Relevance of 3-D Effects in Electromagnetic Simulations of Synchronous Motors for Industrial Drives

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***Abstract*- The modern motor design tendency is to develop and manufacture an industrial drive within a short time according to customer specific requirements. Due to their short CPU time analytical methods for motor analysis are still widely used. The existing analytical methods are based on radically simplified models capable of giving enough information for majority of practical design cases. However, the accuracy of analytical methods has to be enhanced in every design usually by introducing different empirical factors in order to capture complicated 2-D and 3-D effects such as magnetic saturation, hysteresis-, eddy current losses and end-winding effects. This is of paramount importance especially in case of material cost optimization. The purpose of this paper is to present the existing algorithm bases for simulations based 2-D and 3-D analysis of large synchronous motors for industrial drives and by comparing the two to show how relevant is the influence of 3D-effects on the overall accuracy of the electromagnetic simulation of large synchronous motors. Beyond the mentioned numerical aspects, the obtained results are also important for understanding the behavior of the synchronous motor and the entire drive.**

***Index Terms*—Numerical simulations, synchronous motor, industrial drive, 3D effects, end-winding region.**

I. Introduction

SYNCHRONOUS motors (SM) for industrial drives have a high power density due to ever increasing customer requirements. The rated power these motors covers the range 2-30MW and the rated speed goes up to 600 rpm. The mentioned high power density requirement makes the magnetic, mechanical and thermal design of those motors rather demanding. To obtain a motor design which reliably and accurately fulfills the customer requirements all the relevant electromagnetic process in the motor must be taken into account.

While several complicated processes in the motor, such as magnetic saturation, hysteresis- and eddy current losses, can be accurately taken into account at the level of 2-D FEM field simulations [1, 2], some effects, such as the effect of the end-winding region, are very problematic and can be captured only by performing time consuming 3-D field simulations. However, according to the available literature, for example [3], the stray fields of the end-winding region play an important role by computing the correct values of motor reactances and losses.

The modern motor design tendency is to radically shorten the development time of an industrial drive in development of which a synchronous motor is the most complex and time demanding component. In case of customer specific requirements this usually means an optimization procedure involving a large number of motor performance calculations in order to find an acceptable solution in terms of cost and performance quality. This is evidently conflicting with the above mentioned long CPU-time of highly accurate 2-D and 3-D field simulations. Therefore, it is of paramount importance to know the relevance and influence of the motor parameters that are most expensive to calculate in terms of CPU-time.

To develop large synchronous motors for industrial drives design teams usually use internally developed calculation tools based on different analytical methods available in the existing literature, for example [3], [4]. The analytical methods radically simplify the motor's geometry in order to keep the CPU-time short and therefore cannot take into account neither the complexity of the real geometry nor the complicated processes such as magnetic saturation, hysteresis- and eddy-current losses, etc. [2, 4]. More precisely, the following effects are considered to be very complicated and, in terms of the CPU-time, very expensive to take into account:

- Stray reactance of the end-winding regions,
- Losses in stator winding due to circulation currents,
- Losses in stator winding due to radial field penetration in slots (saturation effect),
- Losses in structural components due to the stray field of the end-winding region,
- Losses in the stator yoke due to the main- and higher field harmonics.

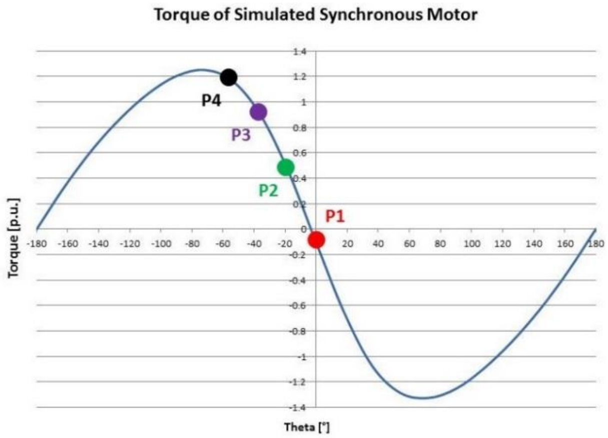
The main purpose and contribution of this paper is manifold: (a) to present a highly accurate synchronous motor calculation procedure based on 2-D and 3-D FEM field simulations, (b) to compare the two in order to show the relevance of the 3-D effects (above all the relevance of the end-winding stray reactance), and (c) to compare the obtained results against the available analytical estimations in order to evaluate their accuracy.

