Design and Study of a Multiphase Axial-Flux Machine

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In this paper, a 7-phase axial-flux double-rotor permanent magnet synchronous machine is studied using analytical and finite element methods. This type of machine shows a higher sensitivity to the inductance harmonics and electromotive force (emf) compared with the 3-phase machines. So, the conventional analytical modeling method, in which only the first harmonic is taken into account, leads to significant errors in the determination of the control parameters, e.g., the frequency of pulse width modulation voltage source inverter. A multimachine model explains the reasons for this sensitivity and a more sophisticated analytical method is used. Results are compared with those obtained by the 3-D FEM.

***Index Terms*—Axial flux machines, finite 3-D element method, harmonics, magnetostatic.**

I. Introduction

Multiphase machines have various advantages over the conventional 3-phase machines, such as higher reliability, higher torque density, lower pulsating torque, and a decomposition of the power supplied by the static converters. However, because of its specificities compared with the classical machines, the modeling and control of this type of machine must be reconsidered.

A vectorial formalism has been proposed to design a comprehensive model of this type of machine [1]. Thus, a wye-coupled 7-phase machine without reluctance and saturation effects has been proven to be equivalent to a set of three 2-phase fictitious machines [2]. Each machine is characterized by its own inductance, resistance, emf, and family of harmonics. The torque of the real machine is equal to the sum of the three torques of the fictitious machines.

For a 3-phase machine a first harmonic model often gives sufficient results (first-order model) to achieve a good control of the system. The reason is that there is only one fictitious machine in this case. For a 7-phase machine, as there are three fictitious machines, three spatial harmonics should be considered in order to correctly design the machine. By acting on windings and permanent magnet shapes, it is possible to modify the harmonic spectrum of magnetomotive and electromotive forces. From this point of view, the axial machines offer a wide variety of possibilities [3], [4].

In this paper an axial double-rotor single stator NN permanent magnet machine with toroidal windings has been chosen. Three approaches are proposed to synthesize the model of this machine, based on the harmonic decompositions. The first two methods are based on analytical solutions. The first one is a conventional approach that takes into account only the first harmonic. The second one considers all the harmonics. Finally we use the finite element method (FEM).

The results (inductances, electromotive force, and time constants) obtained by the three methods will be compared. We show also the possibilities of the 3-D FEM which will be take as a reference.

Digital Object Identifier 10.1109/TMAG.2006.872418

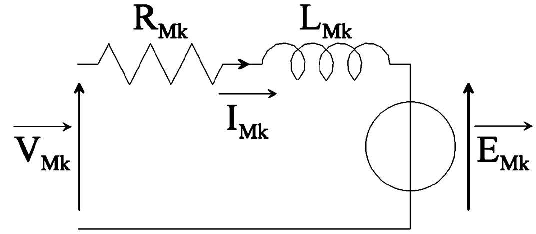

Fig. 1. Equivalent circuit of one fictitious machine.

II. Machine Models

A. Multiphase Machine Model

The vectorial formalism [1] is based on the properties of the 7 by 7 inductance matrix [Ls] of the stator phases. This matrix is symmetrical and circular: consequently four parameters $L_{11}, m_{12}, m_{13}, m_{14}$ are necessary to determine it. A linear application is associated with this matrix whose the eigenvalues are the inductances L_{Mk} of the fictitious machines. In the same way the electromotive forces $\overrightarrow{E_{Mk}}$ are the vectorial projections of the emf vector of the real machine onto the eigenspaces.

In the eigenspace, the electrical equation of Mk, the fictitious machine number k, can be written as follows:

$$\overrightarrow{V_{Mk}} = R_{Mk}\overrightarrow{I_{Mk}} + L_{Mk}\frac{d\overrightarrow{I_{Mk}}}{dt} + \overrightarrow{E_{Mk}}. \quad (1)$$

From this equation we can introduce an equivalent circuit for each machine as represented in Fig. 1 Moreover, a harmonic characterization of the fictitious machine is possible. From this perspective, the periodic components of any vector of the real machine are expanded using Fourier series. Then, any vector is projected onto the different eigenspaces: a harmonic repartition as summarized in Table I, [1] is obtained.

