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IRON LOSS CALCULATION FOR SYNCHRONOUS RELUCTANCE MACHINES

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Abstract: **A numerical method for iron loss calculation is presented in this paper. The method is suitable for any synchronous and most dc machines, especially if the current waveforms are known "a priori". This technique will be principally useful for high speed machines and in particular for the synchronous reluctance machine, where the iron losses are often an important issue. The calculation is based on Finite Element Analysis, which provides the flux density waveforms in the iron, and on the Fourier Analysis of these waveforms. Several Finite Element Simulations are necessary to obtain the induced voltage versus time waveforms. To reduce the post-processing time the majority of the elements of the model are grouped together to create super elements. Also the periodicity of the motor can be used to reduce the number of required simulations. The method is applied to the calculation of the iron losses of a synchronous reluctance generator, and a number of interesting results are discussed in the paper.**

I. INTRODUCTION

Iron losses are often an important issue in the design of synchronous reluctance motors, and in high speed applications they can become the major cause of power dissipation. Therefore, whereas in other kind of machines a rough estimation of these losses can be accepted, their importance in synchronous reluctance machines justifies a greater effort in calculating them more precisely. A method to determine iron losses, based on Finite Element (FE) and harmonic analyses, has been developed and will be presented in this paper. The proposed technique is suitable for any kind of synchronous machine and will be applied to the losses calculation of a three phase synchronous reluctance generator.

II. IRON LOSS CALCULATION IN A THREE PHASE ELECTRICAL MACHINE

The results of any finite element analysis must be regarded as an instantaneous value being related to a particular current and rotor position. This can be used to simulate either transient or steady state conditions: the instants of time must reproduce a "real time" sequence, so that the simulations can be concatenated. For the steady state simulation of an electrical machine, a period is divided in discrete time intervals and the rotor position and stator current are updated to simulate a steady state operating point. The results are then expressed as a discrete function of time. Even if the purpose of the set of simulation is to obtain the behavior of the flux density in the iron core, torque and power factor can be easily obtained. For a significant representation of the time varying distribution of the flux density, the finite element mesh must be rotated rigidly, so that each element retains constant shape and relative position. For the best effectiveness of the method both the radial and tangential component of the flux density must be stored for every element of the iron core. This provision allows to take into account not only the amplitude variation of the flux density but also the changes in the direction of the vector. The flux density can be represented by a family of functions:

$$B_{i,k}\left(t_j\right) \tag{1}$$

where k is the number that identifies the element to which the function belongs,
i (=x or y) is one of the orthogonal components of B,
and t_j is the discrete time variable.

A complete period must be studied, taking into account that the periodicity can be different for the stator and the rotor. The fundamental harmonic is the lower for the stator, while the smaller of the values between the sixth harmonic (space harmonic) and the lowest tooth harmonic should be considered for the rotor. A continuous function can simply be obtained interpolating the discrete function with any suitable technique.

For each time function a Fast Fourier Transform (FFT) must be performed to separate the contribution of different frequency harmonics. That is,

$$B_{i,k}(t) = \sum_{n=0}^{m} B_{i,k,n} \cos(n\omega t + \psi_{i,k,n}) \tag{2}$$

The maximum harmonic order m to be considered should not exceed 1/2 of the samples (i.e., 1/2 of the FE simulations) for the Fourier coefficients to be significant. For this reason at least 4 points per tooth pitch should be calculated to allow a feasible harmonic analysis, but a higher number is strongly recommended for an adequately detailed analysis. The power loss per pound for each harmonic is obtained for the k-th element from the classical expression:

$$P_{i,k,n} = k_h f_n B_{i,k,n}^{\zeta} + k_e d^2 f_n^2 B_{i,k,n}^2 \tag{3}$$

where k_h is the hysteresis loss coefficient,
f_n is the harmonic frequency,
ζ is the hysteresis loss exponent,
k_e is the eddy current loss coefficient,
and d is the lamination thickness.

These coefficients can be calculated from manufacturer data sheets [2], and care must be taken to make sure that the selected value is suitable for the flux density range being considered. The total losses on each element are then calculated summing the contribution of the first m harmonics:

$$P_k = V_k \delta \sum_{n=1}^{m} (P_{x,k,n} + P_{y,k,n}) \qquad (4)$$

where V_k is the volume and
δ is the density of the k-th element.

