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LOSS CALCULATION USING FEM PROGRAM

ABSTRACT *In this study, the authors have concentrated to a cage-induction motor. They compare the loss calculations by FEM (Finite Element Method) magnetic field analyser with the loss measurements made by calorimetric chamber. The FEM program has its problems of working. The material properties and the manufacturing tolerances has to be taken into account using correction factors to the material properties of electric sheets, the current losses are solved by time stepping method and together with the magnetic field solution, but the iron losses are solved after the field analysis. The iron losses have no feedback to the field analysis. At no-load calculations, the cage-induction motor has to have a non-zero slip.*

1. INTRODUCTION

The routine to design an electrical machine needs the knowledge of losses and loss distribution in the machine. There are several ways to define the losses and the loss distribution.

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The standards define the way to make the testing of losses, the temperature corrections of losses, and how the loss components are transferred to the losses of a running machine. These rules are necessary to get a loss standard to compare a real machine with the demands of a customer. The new machine types and the new electrical supplies using power electronics have formed different weighting of loss sources in the machine. The design engineer needs a knowledge about "the real loss values" which are more exact, and knowledge about the sources of the loss components.

The authors have compared loss definitions by measurements: an electric method and a heat dissipation method [1]. The heat dissipation method was chosen according to these comparisons for the present study as the comparison tool. The cooling-air-based calorimetric chamber is manufactured in Electrotechnical Institute. All the loss measurements were made in Electrotechnical Institute. The loss calculations have been made using a FEM analysing program of magnetic fields. The FEM analysing program is developed in Laboratory of Electromechanics. The loss definition was made at steady state operation and analysing the motor operation by time-stepping method, 400 calculation steps per period.

This study concentrates to the problems analysing the measured motor with design data and FEM modelling.

2. FITTING THE ANALYSING FEM MODEL

The losses were analysed using the FEM analysing program developed by Laboratory of Electromechanics to analyse magnetic fields in rotating machines. The analysing model is 2-dimensional. The skewing is not possible to take into account in this analysis.

The target machine was a 5.5 kW cage-induction motor supplied with a sinusoidal voltage when the motor was running at no-load and at different loading conditions. The parameters of the motor are in Table 1. The sinusoidal voltage supply was chosen as a target to simplify the loss definition and to get a base for the discussions about the problems when working with the available tools.

One basic problem was notified in the analysis of the motor when the calculated results were compared with the measured ones. The computer model could not give the correct reactive current component. The problem in the fitting of FEM analysis was the low level of reactive power needed in the analysing model in comparison to the measured one. The stator current was too

small in comparison with the measurements and this complicated the comparison of the winding loss calculations with measured ones.

TABLE 1
Parameters of motor

Output P_N	5.5 kW		
Voltage U_N	380 V	Connection	Delta
Current I_N	11.6 A	Torque T_N	36.2 Nm
Frequency f_N	50 Hz	Slip s_N	3.33 %
Efficiency η	85.5 %	Power factor	0.84

The error was tried to compensate by changing the magnetic state of the motor in the analysis, e.g. increasing the saturation of the flux paths in modelling cross-section of motor. The most obvious reason for the difference between the material properties of iron sheets used in the computer model and the real properties of the motor is the manufacturing tolerances. The best choice to solve the problem is by approximating the changing in filling factor of the core. As a result, the core of the motor is modelled like using different reluctivity function of iron sheets but having the real reluctivity function of sheet manufacturer as constant.

Two alternatives of filling factor were chosen to present the effect as examples: the original filling factor of the design data $\eta_{fe} = 0.95$ and the "correct" alternative $\eta_{fe} = 0.90$ chosen from the analysed ones. These two models will be presented as A and B versions of the motor in the following discussions.

In Figure 1, the reactive power of motor is presented as a function of slip. The reactive power is presented in proportion to the shaft power. When comparing the characteristics of versions A and B to the measured one, the characteristics B follow the measured characteristics over the whole studied slip area. This is also the reason to name the version B as the "correct" model.

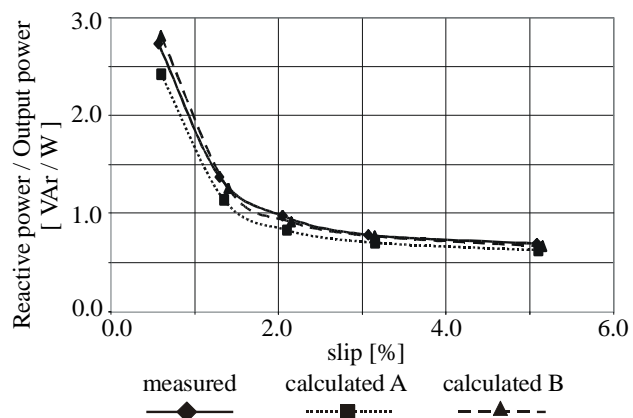


Fig. 1. Reactive input power as a function of slip

3. NO-LOAD CURRENT

The problem of incorrect reactive current in the analysis was studied also at no-load. The calculated and measured no-load currents and the power factors at rated voltage are compared in Table 2. Both the calculated versions were analysed at zero slip.

