Design of Permanent Magnet Machines for Hybrid Vehicles

Gurakuq Dajaku 1), Dieter Gerling 2)

1) FEAAM GmbH
   Neubiberg, Germany

2) Institute for Electrical Drives, University of Federal Defense Munich
   Neubiberg, Germany

Summary
This paper deals with the analysis of different PM machines for hybrid electric vehicles application. The main machine parameters, electromagnetic torque and the skewing effect is investigated using ANSYS program. The model parameters of the PM machines are derived with Fixed Permeability Method (FPM). With this method the components of the PM machine can be calculated with high accuracy. Different FE calculation methods (Maxwell’s stress tensor method and the new mathematical model for the PM machine) are used to calculate the electromagnetic torque of the machine. Also the skewing effect on the torque performance of the PM machine is investigated.

Keywords
Hybrid electric vehicles, PM machine, ANSYS, Fixed Permeability Method (FPM), Torque calculation, Machine parameters, Skewing effect
1. Introduction

Hybrid electric vehicles (HEVs) are offered by numerous manufacturers and are becoming increasingly more available. Hybrid-electric vehicles combine the benefits of gasoline engines and electric motors and can be configured to obtain different objectives, such as improved fuel economy, increased power, or additional auxiliary power for electronic devices and power tools. Some of the advanced technologies typically used by hybrids includes:

**Regenerative Braking.** The electric motor applies resistance to the drivetrain causing the wheels to slow down. In return, the energy from the wheels turns the motor, which functions as a generator, converting energy normally wasted during coasting and braking into electricity, which is stored in a battery until needed by the electric motor.

**Electric Motor Drive/Assist.** The electric motor provides additional power to assist the engine in accelerating, passing, or hill climbing. This allows a smaller, more efficient engine to be used. In some vehicles, the electric motor alone provides power for low-speed driving conditions where internal combustion engines are least efficient.

**Automatic Start/Shutoff.** Automatically shuts off the engine when the vehicle comes to a stop and restarts it when the accelerator pedal is pressed. This prevents wasting energy from idling.

The following figure 1-a shows the principle sketch of a hybrid drive system. HEVs can have a parallel design, a series design or a combination of the two. In a parallel design, the energy conversion unit and electric propulsion system are connected directly to the vehicle's wheels. The primary engine is used for highway driving; the electric motor provides added power during hill climbs, acceleration, and other periods of high demand. In a series design, the primary engine is connected to a generator that produces electricity. The electricity charges the batteries, which drive an electric motor that powers the wheels. HEVs can also be built to use the series configuration at low speeds and the parallel configuration for highway driving and acceleration.

![Fig. 1: a) Schematic of a HEV drive train configuration [6], b) Motor performance curve.](image)

The electric drive system of the HEV consists of the electric machine, inverter and the energy storage device (battery or supercapacitors). The permanent magnet (PM) electrical machine is also gaining popularity. The high interest in this machine type is due to its superiority concerning high efficiency, high torque density, and constant power over a wide speed range. These advantages make the PM machine especially suitable in applications like electric vehicle, robotics and high efficiency industrial drive. The characteristics of the electrical machines affect the vehicle performance, especially fuel consumption. The motor requirements for HEV application are: high torque per volume, high efficiency, constant power over a wide speed range and low torque ripple. Figure 1-b shows the required torque characteristics for the traction drive motor.
2. Permanent magnet machines

Permanent magnet synchronous machines (PMSM) gain more and more importance for special drive applications. Up to recent years, PMSM were known for small drives, e.g. for servo applications. In the last years, PMSM are increasingly applied in several areas such as traction, automobiles, etc. The stator of a PM synchronous machine has a conventional three-phase winding, and the rotor can have magnets mounted on the surface of the rotor, or there can be magnets buried inside the rotor (interior permanent magnet machine).

2.1 Location of the permanent magnet

The rotor construction and location of the permanent magnets have a considerable effect on the motor properties. Figure 2 shows six basic configurations of the radial flux PM machines. Mainly, the magnets could be placed on the rotor surfaces or buried in the rotor. The interior construction simplifies the assembly and relieves the problem of retaining the magnets against centrifugal force. It also permits the use of rectangular instead of arc shaped magnets, and usually there is an appreciable reluctance torque which leads to a wide speed range at constant power. Depending on the rotor construction the motors are often called salient-pole or non-salient-pole machines.

Fig. 2: Different rotor construction of radial flux PM machines; a) Surface mounted magnets, b) Inset rotor magnets, c) Buried tangential magnets, d) Buried radial magnets, e) Buried V magnets, f) Buried multilayer V magnets.
2.2 Winding topologies

The operation principle of electric machines is based on the interaction between the magnetic fields and the currents flowing in the windings of the machine. The winding constructions and connections as well as the currents and voltages fed into the windings determine the operating modes and the type of the electric machine.

