

Challenges and Solutions for IPMSM to be Used as a Next Generation Electrical Machine

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Abstract

The use of permanent magnet machines has been increased because of higher efficiencies and larger power densities. This paper presents the challenges to develop IPMSM used as a next generation electrical machine and proposed solutions for overcoming those challenges. Rotor and stator designs affecting the efficiency of a machine are discussed. Increased torque density reduced vibration and noise of a machine are vital characteristics for machine which are described for proposed IPMSM machines. High torque capability up to base speed for accelerating and wider operating speed range can be achieved by controlling the d-axis current of the IPMSM. Fault tolerant, high speed and constant power operation are selecting factors for machine reliability and performance, respectively. The machine losses can be reduced by modifying the design of PMSM and selecting the proper core materials.

Keywords

IPMSM, torque density, vibration and noise, fault tolerant, machine losses.

1. INTRODUCTION

Performance of a machine and which machine can be used as a next generation machine basically depends on the application of that machine. But in general the next generation machine should have some significant properties, such as maintenance-free operation, high controllability, robustness against the environment, high efficiency, high power factor operation, low loss, high power density, fault tolerant capacity, low manufacturing cost, low operating cost, noise and vibration less operation capacity etc. The development of high performance magnetic material and the cost reduction in addition to environmental problems have expanded the field of application of permanent magnet synchronous motor (PMSM). The interior permanent magnet synchronous motor (IPMSM) has a permanent magnet embedded in the rotor. High-speed operation is possible by IPMSM as the permanent magnet will not break or scatter. IPMSM is used in various fields because of the eddy current loss on the surface of rotor can be significantly decreased. The flux-weakening control acts effectively in IPMSM, hence high-speed operation and wide constant-power operation can be achieved. Moreover, IPMSM has many degrees of freedom in the design of both mechanical structure and torque-speed characteristics. However, IPMSM has some drawbacks which can be eliminated by implementing different techniques. Then, IPMSM can be the machine for next generation. The feasibility of different solutions for IPMSM is discussed and final design hints are discussed.

2. IMPROVING EFFICIENCY

2.1 Stator design

In order to improve more efficiency the stator configurations of IPMSM are examined [1]. Either distributed winding or concentrated winding is used in IPMSM. It is evident that the coil end of the concentrated winding becomes very short compared to that of distributed winding. Result, the armature resistance of concentrated winding becomes smaller than that of the distributed winding, and thus copper loss decreases and high-efficiency drive can be achieved. Using concentrated winding increases the efficiency, especially in low speed regions, in which copper loss is more predominant than core loss [1]. In this case, the total loss decreases and the efficiency is improved by using concentrated winding; but the efficiency of concentrated winding IPMSM might become worse in high-speed regions, in which core loss is more predominant than copper loss [1]. However, excluding the special situation where downsizing and thin motors are especially required, the use of the distributed winding is common in high power applications including electric vehicle (EV), hybrid electric vehicle (HEV) and traction drive.

Although concentrated winding is effective to reduce the motor size and copper loss it has some disadvantages caused by the harmonics of magnetic flux distribution. Such harmonics cause increase of core loss, and vibration and noise may increase, too. Moreover, the reluctance torque of IPMSM with concentrated winding will decrease compared to the distributed winding. To suppress the increase in core loss and vibration, the rotor design of the concentrated winding PMSM has been devised. The technique of reducing these challenges such as core losses and vibration are discussed later.

2.2 Rotor design

Increasing the ratio of torque per current ampere improves efficiency by decreasing the copper loss. The torque equation

$$T = \frac{P}{2\pi} (\psi_a i_d - \psi_d i_q) \quad (1),$$

where, i_d , i_q are the d and q-axis armature currents, ψ_a , the magnet flux-linkage, L_d , L_q , the d and q-axis inductances, and P is the number of poles. It is evident that such demand can be achieved by either increase of magnetic flux-linkage ψ_a or increase of difference between d-axis and q-axis inductances ($L_q - L_d$). The increase of the difference of inductances ($L_q - L_d$) can be achieved by optimal rotor design [2]. The q-axis inductance becomes large and the reluctance torque increases because the magnets are placed inside the rotor deeply for the case of IPMSM. The maximum efficiency of IPMSM reaches 95%. The efficiency at low speed is more than 80% which is about 20% and 10% higher than that of IM and SPMSM, respectively [3].

3. INCREASE TORQUE DENSITY

To achieve maximum torque density, it is desirable to have as many copper conductors as possible in the constrained slot area. The number of turns that can be achieved depends on the packing factor. A high packing factor not only increases machine torque density but also reduces I^2R heating losses by lowering coil resistance. In distributed windings, due to the overlapping coils, it is not possible to split stator teeth, hence a maximum packing factor of only 40% can be achieved. Whereas for concentrated windings, a packing factor of up to 80% can be achieved [4]. This is due to the property of being able to separate stator teeth by the use of hinges between teeth or having separable tooth pieces where compression can be used to tightly pack the windings. On the other hand the use of rare-earth permanent magnet on the rotor which has magnetic energy density is about 10 times higher than that of ferrite permanent magnet, is effective for increasing magnet flux-linkage [1]. The use of rare-earth permanent magnet in a PMSM has become common by improving performance and reducing the price of the rare-earth permanent magnet. Neodymium magnet (NdFeB) can be used to meet the mentioned criteria.