The total losses are then obtained integrating the element losses over the machine cross section:

$$P_{fe} = \sum_k P_k \qquad (5)$$

A variety of different approaches have been suggested to take into account the harmonic content of the flux density in the hysteresis loss calculation. The hysteresis losses are in fact related to the minor hysteresis loops more than to the harmonic content of the flux density. For example it is known that losses generated by low order harmonics are deeply affected by the phase relation between the fundamental and the harmonics [6]. In spite of the high non linearity of this phenomenon a simple and accurate correction factor was proposed by Lavers et al. [9]:

$$Factor = 1 + \frac{0.65}{B_p} \sum_{1}^{N} \Delta B_i \qquad (6)$$

where B_p is the peak flux density,
ΔB_i is the amplitude of one of the N flux reversals.

This approach can lead to a very good accuracy if the sinusoidal losses are known, a requirement very difficult to meet when dealing with electrical machines. The method, however, introduces an additional computational task, for it requires an estimate of the flux reversals for every element being considered in the loss calculation. Moreover the rotor flux density does not alternate but has a constant bias in the case of a synchronous reluctance machine, and there is no straightforward extension of the method availabale for this operating condition. In addition, the high speed of the application and the heavy weight of high order harmonics have made the hysteresis losses small compared to the eddy current losses.

For all the above reasons the simple approach of Eq. 3, that calculates the losses of every harmonic independently, was maintained.

III. SIMPLIFIED METHOD FOR IRON LOSSES CALCULATION

The method just described can become difficult to accomplish if a large number of elements are needed to build a proper FE model. However several provisions can be taken to simplify the procedure and to reduce the amount of data necessary for the iron loss calculation, without significantly affecting the results. First the discretization of the model for those aspects which concerns the losses does not have to be as fine as the real FE mesh. In fact it is possible to group several elements of the mesh to create a "super element" aimed at the calculation of the iron losses; the $B_{i,k}(t)$ of the super element is assumed to be equal to the average of the $B_{i,k}(t)$ of the elements that are grouped in the super-element. Care must be taken to maintain a fine discretization on the airgap surface, while reasonably large super-elements can be defined in the yoke and also in the teeth. The adoption of this technique can reduce the number of functions $B_{i,k}(t)$ from several hundred or even thousands to few dozen, without affecting the final results. The error introduced by this approximation was found to be smaller than the tolerances on the manufacturer data sheets from which the losses coefficients were taken.

Another important aspect for simplifying this procedure is to realize how the periodicity of the structure can be used to reduce the number of FE analyses. If the mesh is identical for every stator tooth, any simulation yields not only one point on the $B_{i,k}(t)$ curve, but q points, where q is the number of teeth per pole. In fact all the teeth experience the same flux density waveform, displaced by $\frac{\pi}{q}$ electrical degrees. For this reason the number of FE simulation is usually determined by the requirements of the rotor. The required total number of FE simulations is a function of the stator slot number and is given by:

$$N_{sim} = \frac{1}{6} 2 q N_s \qquad (7)$$

where N_s (ranging from 4 to 12) is the number of samples per tooth pitch.

IV. IRON LOSS EVALUATION FOR A HIGH SPEED SYNCHRONOUS RELUCTANCE GENERATOR

For this paper the above procedure was applied to a high speed fly wheel generator. The machine cross section is given in Fig. 1. The machine is a four pole synchronous reluctance machine rated 16 kW at 80000 rpm, 80 kW peak, with 36 slots and with the rotor pole divided into 4 rotor segments. The small number of rotor segments is necessary to achieve the high mechanical stiffness required by a very high speed application. The rotor lamination is 14 mil (0.355 mm) thick and the stator lam is 7 mil (0.178 mm). The actual details of the manufacturing process of the rotor lamination is protected by a confidentiality agreement between the authors and the company constructing the prototype.

