Single-phase PM synchronous motor simulation with Matlab/Simulink

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Abstract. The permanent magnet (PM) synchronous motors have a major advantage compared to the asynchronous motors, namely that there are no losses in the rotor. As regarding the single-phase motors must be considered the possibility to obtain the starting torque. A simple and inexpensive constructive solution is the motor with tapered air-gap, which can develop a starting torque (although specific starting torque is small) in a well-defined direction, simply by powering the stator winding from the network of industrial frequency. Starting torque occurs due to the fact that the axis of the rotor field created by PM in the rest position differs from the axis of the stator because of the tapered air gap. Therefore this motor is more often used in low power household appliances. The development and the implementation in Matlab / Simulink of the motor model will be presented in this paper. The model is based on a mathematical model with lumped parameters, parameters that are determined through calculations and finite elements analysis. The motor behavior will be studied, both in stationary and dynamic operation. The accuracy of the model is verified by comparing simulation results with results obtained by measurements.

1. Introduction

It is known that the cheapest energy and with the smallest negative effect on the environment is the saved energy. For this reasons the new standards have imposed the continuous increase of energy conversion efficiency. In order to increase the efficiency of conversion of electrical energy into mechanical energy through the motors only few measures are possible: the using of new materials with improved qualities; the using of new constructive solutions concretized in new motor types; in some cases, the reducing of electrical and magnetic loads by increasing the geometrical dimensions.

As regarding the first solution, limitations arise because of relatively low technical progress in the field. In the last case, the new costs which will be higher should be considered. Restrictions regarding enclosing the motors in a certain class of sizes also will arise in this case. The conception of a new type of motors is always of great interest, but they must have a proven advantage (for certain applications), and usually, they must be simple and cheap.

Until recently, usually in small power electrical drives, asynchronous motors were used due to their robustness and simplicity. In recent years there is a trend of replacing these motors with different types of synchronous or D.C. brushless motors. The permanent magnets (PMs) motor and switched reluctance motor are among the most commonly used synchronous motors. In order to supply the switched reluctance motors, special sources are required, and for this reason, the drives with these
motors are usually more expensive. In case of PMs synchronous motors, there are solutions that can be powered directly from industrial frequency network. Generally they are with three-phase and the starting process is performed in asynchronous operation.

In case of small power drives, when the motor is supplied from the single-phase network, a very simple solution is the PM synchronous motor with tapered air-gap, Figure 1.

![Figure 1. Cross section of the single-phase PM synchronous motor with tapered air gap](image)

This motor has the great advantage that it is able to develop starting torque based on the initial phase shift existing between the stator field axis and the axis of the rotor flux produced by PM. This initial phase shift is due to the uneven air gap, consisting of two main areas: one with large air gap, \( g_1 \), and another with small air gap, \( g_2 \). If the load torque is smaller than the initial torque, the rotor begins to move and it synchronizes after a few half-cycles.

Electrical equivalent circuit of single-phase synchronous motor with PMs and tapered air-gap is presented in Figure 2 [1]. The material of PMs is Ferrite type, with parallel magnetization.

![Figure 2. Electrical equivalent circuit](image)

Based on electrical equivalent circuit, the motor equations can be written [1-3],
The induced voltage is given by relation,

\[ V = iR_{Cu} + i_{Fe}R_{Fe} \]  

(1)

The motion equation is,

\[ i_{L} + i_{Fe} = i \]  

(3)

The induced voltage is given by relation,

\[ v_e = -\frac{d\psi}{dt} = -\frac{d\psi}{d\theta} \frac{d\theta}{dt} = 2N\phi_{rp}\sin(\theta - \theta_0)\frac{d\theta}{dt} \]  

(4)

The motion equation is,

\[ J\frac{d\Omega}{dt} = 2Ni\phi_{rp}\sin\theta - T_{rp}\sin[2(\theta - \theta_0)] - T_l \]  

(5)

It has been noted: \( V \) – rated voltage; \( R_{Cu} \) – winding resistance; \( R_{Fe} \) – resistance corresponding to the iron losses; \( i \) – stator current; \( i_{Fe} \) – current corresponding to the iron losses; \( i_{L} \) – current corresponding to the magnetic flux produced by stator winding; \( v_e \) – voltage induced by PM; \( \psi \) – total flux of PM linked by stator winding; \( N \) – number turns of one stator coil; \( \phi_{rp} \) – peak rotor flux; \( \theta \) – angle between stator and rotor axis; \( \theta_0 \) – initial angle (rest position of the rotor); \( J \) – total moment of inertia of the rotor; \( \Omega \) – rotor speed; \( T_{rp} \) – peak reluctance torque; \( T_l \) – load torque.

In the previous equations it was assumed that the reluctance torque and the flux created by PM have a sinusoidal variation depending on the rotor position (\( \theta \)). This assumption is not far from reality as it can be seen in Figure 5 and Figure 6.

2. Finite elements analysis

In order to obtain some of the motor parameters required for implementation of the motor model in Matlab/Simulink, the numerical model of the motor has been created in FEMM and magnetostatic analysis has been performed. The PMs properties have been chosen so that the PM flux to be the same with the magnetic flux determined based on the induced voltage, experimentally recorded in no load operation, the machine being driven by another motor, Figure 3 [4].

![Figure 3. Recorded voltage induced by PMs](image-url)
Figure 4 shows the flux lines and magnetic flux density map for two rotor positions, without stator winding current: the rotor axis at 90° to the axis of the stator (a), and rotor axis aligned with stator axis (b).

With FEMM, the torque was obtained by Maxwell Stress Tensor Method [5], for different rotor positions. The dependence $Tr=f(\theta)$ is showed in Figure 5. From $Tr=f(\theta)$, the rest position of the rotor is also obtained. This corresponds to the angle for which the reluctance torque is zero. The dependence of the total flux of PM linked with stator winding by rotor position is presented in Figure 6.

The stator winding resistance is measured without problems, but during operation, its values changes as the winding heats.

A method for analytically determination of the stator winding inductance, depending on the stator geometry and materials, is presented in [1], [6], [7].
The inductance can also be measured ([1], [8]) or determined by finite elements analysis. It should be noted that it depends on the rotor position ($\theta$), Figure 7.

3. **Motor modeling in Simulink**
   Once the rotor parameters have been determined, the model can be implemented in Matlab/Simulink. Based on motor equations a model in Matlab/Simulink has been made, it being presented in Figure 8.
A voltage source has been used for generation of the sinusoidal voltage signal, and a lookup table for variable stator inductance [9]. The other blocks are common for Simulink. For visualization of different parameters, many oscilloscopes have been used.

4. Results and conclusion
The simulations have been performed for five seconds. In the following the obtained results regarding some of the motor characteristics are presented.
Figure 10. Stator current [A] variation in time

Figure 11. Induced voltage [V] variation in time
Some conclusions concerning the presented results must be done. The rotor speed is not constant, but the motor runs with an average speed equal to that of synchronism (3000 rot/min).

The induced voltage is not the same with the recorded voltage. The one recorded has a sinusoidal shape, and that obtained by simulation is deformed. Also, the stator current in no load operation, obtained by simulation, has constant amplitude, while the recorded no load current varies around of an average value, Figure 12.

At this time the accuracy of the model is not satisfactory. Although the average values seem to be alright, the model will be studied to achieve results like those recorded. This will be done in a next paper.

![Figure 12. Recorded no load current](image)

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