4. VIBRATION AND NOISE REDUCTION

The ripple torque and cogging torque of IPMSM become large compared with surface mount permanent magnet synchronous machine (SPMSM) because of the discontinuity in reluctance change between the rotor and stator. Moreover, the IPMSM with concentrated winding is noisier because of the stator frame deformation by the radial forces.

A common strategy to minimize the torque ripple, such as cogging torque and torque ripple due to the air-gap MMF distribution harmonics, is to avoid the periodical combinations between pole (p) and slot (Q_s) [5], [6]. The pole/slot combinations giving winding layouts without any symmetry such as combinations with $Q_s = 9+6k$, $k = 0, 1, 2, \dots$ and $p = Q_s \pm 1$ are not recommended. For example, the magnetic pressure for a design with 60 poles, 72 slots and a symmetry in the winding in one sixth of the machine has no resulting force as the forces are compensating each other [7]. The harmonic winding factor decreases for all but the main harmonic which remains close to unity [8], yielding a considerable reduction of the torque ripple. In fact, torque is given by the interaction between each harmonic of the stator electric loading distribution and the same harmonic of PM flux density or of the same harmonic of rotor geometry [9]. However, a fractional-slot winding may produce MMF sub-harmonics that are particularly bothersome since they often have high amplitude. They cause high rotor losses if the rotor is not laminated. They cause an unbalanced saturation among the machine poles which results, high torque ripple especially in machines with small air gap.

In the general design of IPMSM, the magnets and the flux barriers are symmetrically arranged. In this conventional design, the relative positions between the outer edges of the flux barriers and the teeth are the same in all poles; as a

result they meet and part at the same time. This situation causes a change of torque by rotor position and the torque vibration is generated. In order to reduce the torque vibration, the flux barriers are asymmetrically designed so that the relative positions between the outer edges of the flux barriers and the teeth do not correspond [10]. The asymmetrical flux barrier design greatly improves the torque ripple. In this design [1] the torque ripple can be greatly decreased without sacrificing the average torque and without decreasing efficiency.

The vibration and noise increase by using the concentrated winding. In the concentrated winding IPMSM, the radial force that intensively acts on stator causes the acoustic noise and the vibration. In order to reduce the radial force and the torque ripple, the rotor design with some holes inside the rotor is proposed [1]. The holes inside the rotor decrease the equivalent opposed area of the stator and the rotor, and the magnetic flux density is reduced. The efficiency of the concentrated winding IPMSM with holes decreases at low speed region, but it is improved at high speed region. The vibration velocity of the concentrated winding IPMSM is larger compared to the distributed winding IPMSM, but it can be reduced by making holes in the rotor [1].

5. TRACTION DRIVE APPLICATION

The motor for traction drive application has many requirements such as high torque capability up to base speed for accelerating and wider operating speed range for achieving sufficient output at the maximum speed. The output capability of PMSM depends on the machine parameters and the control scheme [9]. The profile of the speed versus torque and power characteristics as well as the constant-power speed range depend on the minimum d-axis flux-linkage ψ_{dmin} , which is defined by $\psi_a - L_d I_{am}$ where I_{am} is a ceiling current ampere. The condition of $\psi_{dmin} = 0$ is optimum for an ideal constant-power operation implying that the theoretical constant-power speed range becomes infinity [1] and the output power is enlarged as much as possible. For the application demanding a wide constant-power speed range such as a traction drive, the specific parameter ψ_{dmin} of PMSM has to be designed close to zero. In such a design, the magnet flux linkage ψ_a may become comparatively small. The high-speed constant-power operation is usually achieved by the flux-weakening control, where the terminal voltage is maintained within the ceiling voltage by using the negative d-axis armature reaction $L_d i_d$ [11]. In this control, the danger of falling into the uncontrolled generator mode when the inverter unexpectedly stops has to be considered. The magnet flux linkage has to be designed so that the open-circuit induced voltage at the maximum speed is less than the maximum voltage rating of switching devices. Therefore, the magnet torque is limited by such constraints of the maximum open-circuit voltage, and thus an effective use of the reluctance torque by the optimal rotor design is important from a standpoint of supplementing the limited magnet torque with the reluctance torque.