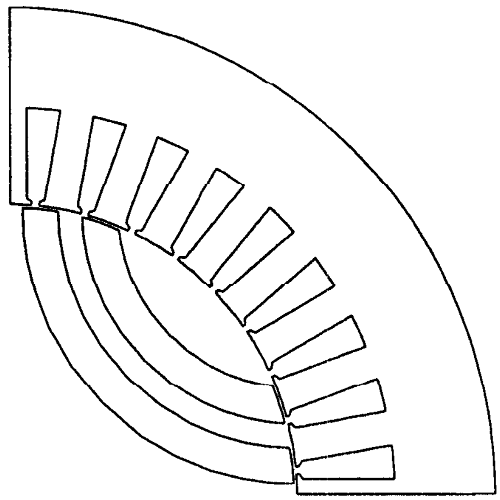

Fig.1 Synchronous reluctance generator: cross section

The super-elements subdivision is shown in Fig. 2. It shows a layer of small elements on both sides of the airgap. The rest of any stator tooth other than the tooth head is modeled with on single super element. The stator back iron is modeled with one super element per tooth. The rotor segments are divided in three super elements each, referred to as the upper, central, and lower part.

The time stepping simulation was carried out keeping a constant mmf angle equal to 70 electrical degrees which maximizes the power factor and is assumed to be the operating condition at peak power. The angular step was chosen to be 2 electrical degrees, leading to a total of 30 simulations. According to Eq. 7 these solutions are necessary to perform a detailed simulation containing all the harmonics.

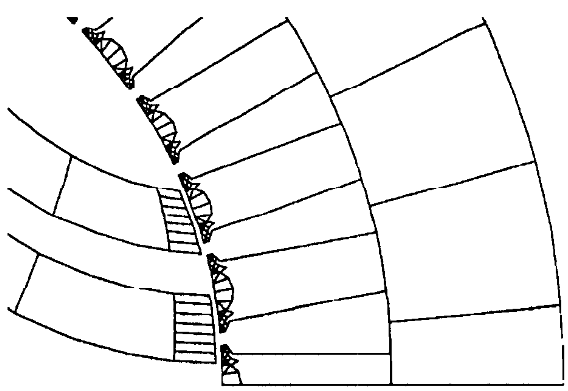

Fig. 2 Super elements and surface elements

It is very important to note that the rotor segments must be designed properly in order to minimize the rotor losses of this machine since the flywheel was designed to operate in a vacuum. It can be established that if two slots appear together on both sides of a rotor segment, a considerable flux depletion occurs in the entire segment and the losses in every element are affected. On the other hand if the slots appear alternately on one side or the other, the flux depletion remains localized in the region closed to the airgap and the inner elements of the segment are not influenced.

Another possibility to reduce the flux pulsation in the rotor segment is to design the segment to be as large as one slot pitch. In this case an entire slot and tooth are always present on both sides of the rotor segment. Hence, this arrangement keeps the rėluctivity seen by the segment constant and therefore minimizes the flux pulsation.

In this example one of the segments (the longer) is designed in contrast to these principles to emphasize their importance.

The Fourier transformation of the flux density in the rotor elements revealed that the most significant harmonics in the rotor are the sixth, corresponding to the 5th and 7th stator space harmonics, and the 18th, caused by the stator tooting.

TABLE I.a

ROTOR LOSSES CALCULATION:

FIRST (SHORTER) ROTOR SEGMENT

PARTS -->	UPPER	CENTR.	LOWER
Average B [T]	0.909	1.143	1.262
Loss per pound	0	0	0
6th Harmonic B [T]	0.068	0.068	0.076
Loss per pound	13	13	16
18th Harmonic B [T]	0.030	0.007	0.011
Loss per pound	17	1	3
Total losses [w]	3.2	2.3	2.1

TABLE I.b

ROTOR LOSSES CALCULATION

SECOND (LONGER) ROTOR SEGMENT

PARTS -->	UPPER	CENTR.	LOWER
Average B [T]	1.306	1.150	0.987
Loss per pound	0	0	0
6th Harmonic B [T]	0.033	0.031	0.041
Loss per pound	3	3	5
18th Harmonic B [T]	0.072	0.067	0.069
Loss per pound	94	82	86
Total losses [w]	14.6	19.1	13.8

Rotor Surface losses 380w, Total Rotor Losses 600w

The rotor pulsation losses are reported in tables I.a and I.b, where the most significant harmonics are placed in evidence. In spite of semi closed slots, the stator teeth are responsible for 84% of these rotor losses, and 81% of the total losses are concentrated on the longer segment.