TABLE 2
No-load characteristics by FEM analysis

	Version A $\eta_{fe} = 0.95$	Version B $\eta_{fe} = 0.90$	Measured
Current I_{0N}	4.74 A	5.53 A	5.88 A
Power factor	0.032	0.040	0.086

The no-load current of version B is about 93 % of measured current. It is possible to get just the right current at no-load from analysis but then the filling factor should be about $\eta_{fe} = 0.88$. This could not be the right solution because the saturation at load is too high. This means too high winding losses at load and the loss definition will come difficult. The better choice should be then to change the leakage reactance by re-dimensioning and to take into account the skewing. This procedure needs more knowledge about the motor series and its measured motors to keep the reality also in the modelling.

As in every measurement tool, also in the analysing tool, there are different problems. The problem described in the previous chapter was one. Another problem came obvious in the field analysis made in previous chapter, the problem of loss definition. The magnetic field solution is solved by time-stepping method at steady state. The currents and the current losses are solved together with the magnetic field solution. But the iron losses both in the stator and in the rotor are solved after the field analysis is done. The iron losses are calculated by conventional loss equations in every triangle element of the FEM model. The flux-density variation of the element is divided to Fourier time series. The iron losses are calculated according to the peak-values of harmonics of the flux-density time-variation. Because of the post-processing, the iron losses have no feedback to the field analysis.

In this study, the error of missing iron losses was taken into account by approximating the iron losses as extra output consumption on the shaft. This means that there comes a new analysing error. The iron losses of stator travel

through the air gap and increase the air-gap power and the rotor current of the motor. The motor was analysed again. The pre-calculated iron losses were included in the needed shaft torque, which should be iterated to get the correct steady state loading and the "correct" loss distribution.

One speciality in this approximation is that the no-load analysis has to be made at non-zero slip. In the case of B version, the effect of the non-zero slip to the "no-load" current was a decreasing current, Table 3. The reason was a better power factor. The decreasing of current was 0.01 A but the increasing of power factor was from 0.040 to 0.093. In the case of A version, the only effect was a better power factor from 0.032 to 0.098.

TABLE 3
"No-load" characteristics by FEM analysis

	Version A $\eta_{fe} = 0.95$	Version B $\eta_{fe} = 0.90$	Measured
Current I_{0N}	4.74 A	5.52 A	5.88 A
Power factor	0.098	0.093	0.086

4. NO-LOAD LOSSES

The zero-slip field analysis, in association with Table 2, gave the detailed loss distribution presented in Table 4. The iron losses are defined after the field analysis, and these losses as well as the rotational losses are not supplied to the stator winding. The iron losses are calculated afterwards from the magnetic field analysis using the Fourier analysis to the flux density time-variation of every triangular element. As a result of this, the stator current as well as the power factor is smaller than needed for the no-load condition of motor. The total losses, P_h in Table 4, include only the losses calculated from the FEM analysis, not the rotational losses ($P_p = 58$ W).

The error of no-load current was taken into account by a new analysis where the iron losses as well as the rotational losses were added as extra power consumption on the shaft. In this approximation, the no-load analysis has to be made at non-zero slip. The new "no-load" field analysis, in association with Table 3, gave the detailed "corrected" loss distribution presented in Table 5.

TABLE 4
No-load losses by FEM analysis

Region	Symbol	Losses [W]		
		Version A	Version B	Measured
Stator winding	$P_{cu1,W}$	64.8	89.9	
Stator yoke	$P_{fe1,y}$	78.9	83.6	
Stator teeth	$P_{fe1,t}$	34.0	34.9	
Stator tooth tips	$P_{fe1,tp}$	7.6	8.1	
Rotor winding	P_{cu2}	19.9	25.3	
Rotor yoke	$P_{fe2,y}$	0.0	0.0	
Rotor teeth	$P_{fe2,t}$	14.6	15.6	
Rotor tooth tips	$P_{fe2,tp}$	29.0	30.7	
Total	P_h	248.7	288.1	276

TABLE 5
"No-load" losses by FEM analysis

Region	Symbol	Losses [W]		
		Version A	Version B	Measured
Stator winding	$P_{cu1,W}$	64.7	89.5	
Stator yoke	$P_{fe1,y}$	78.7	83.4	
Stator teeth	$P_{fe1,t}$	34.0	34.9	
Stator tooth tips	$P_{fe1,tp}$	7.6	8.1	
Rotor winding	P_{cu2}	20.0	25.4	
Rotor yoke	$P_{fe2,y}$	0.0	0.0	
Rotor teeth	$P_{fe2,t}$	14.6	15.6	
Rotor tooth tips	$P_{fe2,tp}$	28.9	30.6	
Total	P_h	248.4	287.5	276

The difference between these two analysis results is very small, almost meaningless. The basic error is in the idea of the power consumption and the power (loss) flow. As a comparison, the total non-rotational losses, P_h , deviates about 4 % in version B from the measured ones.