The armature winding of a three-phase electric machine is usually constructed in the stator, and it is spatially distributed in the stator slots. The following figure 3 shows two different winding topologies for electric machines. It is desired that the magneto-motive force (mmf) produced by stator windings to be as sinusoidal as possible. However, practical windings are never perfectly distributed sinusoidally. If a high number of slots per pole and phase (large q) is used, fractional slot pitch or double layer slots with a spanning less than a full pitch there's a possibility to get quite sinusoidal mmf waveform. A machine with a high pole number and a high number of slots per pole and phase is difficult and expensive to build. Also this winding type is characterized by large end-winding length which leads to high cooper losses.

The concentrated winding machines have potentially more compact designs compared to the conventional machine designs with distributed windings, due to shorter and less complex end-windings. With such windings, the volume of copper used in the end-windings can be reduced in significant proportions, in particular if the axial length of the machine is small. Permanent magnet (PM) machines with concentrated fractional pitch stator windings are increasingly used because of their cost-effectiveness. PM machines with concentrated fractional pitch stator windings may be much cheaper because they have simple windings around one tooth that can be wound automatically. Using fractional slot windings different combination of numbers of poles and numbers of teeth are possible. However, the magnetic field of these windings has more space harmonics.

![Distributed Windings](image1)

![Concentrated Windings](image2)

Fig. 3: Different winding topologies.
3. Analysis of PM machines using FEM

As one of the numerical calculation methods, finite-element method (FEM) allows accurate determination of machine parameters through magnetic field solutions as it takes into account the actual distribution of the winding, details of geometry, and the non-linearity of the magnetic materials of an electrical machine. The machine parameters and the electromagnetic torque are very important considerations for both analysis and design of electrical machines.

In this paper the main performances of the PM machine are calculated using ANSYS 2-D program;

- PM machine parameters
  - Self-, mutual and phase inductances
  - dq-inductances
  - PM flux-linkage & back-emf
- Electromagnetic torque and torque ripple
- Skewing effect

Figure 4 show the PM machines analysed in following. The machine parameters are calculated using fixed permeability method. Different FE methods are used for the torque calculation.

![Fig. 4: Geometry of the studied PM machine; a) PM-V1 machine, b) IPM machine.](image)

4. PM machine parameters

The analysis and control of electrical machines requires an accurate mathematical model for performance assessment and system simulation. During mathematical modeling of the electrical machines, we try to establish functional relationships between entities which are important. As is known, various mathematical models for the salient-pole PM machines exist today. Three-phase models in stator reference frame, and two-phase models in rotor reference frame for the linear and non-linear operation conditions of the PM machines are widely analysed in many literatures. Depending on the mathematical model, self-, mutual- and phase inductances, or dq-inductances and also the PM flux-linkage (back-emf) appear in the main mathematical relations of the PM machine. Therefore the winding inductance and PM flux-linkage are important parameters required to model the performances of electrical machines. In general, these parameters can be determined analytically, or using finite element (FE) method.

In following analysis the model parameters for different PM machines are calculated using FE method. To take into account the saturation effect on the model parameters (PM flux effect on the inductances and vice versa) the model parameters of the machine are derived using the fixed permeability method. With this method the parameters of the PM machine can be calculated with high precision.
4.1 Self-, mutual and phase inductances

In the case of salient pole synchronous machines the effective air-gap length (reluctance of the magnetizing path) isn’t constant along the circumferential direction. As a result, the inductances of such machines change with the rotor position. The variation of the stator self-, and mutual inductances with the rotor position for the PM-V1 machine are shown in the following figure 5.

![Fig. 5: Self- and mutual inductances of the PM-V1 machine.]

Further, in analogy to non-salient pole machines it is often assumed that also for the salient pole machines the phase inductance can be calculated according to: $L_{\text{phase}} = \frac{3}{2} \cdot L_{\text{self}}$ (e.g. in [4, 5]). Based on this hypothesis, the phase inductance is a function of rotor position, since the self inductance of this type of machines depends on the rotor position. Deriving a correct formula for the total phase inductance for this type of electric machines [1], it is shown that this parameter is constant with rotor position, and doesn’t vary as is assumed in many literatures. For the linear case this parameter depends only on the load angle $\delta$. The following figure 6 shows the variation of the phase inductance with the load angle. It is shown that the total phase inductance is equal to the $q$-, respectively $d$-inductance for the case when the total flux due to currents flows through the $q$-, respectively $d$-rotor axis.

