IEEE TRANSACTIONS ON

ENERGY CONVERSION

A PUBLICATION OF THE IEEE POWER ENGINEERING SOCIETY

SEPTEMBER 1999 VOLUME 14 NUMBER 3 ITCNE4 (ISSN 0885-8969)

ELECTRIC MACHINERY COMMITTEE

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Comparison of standards for determining efficiency of three phase induction motors

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Abstract: The paper describes a set of experiments and discusses their results for determining the efficiency of low voltage, three phase squirrel cage induction motors. The measured efficiency of an induction motor directly connected to the grid, strongly depends on the method used to evaluate the results and the standard according to which the measurements are performed. Different standards as IEEE 112 and IEC 32 are mentioned and their similarities and differences are discussed. The main discrepancies between the various standards is the way in which the values for the stray load losses are obtained at different load levels.
A short description of the measurement setup is given and measurement results for motors of several manufacturers accounting for different standards are proposed. The results clearly demonstrate the necessity to handle the efficiency data given by the manufacturer with a lot of care.

Keywords: induction motor, efficiency, standards, stray load losses

I. Introduction

Three phase, low voltage squirrel cage induction motors are the most common used electric motors in industry. They can be found from a few hundred watts up to several Megawatts. The induction motors are characterized by data provided by the manufacturer as rated speed, power, voltage, current and efficiency. In the past, the efficiency value was of minor importance. Nowadays, with the growing emphasis on energy conservation and the increasing energy prices, the efficiency value has become very important and even dominant for applications in industry. The efficiency values given by the manufacturer are measured or calculated according to certain standards.

PE-441-EC 0-07-1998 A paper recommended and approved by the IEEE Electric Machinery Committee of the IEEE Power Engineering Society for publication in the IEEE Transactions on Energy Conversion. Manuscript submitted August 7, 1998; made available for printing July 2, 1998.

World-wide, there exists several standards for testing electric machinery. For induction motors, the three most important are:

- IEEE Standard 112-1996 [1]
- IEC 34-2 and IEC 34-2A [2]
- JEC

Several national standards are harmonized with regard to one of the three general standards above. The NEMA MG-1-1993 standard and the Canadian standard C390 correspond to the IEEE standard, while in most of the European countries, the standards are harmonized to IEC 34-2. JEC stands for the japanese standard. The efficiency value obtained from the considered testing standards can differ by several percent, as will be shown in the measurement results. Moreover, one standard can contain different methods that do not necessarily lead to one firmly determined value.

All this seems in contradiction with the theoretically simple definition of the efficiency:

$$\eta = \frac{\text{power out}}{\text{power in}} = 1 - \frac{\text{overall losses}}{\text{power in}} \qquad (1)$$

The main difference between the standards emerge from the way in which the stray load losses as a part of the overall losses, are treated. The paper first discusses the different losses with special emphasis to the stray load losses. Then the different standards are discussed for measuring the efficiency of low voltage, three phase squirrel cage induction motors. In the last chapter, the measurement results are discussed, and the efficiency values following the application of the different standards, are compared.

II. Losses in Induction Machines

The losses in a three phase squirrel cage induction machine in motor mode are graphically represented in the Sankey diagram (Fig. 1). The area of the arrows represent the relative importance of the loss components. The measurement of the individual loss components is now discussed in some detail. Special literature exist discussing the tests in great detail as for instance [3,4].

Stator and rotor I^2R losses

The stator copper losses are obtained by measuring the stator resistance at the specified motor temperature and the stator currents at the considered operating point of the machine. The rotor I^2R losses are obtained from the airgap power P_δ and the slip s according to

$$P_{I^2R,2} = s.\,P_\delta \tag{2}$$

Slip measurements must take place at the specified motor temperature and should be corrected to the specified stator temperature as follows [1]:

$$s_s = \frac{s_t\left(t_s + k\right)}{\left(t_t + k\right)} \tag{3}$$

where

s_s slip corrected to the specified stator temperature, t_s
s_t slip measured at the specified stator temperature, t_t
t_s specified temperature for resistance correction [°C]
t_t observed stator winding temperature during load test [°C]

k is a constant depending on the conductivity of the rotor conductor material: 234.5 for 100 % IACS conductivity copper or 225 for aluminium, based on a volume conductivity of 62 %.