The losses on the small elements at the gap are regarded as surface losses and they were evaluated in the same manner the pulsation losses (Figs. 3a and 3b). The behavior of the two segments is similar, because the surface losses are not affected by the segment placement or width. These losses account for the 63% of the total rotor losses.

The rotor losses were calculated again without the super-element approximation but no significant difference was found. An explanation can be found in the fact that below the rotor surface the flux tends to spread and reach a uniform distribution. This results in an even flux density in the segment and in a good accuracy of the proposed simplified method. As a further simplification the super element losses were calculated considering only the modulus of the flux density vector, without resorting to a two axis decomposition (FIgs. 4a and 4b): the results of the comparison with the fine element case is summarized in Table II. The introduced error reaches 12% of the segment losses corresponding to 5% of the total calculated rotor iron losses.

TABLE II

ROTOR LOSS CALCULATION

COMPARISON BETWEEN CALCULATION METHODS

LOSS LOCATION	Super Element	Small Elements
LONGER SEGM.	47.5 W	52.0 W
SHORTER SEGM.	7.6 W	10.7 W

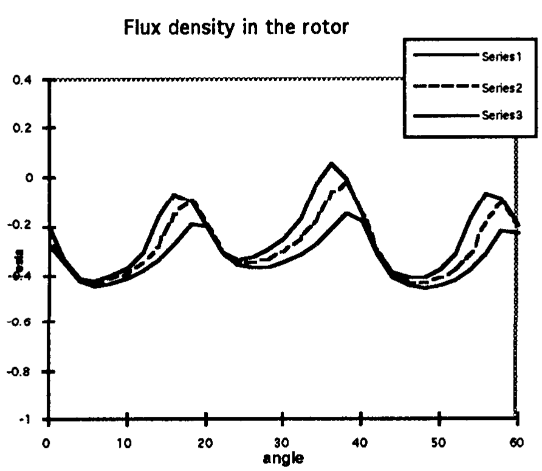

Fig. 3a Flux density in ample elements of the rotor surface: tangential component

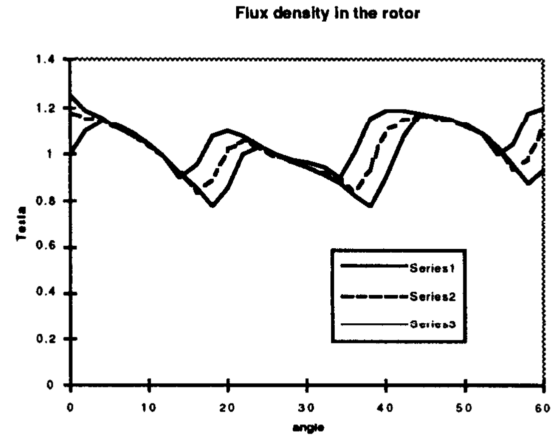

Fig. 3b Flux density in sample elements of the rotor surface: radial component

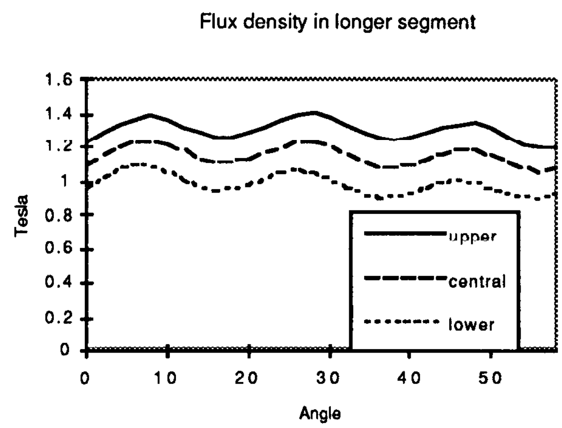

Fig. 4a FLux density in the three portions of the longer rotor segment.

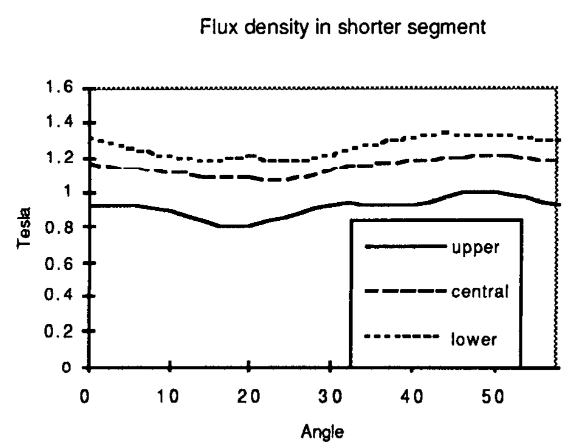

Fig. 4b FLux density in the three portions of the shorter rotor segment.