6. FAULT TOLERANT

The term fault tolerant may have two different meanings. The first duty of a fault-tolerant machine is to support a temporary fault, such as a phase-to-phase or a three-phase short circuit, without being damaged. To achieve that, the machine is conveniently designed with an inductance as high as to limit the short-circuit current to a given threshold. This design is not costless, since a high inductance implies a low power factor during the healthy operations [9]. The second duty is to work even under faulty operating conditions, e.g., with an open-connected phase or a short-circuited phase. In this case, the designs of the machine and the inverter cannot be kept distinct, and different solutions can be adopted [12]. A multiphase drive can be designed [13]. For these solutions, the machine cost does not increase; while the converter cost could be even double that of the conventional three-phase inverter. Then, the design terms include 1) An electrical separation among the phases. 2) A physical separation of phases to prevent a phase-to-phase fault. 3) A phase inductance so high as to limit the short-circuit currents 4) Low mutual inductances among the phases to prevent healthy phases sustain the fault [9].

To obtain electrical separation among the phases, each phase is fed by a full-bridge converter. The advantage of the full-bridge converter is that the drive can operate even with a short-circuited phase since it is no longer fed by the corresponding bridge of the converter. A physical separation of phases can be obtained with a fractional-slot machine by winding each phase coil around a single tooth. Moreover, one coil of each phase can be removed while the turns of the remaining coils are doubled. Fractional-slot machines inherently exhibit a higher leakage inductance. As the phase inductances are so high its limit the short-circuit currents. So a short-circuit fault of a fractional slot machine is not as dangerous as for other machine types. Some winding solutions are characterized by a very low mutual inductance among phases. Even low mutual inductances among the phases are obtained by means of a fractional-slot machine and a suitable choice of the number of poles and slots. Moreover, Some solutions characterized by no mutual coupling among the phases exist.

Though fractional-slot winding with non-overlapped coils is an interesting solution for fault-tolerant applications due to its high leakage inductance and low mutual coupling among the phases, the fractional-slot configurations exhibit a high harmonic content in the air-gap MMF distribution [9].

7. REDUCTION OF LOSSES

Analyzing the MMF and its harmonics is of interest since it can cause iron losses. The MMF is calculated analytically with the method fully described in [14]. The harmonics are calculated by taking into account the periodicity of the MMF waveform that is the number of symmetries in the winding. Moreover, the star of slots can be used to represent the harmonics of the armature MMF distribution [9].

The windings without symmetries also present many more harmonics in the MMF than those with symmetries. Due to these harmonics, alternating magnetic fields appear in the rotor. The flux density in the rotor is indeed not constant. This gives rise to eddy currents in the permanent magnets and iron losses in the rotor iron. These losses should therefore be estimated during the design process when using concentrated windings. If they are too high, a laminated rotor and permanent magnets in small pieces can help. Therefore an appropriate choice of material which has a narrower hysteresis loop and the ability to be made into very thin laminations is desired. Non-oriented (N.O) silicon sheet steel is the most common choice in AC drives. The cores are formed by stacking the laminations to reduce eddy current losses. Silicon steel is relatively cheap, has total core loss of between 1 to 2W /Kg at 50Hz, has saturation magnetization of up to 1.9T and can come in sheets as thin as 0.2mm [15].

Moreover, When stator slot number (n_s) = rotor slot number (n_r) is the best solution for high speed harmonic losses, since the total loss (stator + rotor) rise progressively as the distance between n_r and n_s increases. In particular, higher n_s number is in general beneficial for the torque ripple but for $n_r < n_s$ the stator losses prevail while the rotor losses prevail for $n_r > n_s$ [16]. However, two-layer rotors are much more effective than one-layer rotors for reducing the harmonic eddy-current losses in the stator teeth under flux-weakening operating conditions.

8. HIGH SPEED AND CONSTANT POWER OPERATION

When the PMSM is operated at high speed and constant power, the field flux (flux of the permanent magnet) cannot be directly controlled. Moreover, seven harmonic of mmf is dominating during high speed and leads to excess core losses. Now a day, this is a question how to mitigate this harmonics especially for high speed operation. However, flux reduction control [17] has been used to restrain the voltage rise and to achieve constant-power operation in which the field is reduced equivalently by utilizing the demagnetizing magnetomotive force. However, this method leads to the problem of decreased efficiency due to increased copper loss. In particular, degradation of efficiency under light load in the high-speed reduced-field operation range has been a problem. Another problem is that excessive electromotive force is generated at the motor terminals when the inverter is stopped in the reduced-field control operation range.

Constant-power operation can be realized at speeds up to 5 times the base speed. The induced voltage due to the permanent magnet is low; less than 30% of the total voltage for the base speed [18]. As a result, there is less possibility of producing excessive voltage, even, if the inverter stops in the high-speed constant-power operation. The d-axis current can be used to reduce the flux. Consequently, the efficiency is high in the constant-power operation range, and efficiency degradation can be avoided at light load.

9. CONCLUSION

Though IPMSM has distinguishing features to be a next generation machine, some modifications are still required in its design. Some design has been proposed to mitigate the barrier of higher performance but when all the techniques are considered altogether need trade off among the performances of the machine. Proper using of fractional slot concentrating stator winding, high packing factor stator winding, neodymium magnet (NdFeB) as a rotor PM, asymmetrical two layer laminated hole rotor, wider range of power speed control can be the best solution to overcome the challenges for IPMSM as a next generation machine.

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