the direct-design approach in the design of a polyphase PM excited motor with inset magnets has been carried out using a computer program -DESIGN [7]. A general magnetic model of the machine was established, and it was shown that the electric and magnetic loadings of the machine depend on the angle ψ between the armature and magnet excitations, and that there exists an optimal value of ψ that yields maximum torque for maximum allowable flux density in the stator teeth and another one that yields the minimum magnet volume. Both of these values have been shown to be in the same neighborhood of $|\psi| \tilde{=} 70$ electrical degrees. [7], [8]

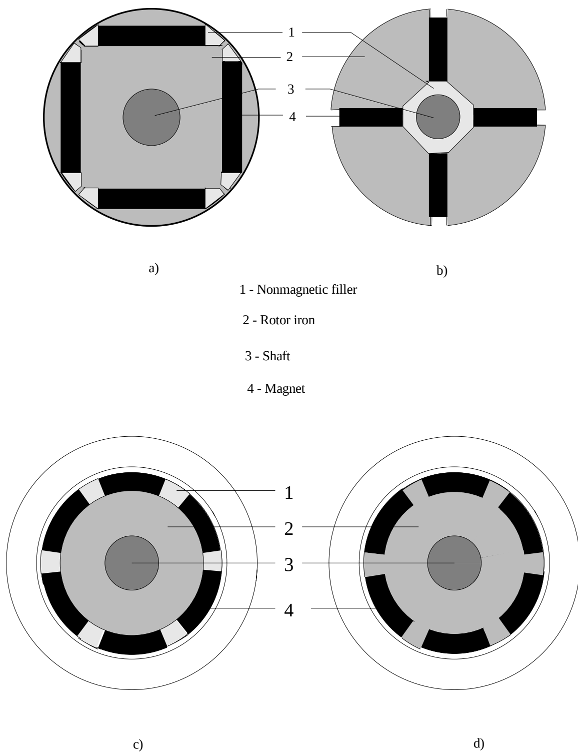

Fig 1:- Examples of PM Rotor Designs: a)Internal magnets with radial flux b)Internal magnets with circumferential flux c) Surface magnets d)Inset magnets

B. Surface-Magnet Rotor

Motors with surface-mounted radially-oriented permanent magnets have only become of practical importance with the developments of newer PM materials having high residual-flux densities. The surface-magnet rotor has a better utilisation of magnetic flux than is achievable with the flux-concentration designs using materials of lower residual-flux densities. The surface-magnet motor can be designed to be magnetically nonsalient by making sure that the inter-magnet gaps, if filled, are iron free. Thus the low reluctance in the d-axis due to the presence of the magnets is equally present in the q-axis so that magnetic saliency is virtually absent. The effects of armature reaction are weakened by the large effective airgap in both the d- and q- axes. The design, analysis and control of such a machine become relatively easier and the optimum value of the angle ψ is simply zero, when the maximum torque is developed. On the other hand, operation beyond base speed is not possible since flux-weakening cannot be implemented. Furthermore the absence of reluctance torque means that these machines have less torque capabilities than the those with internal magnet construction. Another source of worry for this type of construction is how to retain the magnets and prevent them from moving relative to the rotor in any direction. Since these problems are directly affected by rotor speed, the surface magnet motor is mainly a low speed machine, except in cases when the magnets are retained by special cylinders.

C. Inset-Magnet Rotor

When the rotor magnets are placed in slots on the rotor surface, the inset-magnet machine results. Depending on the depth of the slot into which the magnets are placed, the machine can be either magnetically salient or display very little saliency. Machines that have shallow slots effectively perform as surface-magnet types. On the other hand if the slots are deep, and the magnets are almost entirely inset the result is a magnetically salient motor, with the characteristics similar to those of the buried- or internal-magnet machine.

III. CHOICE OF PM MATERIALS

The choice of magnet materials for motor applications is based not only on their magnetic characteristics but also on their mechanical and thermal properties, coupled with the cost effectiveness.