The stator losses of this machine are summarized in Table III. Because of the irregular distribution of the rotor segments the harmonic content of the flux density in the stator teeth differs from what could be expected. The most important harmonics are found to be the 13th and 15th in the teeth, while the intensity of all the harmonics fades in the stator yoke. The surface losses are calculated separately: as for the rotor, they play an important role in the power dissipation (30%). The percentage is smaller only because the stator iron volume is greater than the rotor volume, but the gap surface is approximately the same. The two components of the flux density in some elements on the tooth top are illustrated in Fig. 5.

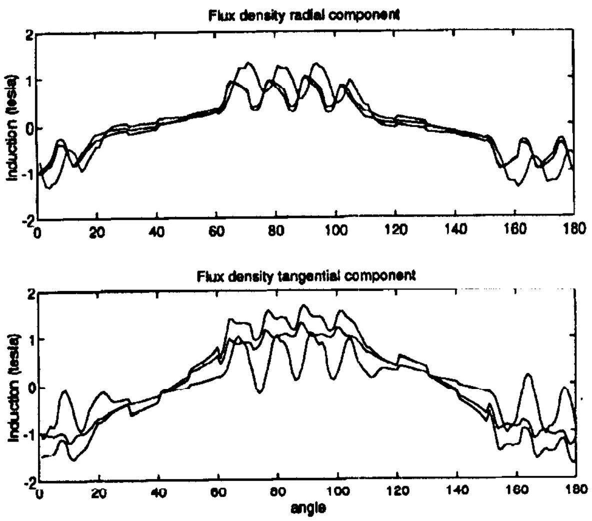

Fig.5 Flux density waveform in some elements of the stator teeth

TABLE III.

STATOR LOSS CALCULATION

	TEETH	YOKE
Fundamental B [T]	1.080	1.024
Loss per pound [w/lb]	36	32
3rd Harmonic B [T]	0.158	0.110
Loss per pound [w/lb]	6	3
13th Harmonic B [T]	0.107	0.032
Loss per pound [w/lb]	41	4
15th Harmonic B [T]	0.100	0.031
Loss per pound [w/lb]	47	5
17th Harmonic B [T]	0.035	0.029
Loss per pound [w/lb]	8	5
Total losses [w]	612	493
Stator surface losses [w]	470	
Stator total losses [w]	1575	

From this set of finite element simulations other important quantities can be calculated such as the torque and the d and q axis inductances. In each case the average value as well as the ripple can be accurately estimated. The torque waveform for this synchronous reluctance generator is shown in Fig. 6.

IV. CONCLUSIONS

A novel method to calculate iron losses based on Finite Element Analysis was presented. The fundamental steps of this method are essentially three: the first is the construction of the 'induction versus time' function for the finiete elements, accomplished through several Finite Element simulations repeated for different rotor positions. The second step is the FFT of the induction functions, to evaluate the harmonic content. The third is the calculation of the losses caused by each harmonic in every element and their final sum.

A simplified version of this calculation is presented. In this case many elements of the finite element model are grouped together to create super elements, with the purpose to reduce the number of stored data and of FFT to perform. The method is suitable for any three phase synchronous machine and was, in this paper, applied to the loss calculation of a synchronous reluctance generator.

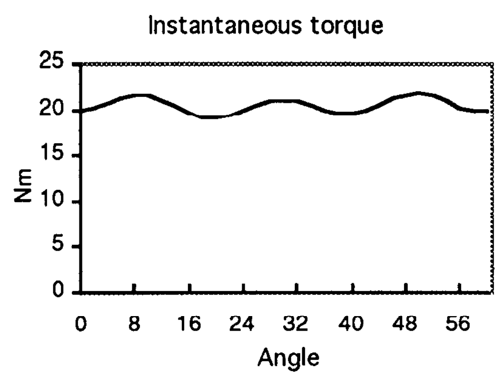

Fig. 6 Instantaneous torque for the test machine

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