II. Numerical Methods and Initial Results

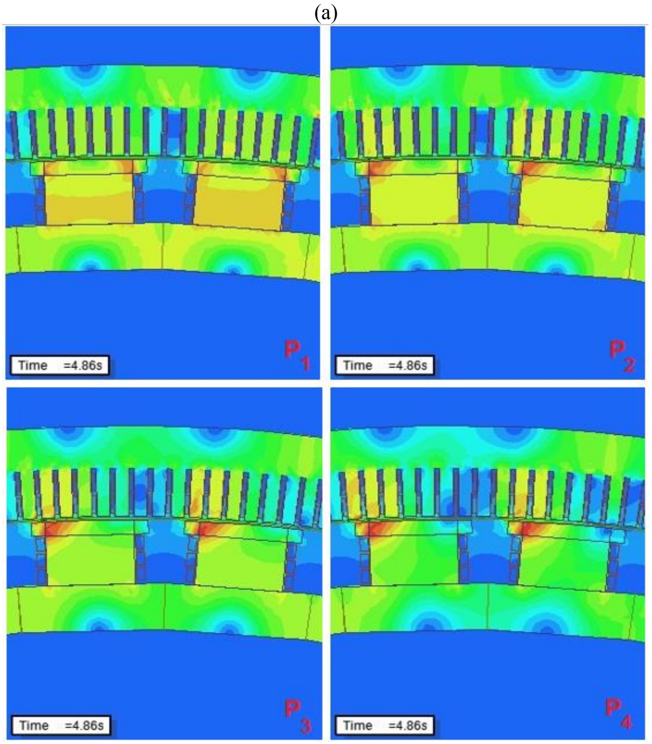
The mentioned analytical methods are usually based on the vector diagram and the following voltage equation of the stator circuit [2-4]:

$$\underline{U} = R\cdot\underline{I} + jX_{\sigma 1}\cdot + jX_{ad}\cdot\underline{I_d} + jX_{aq}\cdot\underline{I_q} + \underline{U_p} \quad (1)$$

where U is the stator terminal voltage, I is the stator current, I_d is the direct component of the stator current (the d-axis current component), I_q is the quadrature component of the stator current (the q-axis current component), U_p is the synchronous generated voltage of the stator winding induced by the rotor's rotating field, X_σ is the stator stray reactance, X_{ad} is the d-axis armature reaction reactance, and X_{aq} is the q-axis armature



(a)



(b)

Fig. 1. The simulated torque curve (a) and the corresponding distributions of the magnetic flux density (b) of the chosen typical ABB synchronous motor with salient pole rotor (15.6MW, 3'900V, 5.6Hz) for industrial drives are presented.

reaction reactance. The stator stray inductance has the following important components [3-5]:

$$X_{\sigma 1} = X_{\sigma 1\_slot} + X_{\sigma 1\_airgap} + X_{\sigma 1\_end-winding} \quad (2)$$

As opposed to this analytical approach the calculation procedure based on 2-D and 3-D FEM [6-8] field simulations, reported in [1] and [2] in detail, is based on the voltage equation of the following form:

$$u(t) = R \cdot i(t) + L_{\sigma ew} \cdot \frac{di}{dt}(t) + u_{ind}(t) \quad (3)$$

where $L_{\sigma ew}$ is the stray inductance of the stator's end-winding region, and u_{ind} is the total induced voltage of the stator winding due to the rotating magnetic flux, the stray magnetic flux and the armature reaction flux of the motor.

Equation (3) is written and solved in time-domain in order to accurately capture nonlinearities. As reported in [1] the coupling channel between the FEM 2-D FEM simulations and the voltage balance equation (3) is the induced voltage:

$$u_{ind}(t) = N \cdot \frac{\partial \Phi}{\partial t}(t) = N \cdot L \cdot \frac{1}{S} \frac{\partial}{\partial t} \iint_{(S)} A_z(x, y, t) \cdot dS \quad (4)$$

where N is the number of turns of the stator winding, L is the axial length of the motor, A_z is the z-component of the magnetic vector potential and S is the surface area of the stator coil covering all its slots.

The above numerical method based on Equation (3) and (4) has yielded the results presented in Figure 1 for a chosen typical ABB synchronous motor with salient pole rotor (15.6MW, 3'900V, 5.6Hz).

Evidently, based on the obtained results shown in Figure 1 already at the level of 2-D simulations several important effects such as magnetic saturation, hysteresis and eddy-current core losses, eddy-current winding losses can be taken into account.

The mentioned 3-D effects such as, for example, the stray reactance of the end-winding region cannot be captured by the 2-D model shown in Figure 1b. The 3-D model of the chosen large synchronous motor along with the simulation algorithm will be presented in detail at the conference and in the subsequent full paper.

The obtained 3-D results will be compared against the presented 2-D results in order to evaluate the influence of the end-winding region on the motor performance. The obtained stray magnetic field of the end-winding region will be also used to evaluate the mentioned induced losses in structural components of the synchronous motor.

The obtained 3-D results will be also used to evaluate the accuracy of the analytical methods for estimating the end-winding reactance that was used in Equation (3) in order to enhance the accuracy of the results presented in Figure 1.

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