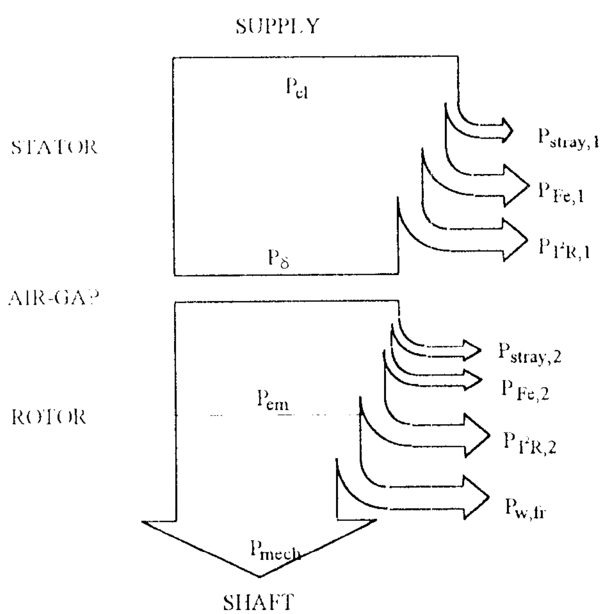

Fig. 1. Sankey diagram of a three phase, squirrel cage induction machine in motor mode

Stator and rotor iron losses

The iron losses consist of eddy current and hysteresis losses in the laminations. They depend on flux density and frequency. The iron losses have almost a constant value in the stator at a given voltage due to the constant frequency in the stator and the constant overall flux level. In the rotor, the iron losses are negligible at rated load as the frequency of the induced currents is very small (slip frequency).

The iron losses can be obtained from the no-load test of the motor at variable voltage after subtracting the windage and friction losses (Fig. 2).

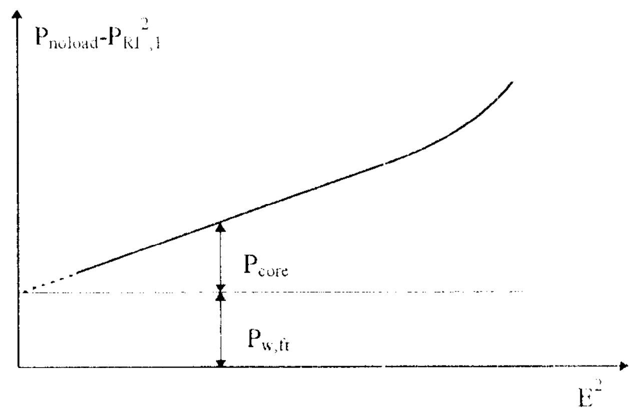

Fig. 2. No Load test

Windage and friction losses

Windage and friction losses are determined by the speed and sometimes by the rotation direction of the motor. They are also obtained from the no-load test of the motor at varying voltages (Fig. 2).

Stator and rotor stray load losses are dealed with in the next paragraph.

III. Stray Load Losses

Stray load losses have been the subject of numerous studies but still are not understood correctly[5-7]. In fact, these are all the losses that are not covered by the above mentioned loss components and therefore, they may be expressed as :

$$P_{stray} = P_{el} - \left(P_m + P_{Fe} + P_{RI^2,1} + P_{RI^2,2} + P_{fr,w}\right) \tag{4}$$

The stray load losses are caused by the space harmonics of stator and rotor and by the leakage flux near the end windings. They can be separated into the following components.

- Flux pulsation losses in stator and rotor teeth; in machines with unskewed slots, the rotor flux pulsation losses are zero.

- Surface losses in the rotor due to space harmonics of the stator and surface losses in the stator caused by the space harmonics of the rotor, the latter being of minor importance.
- I^2R losses in the rotor cage due to rotor currents induced by the hamonics of the flux density.

In the past, several methods have been proposed to measure the stray load losses as the reverse rotation test at slip 2 or half frequency tests at slip -1 and 3. These low power tests make the losses relatively important in comparison with the effectivally generated power.