TABLE IV
RMS VALUES OF FICTITIOUS MACHINE EMF AND RELATIVE ERRORS

	FEM (V)	A_{H1} (V)	A_T (V)	ε_3	ε_4
e_{M1}	87	84	85,5	-7%	-2%
e_{M2}	8	0	7,7	-100%	-3%
e_{M3}	20	0	19,3	-100%	-3,5%

TABLE V
INDUCTANCES OF FICTITIOUS MACHINES AND RELATIVE ERRORS

	FEM (mH)	A_{H1} (mH)	A_T (mH)	ε_5	ε_6
L_{M1}	55	51	52,3	-7%	-5%
L_{M2}	4,1	0	3,2	-100%	-22%
L_{M3}	8	0	6,7	-100%	-16%

TABLE VI
VALUES OF FICTITIOUS MACHINE TIME-CONSTANTS

	FEM (ms)	A_{H1} (ms)	A_T (ms)
τ_{M1}	108,5	100,6	103,2
τ_{M2}	8	0	6,3
τ_{M3}	15,8	0	13,2

and 9, 3, and 11). As before, we calculate, using the FEM as our reference, the errors. We denote ε_3 and ε_4 respectively the errors for A_{H1} and A_T. As we can see from the results (in Table IV), A_{H1} and A_T underestimate slightly e_{M1}. A_{H1} is inappropriate for estimation of e_{M2} and e_{M3} since the projections are equal to zero.

In the same way we present in Table V the L_{Mk} inductances obtained by the three methods. The relative errors (using FEM as our reference) are denoted ε_5 and ε_6 for A_{H1} and A_T respectively.

It can be noted that between the A_T and FEM methods the results are close for the M1 machine (error less than -5%). As the FEM method takes into account the leakage inductance, it is normal to find higher values in this case. The results are less satisfactory for the M2 and the M3 machines. For these two machines the sensitivity of the models is effectively higher since it depends on the third and the fifth harmonics whose values are weaker compared with the first harmonic. For the A_{H1} approach, the unacceptable errors on L_{M2} and L_{M3} confirm the sensitivity of the M2 and M3 machines to the harmonics. The A_{H1} method, usual for 3-phase machine study, can not be used.

V. EFFECT ON THE PWM FREQUENCY CHOICE

From inductances values L_{M1}, L_{M2}, and L_{M3}, the time-constant of each fictitious machine is determined and given in Table VI.

In general, the PWM frequency is chosen according to the smallest electric time-constant. In our case, we have three time-constants. The PWM frequency must then respect the following equation:

$$f_{PWM} \geq \max\left(\frac{5}{\tau_{M1}}, \frac{5}{\tau_{M2}}, \frac{5}{\tau_{M3}}\right). \tag{6}$$

With the A_{H1} method, the minimum value of the PWM frequency can not be determined. In fact, only the τ_{M1} electric time-constant is then considered and the minimum frequency f_{PWM} is equal to $5/\tau_{M1} = 50$ Hz. With the FEM and the A_T methods we find a minimum PWM frequency of 625 Hz. The difference between these two values is extremely large and thus unacceptable. Undesirable parasitic currents appear in the machine if the A_{H1} method is used.

So, it is particularly important to consider the harmonics for the design of a multiphase machine. More generally, a correct predetermination of the inductances L_{M1}, L_{M2}, and L_{M3} of the fictitious machines is necessary to predict the magnitude of the currents in the machine.

VI. CONCLUSION

The determination of the necessary parameters for the control of multiphase machines is not as easy as for 3-phase ones. It has been shown that the analytical method A_{H1} based only on a first harmonic approach leads to insufficient accuracy (e.g., for the determination of the PWM frequency). A multimachine model based on a vectorial formalism has been used to explain the reasons for this phenomenon. It is consequently necessary to use more precise methods of modeling. In the case of the relatively simple studied machine, another analytical method A_T, taking into account harmonics, has been applied. Comparisons with the FEM results show a sufficient accuracy. For more sophisticated machines (skewed slots, different windings, different magnet shapes) the analytical method is still interesting as it allows us to show how to influence the control parameters but does not give precise quantitative results. It is then necessary to use the FEM to get useful values of the control parameters.

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