4. RATED LOAD LOSSES

The rated load condition was analysed also by FEM program using both the A and B versions, see Table 6. Because of the different reactive losses in comparison to the measurements, the analysis target was chosen to fulfil the measured torque as closely as possible. So, the stator current is smaller in the working point in comparison with the measured current. In the operation point, the iron losses and the rotational losses were taken into account by increasing the demanded iterated shaft power in analysis from the value of measured torque.

TABLE 6
Rated load characteristics by FEM analysis

	Version A $\eta_{fe} = 0.95$	Version B $\eta_{fe} = 0.90$	Measured
Current [A]	11.3	11.6	11.3
Power factor	0.859	0.839	0.832
Input power [W]	6400	6400	6440
Slip [%]	3.15	3.15	3.07
Torque [Nm]	35.9	35.7	36.3

The definition of the iron losses was taken into account by iterating the iron losses. The iron losses and the rotational losses were added as extra power consumption on the shaft. The iterative field analysis, in association with Table 6, gave the detailed "corrected" loss distribution presented in Table 7.

TABLE 7
Rated load losses by FEM analysis

Region	Symbol	Losses [W]		
		Version A	Version B	Measured
Stator winding	$P_{cu1,W}$	435	458	
Stator yoke	$P_{fe1,y}$	77	81	
Stator teeth	$P_{fe1,t}$	51	49	
Stator tooth tips	$P_{fe1,tp}$	19	18	
Rotor winding	P_{cu2}	240	244	
Rotor yoke	$P_{fe2,y}$	1.6	1.7	
Rotor teeth	$P_{fe2,t}$	27	27	
Rotor tooth tips	$P_{fe2,tp}$	27	27	
Total	P_h	877	906	907

The accuracy of the total losses in version B in comparison with the measured total losses (without rotational losses P_p) is mainly dependent on the lucky guess of the correction factor called "the filling factor of core". In reality, the filling factor was chosen to give the right loss value at rated load.

5. CONCLUSIONS

This article studied the problems analysing the measured motor with design data and FEM modelling. A cage-induction motor was tested by the heat dissipation method using the calorimetric chamber. The tested motor was analysed by FEM analysis program for magnetic fields using the design data of the motor as initial properties.

Using the FEM analysis, the loss distribution was solved. The FEM analysis defines the iron losses after the field analysis using the Fourier analysis to the flux-density time-variation. The iron losses were taken into the analysis as extra power consumption on the shaft as well as the rotational losses. The material properties in the analysing program were adjusted because the analysis could not give the correct reactive current component at no-load and at loaded conditions. The targets of adjustment were the iron sheet properties, the difference between the properties in the model and the real properties of the motor. The properties were adjusted by changing filling factor η_{fe} for the core, and the analysis was executed by different values of filling factors. From these variants, the model version with filling factor $\eta_{fe} = 0.90$ was noticed to have a better agreement in reactive power and in total losses at rated load with the measurement results defined by heat dissipation method.

LITERATURE

1. Perho J., Ogonowska-Schweitzer E.: Definition of losses. Proceedings of XLI International Symposium on Electrical Machines, 14-17 June, Jarnoltowek, Poland, 2005

OBLICZANIE STRAT ZA POMOCĄ METODY ELEMENTÓW SKOŃCZONYCH

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STRESZCZENIE *W artykule autorzy porównali różne metody określania strat silnika indukcyjnego klatkowego. Porównano straty obliczone metodą FEM (Finite Element Method – Metoda Elementów Skończonych) analizy pola magnetycznego z wynikami pomiaru strat metodą kalorymetryczną. Przedstawiono rozwiązanie problemów występujących w programie obliczeniowym. Własności materiałów oraz tolerancje zostały uwzględnione w obliczeniach za pomocą współczynników dla materiału blach. W programie FEM straty w uzwojeniu obliczano jednocześnie z analizą pola magnetycznego. Straty w żelazie obliczano po przeprowadzeniu analizy pola. W obliczeniach dla biegu jałowego silnika indukcyjnego klatkowego przyjęto, że poślizg nie jest równy zero.*