However, these methods can not be used for determining the efficiency of induction machines. In the next paragraph, it will be explained how the stray load losses are treated in the different standards for testing induction machines.

IV. Standards for Efficiency Measurements

The methods for efficiency measurements can roughly be divided into two categories: direct and indirect methods. The main difference between them is that in the direct methods the torque has to be assessed in one way or another.

Two different standards are discussed: IEEE standard 112 and IEC standard 34-2. The JEC standard totally neglects the stray load losses, and therefore, is irrelevant in the present discussion. It is obvious that motors, tested using the JEC standard will always show a higher efficiency than when tested using IEEE or IEC, already indicating the problem of comparing efficiencies in manufacturer catalogues.

IEEE standard 112-1996

The IEEE 112-1996 consists of five basic methods to determine the efficiency: A, B, C, E and F.

In method A, the input and output power is measured and the efficiency is directly obtained. This method is only used for very small machines.

Method B employs a direct method to obtain the stray load losses. It is not a direct method for determining the motor efficiency. To reduce the influence of the measuring error, a linear regression is made of the stray load losses at different loads, versus the torque squared.

$$P_{stray} = AT^2_{shaft} + B \tag{5}$$

As at zero load the additional stray load losses are zero, the values are corrected by:

$$P_{stray,corr} = AT^2_{shaft} \tag{6}$$

One defines a good measurement if the correlation coefficient of the linear regression is higher than 0.9. Method B is the recommended method for testing of induction machines up to 180 kW.

Method C is a back to back machine test. The total stray load losses are also obtained via a separation of losses for both motor and generator. The stray load losses are then divided between the motor and generator proportional to the rotor currents.

Method E and method E1 are indirect methods, the output power is not measured. In method E the stray load losses are directly measured using the reverse rotation test. In method E1, the stray load losses are set to an assumed value. These values are given in table 1 as a percentage of the rated output power.

In method F and F1, the equivalent circuit of the machine is used. The stray load losses are again directly measured or in the case of F1 an assumed value is used.

There also exist some additional methods as e.g. the use of the equivalent circuit but calibrated at a load point.

TABLE I
ASSUMED VALUES FOR THE STRAY LOAD LOSSES AS A PERCENTAGE OF THE RATED OUTPUT.

Motor rated power	Stray load losses relative to the output power
0.750 - 90 kW	1.8 %
91 - 375 kW	1.5 %
376 - 1800 kW	1.2 %
1800 kW and higher	0.9 %

Motors with ratings higher then 180 kW can be tested using methods B, C, E, E1, F or F1.

IEC 34-2

The efficiency measurement of a polyphase induction machine is performed by determining the overall losses of the induction machine. The overall losses can be obtained from the summation of the separated losses (see paragraph II) or from the measurement of the overall losses. Overall loss measurements according to IEC 34-2 can be made by:

- braking test with torque measurement
- calibrated machine test
- mechanical back to back test
- electrical back to back test

However, the method preferred by IEC 34-2 is the determination of the separated losses. Constant losses as core losses and windage and friction losses and stator and rotor losses are obtained as described in paragraph II. Regarding stator and rotor conductor losses no corrections for the temperature of the windings are made.

The stray load losses are assumed to be 0.5 percent of the rated input power for motors at rated load and to vary as the square of the stator current. The assumed percentage does not depend on the motor rated power. Comparison of this value with the values of Table 1 already shows a large difference for the stray load losses between IEEE and IEC.

It is generally known that the amount of stray load losses can be several percent and will be confirmed by measurement results furtheron. The efficiency values in the catalogues according to IEC are thus overestimated. When comparing the 0.5 % to the values of Table 1, the stray load losses using the IEEE standard are higher than those using the IEC. The IEC efficiency thus is higher than the IEEE value.

V. EXPERIMENTAL RESULTS

Experimental setup

The experimental setup for testing induction machines up to 100 kW at 1500 rpm is shown in Fig.3. The machine is loaded by a DC motor equiped with a four quadrant rectifier feeding the energy back to the supply. The test rig is also intended to be used for assessing the efficiency of speed controlled, inverter supplied induction motors.