![Fig. 6: Phase inductance of the PM-V1 machine versus load angle.]
4.2 dq-inductances

The d-axis is the axis of symmetry centred on one rotor pole. In the PM machine the magnetic flux due to the magnets determines the d-axis. The stator current that leads a maximum flux density through the rotor d-axis is called d-axis current \( i_d \). Otherwise the q-axis is the axis of symmetry centred between two rotor poles. Electrically, the q-axis is 90° electrical degree shifted away from the d-axis. The stator current that leads a maximum flux density through the rotor q-axis is called q-axis current \( i_q \). The following figure 7 shows the flux distribution when the PM machine is excited in the q- and d-axis respectively. For these rotor positions, the variation of the dq-inductances for different dq-currents is presented in the figure 8.

![Fig. 7: Current flux distribution for the q- and d-axis current excitation.](image)

![Fig. 8: dq-inductances for different stator dq-currents.](image)
4.3 PM flux-linkage

In a PM machine there is a flux due to the magnets which links all the windings in turn, and gives the flux-linkage $\psi_m$ in each phase, even when there is no current flowing. Corresponding to this flux-linkage is the “open-circuit” voltage $e_m$ (back-emf), which leads $\psi_m$ in phase by 90°. In the phasor diagram, the flux $\psi_m$ is along d-axis, and therefore $e_m$ is along q-axis.

The following figure 9 shows no-load flux-linkage due to magnets of the IPM machine. The induced back-emf depends on the rate at which flux changes, $e_m = \frac{d\psi_m}{dt}$. Figure 10 shows the no-load induced back-emf of the IPM machine at 1000 rpm.

![Fig. 9: No-load PM flux-linkage of the IPM machine.](image1)

![Fig. 10: No-load back-emf of the IPM machine at 1000 rpm.](image2)
5. Electromagnetic torque and torque ripple

The basic task of any electric machine is to generate torque to accelerate and drive a load over a specific range of speeds. Thus, torque is a very important consideration for both analysis and design of electrical machines. Different methods based on finite element solutions can be used for the calculation of the electromagnetic torque. In [2] three different torque calculation methods are analysed; the Maxwell’s stress tensor-, dq-model of PM machine, and magnetic co-energy method. The use of Maxwell’s stress tensor is probably the simplest method, since it requires only the local flux density distribution along a specific contour around the air-gap of the machine. The accuracy of torque calculation with this method relies on model discretization and on contour selection. According to the virtual work principle, the electromagnetic torque equals the derivative of the magnetic co-energy with respect to angular position at constant current. With this method at least two finite element solutions are required to obtain the co-energy change due to an incremental displacement, and this inevitably increases the computing time. Calculation of the electromagnetic torque with the third method is based on the dq-mathematical model of the PM machine.

In the following analysis the electromagnetic torque of the studied machines is calculated using Maxwell’s stress tensor method and from the new mathematical model for the PM machine developed in [1]. The FE calculations are performed for different rotor positions over one pole pair. Figure 11 compares the torque results for the PM-V1 machine obtained with these methods. Also, figure 12 shows the torque results obtained from the new mathematical model and the measurements. The obtained results show good agreements between different methods.

![Fig. 11: Comparison of different calculation methods: Electromagnetic torque vs. rotor position.](image1)

![Fig. 12: Comparison with measurements.](image2)
6. **Skewing effect**

Although the interest in the PM machines is still increasing, they have also its disadvantages. A drawback of PM machines is the torque pulsation. A lot of research has been performed to analyze and reduce the pulsating torque for this type of machines. Among various approaches, skewing either the stator teeth or rotor poles is known to be the most effective method for reducing of the torque pulsation in permanent magnet machines. The following figure 13 shows two alternative solutions for skewing. Also, figure 14 shows the skewing effect on the torque curve for a PM machine. The skewed machines need to be analysed using 3-D finite element analysis. However, the application of a 3-D field model for the optimization process and analysis of the electric machines is too complex and very time consuming. Therefore, in [3] an electromagnetic model for the skewed PM machine based on the 2-D finite element/analytical technique is developed and analysed. Using this method the calculation time of this type of PM machines clearly is reduced. The new model for the skewed PM machines will be published in a future paper.

![Fig. 13: Two alternative solutions for skewing: a) Stator teeth skewing, b) Rotor with skewed permanent magnet poles.](image1)

![Fig. 14: Electromagnetic torque of a PM machine with and without skewed stator topology.](image2)
7. Conclusions

In this paper, the electromagnetic performances of different PM machines for hybrid electric vehicles application are investigated using finite element method. The main model parameters, electromagnetic torque and the skewing effect is analysed using ANSYS program. The model parameters of the PM machines (inductances, PM flux-linkage, back-emf) are derived with Fixed Permeability Method. Using this method the parameters of the PM machine can be calculated with high accuracy. Two different FE calculation methods (Maxwell’s stress tensor method and new mathematical model for the PM machine) are used to calculate the electromagnetic torque. The electromagnetic torque derived with the new mathematical model is compared with the FE Maxwell’s stress tensor method and measurements. The obtained results show a good agreement between these methods. Also the skewing effect on the torque performances of the PM machine is investigated.

References