The demagnetization curve of some permanent-magnet ma- terials are shown in Fig.2. Alnico has the a very high residual flux density but its relatively low coercivity means it is un- suitable for motor application as it can easily be demagnetized by the stator mmf. Ferrite materials are, on the other hand have high values of coercive force, but relatively low values of residual flux density. Their high resistance to demagnetization coupled with the low cost has made them relatively attractive for motor applications. To enhance torque production, how- ever, special flux-focussing arrangements leading to compli-cated rotor topologies are usually needed. Samarium Cobalt materials have higher residual flux density and coercivity than ferrites but are considerably more expensive.

A relatively new addition to the list of magnet materials for motor applications is Neodymium-Boron-Iron, NdBFe, which, at room temperature, has the highest energy product of all commercially available magnets [4], [10]. However both Ferrite and Neodymium magnets are sensitive to temperature rise and care must be taken where working temperatures exceed 100°C. Thus for very high temperature applications, Alnico or Rare-earth Cobalt magnets are more suitable.

Most magnet materials are brittle especially the ferrite types, and care must be taken when handling them.

IV. FINITE-ELEMENT ANALYSIS

A. FEM in Machine Design

The finite-element method (FEM) is increasingly becoming a very powerful tool in the computation and analysis of electro magnetic fields. The method has found application in the design, and performance analysis of electrical machines due largely to its reliability and relative simplicity which have both been enhanced by the availability of powerful computing facil- ities in the modern design environment. Thus FEM has opened up a whole new approach to the design of electric machinery by making it possible to model, simulate and analyse various designs without building costly prototypes. Thus necessary improvements to a design are carried out thoroughly before a prototype is built, which saves time on repetitive building and testing of physical models. Furthermore computer simulation often provides information which would have been impossible to obtain by conventional testing methods.

It must be pointed out here however, that if strictly accurate results are to be sought, full three-dimensional finite -element analysis would be required. Hysteresis and material anisotropy must also be taken into account for such a standard of accuracy to be attained. Such an approach would be rather difficult and is as yet not cost effective. Thus the usual approach is to employ two-dimensional analysis and reduce the complexity of the analysis either by successive problem refinement, or by using subproblem analysis. [9]

The method of successive refinement involves the initial creation of several simple models and progressively improving the accuracy by reducing their number and increasing the model complexity until finally the most accurate model is arrived at. In subproblem analysis detailed portions of the problem are replaced by simpler ones which may be quite wrong locally, but yield the right external (net) result.

The region under consideration is partitioned into discrete elements and the field problem is solved by a variational approach. The problem is formulated in terms of an expres- sion, the energy functional, which in engineering applica- tions is identified with the stored energy in the system. For electrical machine analysis, under the assumption of infinite axial length, a two-dimensional formulation using first-order triangular elements is often applied. First-order triangular ele- ments are characterised by geometric flexibility which permits easy modelling of complicated electric machine cross-sections. Furthermore their relative simplicity in computation when compared with higher order elements adds considerably to their popularity in machine analysis.

Finite-element analysis can be used to carry out the following:

1) Simulation and analysis of various initial models of the PMSM all having the same main dimensions but differing in rotor configuration, magnet size and/or shape and physical length of the airgap.
2) Simulation and thorough analysis of a final model that was being considered for construction, so as to predict and optimise its performance.
3) Computing the parameters of the designed machine for use in its dynamic and steady-state modelling and for comparison with measured and theoretically determined values.

V. CONCLUSION

A brief description has been given of the design method used in the construction of a 6-pole surface-mounted PM synchronous motor using computer-aided-design techniques. The motor has been designed to operate from a variable-frequency, variable-amplitude inverter with a sinusoidal current output. The method of binding the rotor magnets to the rotor does not involve the use of banding or glue, so that the effective airgap is very small. This has produced a machine that has a very high utilization of the neodymium magnets used.

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