ABSTRACT

Electric machine design involves determining the physical dimensions of the machine for certain desired terminal characteristics. It is an added advantage if the design tools are able to predict the machine performance during design phase. The terminal behavior of the machines is characterized by electrical equivalent circuits (EEC) and are widely used to understand the requirements on the source side and are also used for machine control. However, these EEC do not reveal the internal behaviour in the machines. Knowing the internal behaviour is very much needed for carrying out the design of machines. To this end, magnetic equivalent circuit (MEC) plays a vital role as the internal behavior is depicted in it. Further there exists one-to-one correspondence between the MEC and the machine.

There exist challenges in representing the actual machine into MEC. In rotating machines, the flux profile changes with rotor movement. Hence, identifying the flux path between the stator and rotor during its movement, and representing it by appropriate position dependent reluctance in the MEC is the main challenge. Another challenge is accounting for saturation behaviour of the iron core. As the value of permeability in a core region depends on the value of flux density, permeability cannot be assumed the same for different parts of the core. It is to be determined with the aid of magnetization characteristics. Hence, depicting the rotor movement and core saturation at circuit level requires an appropriate modeling.

In this thesis work, a simplified MEC topology is proposed for modeling the surface-mounted permanent magnet synchronous motor (PMSM) and is analyzed with the aid of mesh analysis. Number of air-gap elements associated with a stator tooth could either be one or two depending on the position of nearby rotor poles. With this, the number of meshes in the whole MEC does not change with rotor

movement. It is worth to mention that the proposed MEC topology makes use of less number of air-gap reluctance elements linking the stator and rotor.

Saturation effects are accounted in the MEC by means of flux-density dependent reluctance elements, and the developed model is solved through mesh analysis and Newton-Raphson method. The instantaneous variation of flux density, flux linkage and torque obtained from MEC agrees reasonably with the results obtained from finite element analysis (FEA) performed in Ansys-Maxwell platform. Subsequently it is demonstrated how MEC can be utilized for assessing machine performance with regard to its flux weakening capability, contribution of reaction and reluctance torque, cogging torque evaluation. As the evaluation of various quantities by MEC analysis agrees reasonably with FE analysis and experimental measurements, the proposed MEC topology and its analysis could be useful during design phase.

In case of surface mounted PMSM with distributed winding, the value of direct-axis inductance is very low and flux weakening is ineffective. By opting fractional slot concentrated winding (FSCW), it is possible to increase its value. However, FSCW introduces more space harmonics in the stator MMF. Among those, subharmonics severely influence performance of the machine.

In this work, an analytical method is proposed to minimize subharmonic in the MMF profile of surface-mounted PMSM with FSCW. Initially significance of winding layer and slot opening on the MMF harmonics is investigated. From the results, four-layer winding is found to have its subharmonic's magnitude as low. A method is proposed to minimize subharmonics by determining the optimum number of turns in the phase coils. For this purpose, voltage induced in a phase due to subharmonic is considered. For assessing the performance of optimum winding distribution, MMF harmonic spectrum and winding factors are used.

To demonstrate the proposed method of minimizing subharmonic, a PMSM that has only one subharmonic is considered with 12 slots and 10 poles (Machine-1). Later the proposed method is extended to a machine that has more than one subharmonic, a PMSM with 18 slots and 14 poles (Machine-2) is considered. Optimum winding distribution is achieved such that subharmonics are minimized (1 in Machine-1; 1 and 5 in Machine-2). It is worth to mention that the synchronous torque producing frequency component remains unaffected (5 in Machine-1; 7 in Machine-2). The results are validated through FE simulation.

In PMSM with FSCW, space harmonics in the MMF gets increased and these space harmonics eventually leads to eddy current loss in magnets. For extending the life of the magnets, it is necessary that the eddy current loss in it is to be minimized. This requires a suitable winding distribution and optimum current control so that the impact of space and time harmonics is reduced. In this work, investigations are carried out for understanding the severity of eddy current loss in magnets corresponding to different winding layers.

An analytical model available in the literature is used for predicting the eddy current loss in the magnets. The results obtained from the analytical model are validated through FE simulation. It is found that the winding distribution with higher magnitude of subharmonic results in higher loss in magnets. Further the loss is found to be the least with four-layer winding (compared to single and two-layer winding distribution). Later, segmented rotor configuration is chosen for minimizing the eddy current loss in the rotor. It can be concluded that four-layer winding distribution in stator with segmented rotor would correspond to energy efficient design.

The proposals and investigations are related to modeling the internal behaviour of the rotating electrical machine, identifying optimum winding distribution for minimizing subharmonics, and suitable winding distribution for minimizing the loss in magnets and rotor. The findings are validated through appropriate FE simulation and few experimental measurements. It is believed that these findings could be useful in the design phase of electrical machines.