The input power, input voltages and currents are measured using voltage and non-contacting current probes, and the signals are digitally processed. The input power accuracy is 0.4 %. The system is capable to handle non-sinusoidal quantities, again with the aim of treating inverter supplied drives.

The output torque is measured with a high precision torque transducer based on strain gauges. The speed is assessed with a high accuracy speed transducer. The overall accuracy of the output power is better than 0.5 %. To avoid measuring errors introduced by slip ring arrangements for transporting the measuring signals to the stationary recording equipment, a non-contacting transmitting system is used, that also supplies the power to the strain gauge measuring bridge. A battery supply is not required, avoiding the eccentricity problems and yielding a safer and more reliable measuring system.

The measured data are read in a computer equipped with a LabView® based data acquisition system. The processing of the measurement data is fully automised.

The motor under test is first operated at low load in order to loosen the bearings. Then motor is loaded at rated load until thermal equilibrium is reached. The required operating points are set (25, 50, 75, 100 and 125 % of the rated load).

The no-load test, performed at different values of the stator voltage, is used to find the value of the mechanical losses.

For squirrel cage induction machines under test, the efficiency is evaluated in four different ways. The first is the direct method as expressed by (1). Then the results of the experiments are used to get the efficiency values according to IEEE standard 112 method B, IEC 34-2 and JEC. Although the measurement data are the same, the efficiency values will differ substantially. The main reason for these differences are the different definitions of the stray load losses, except for the losses in the stator and rotor losses that are slightly different, due to the applied temperature corrections. The latter differences are very small and are not taken into account in the table.

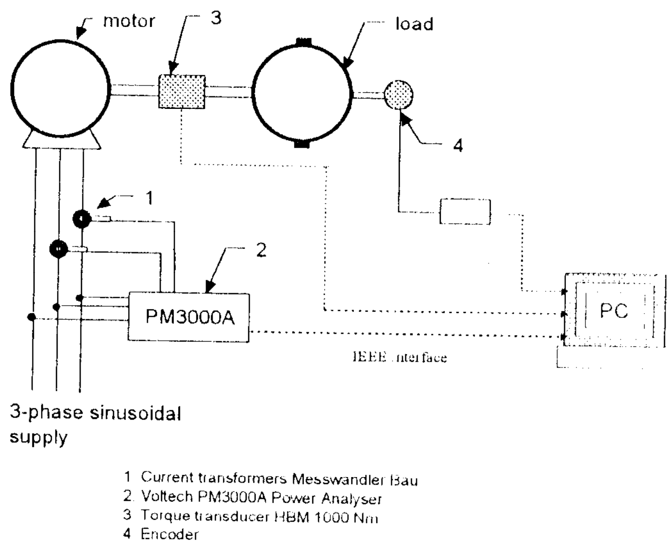

Fig 3. Experimental setup

Practical results

From two different manufacturers, three standard 75 kW, six pole types and rated voltage 400 V are tested. The stators are Δ-connected. Table 2 gives the detailed results for one specific motor from manufacturer 1.

From these results, it becomes evident that the way the efficiency is defined, has a significant influence on the efficiency as stated in the catalogues. The difference may be as large as 2 % at full load between the real efficiency value (direct evaluation of the input and output power) and the JEC value, neglecting all stray load losses. The efficiency as defined by IEEE 112 method B are very close to the actual values, measured directly. Therefore, the definition of the stray-load losses in the IEEE standard is close to the actual values. The measuring error for the efficiency is evaluated to be maximally 0.9 %. Therefore, the IEC and even more the JEC values are out of the tolerance.

In Fig. 4 the measured stray load losses are plotted versus the torque squared.

TABLE 2
EFFICIENCY OF A STANDARD 75 KW SQUIRREL CAGE INDUCTION MOTOR ACCORDING TO THE DIRECT MEASUREMENT, THE IEEE 112 METHOD B, IEC 34-2 AND JEC

Load	25 % load	50 % load	75 % load	100 % load
$U_{average}$ [V]	407.8	404.7	400.2	391.3
$I_{average}$ [A]	71.4	91.2	118.1	149.6
P_{el} [W]	22270	41820	61850	81360
Power Factor [-]	0.44	0.65	0.76	0.80
T [Nm]	182.2	364.0	548.3	723.3
n [rpm]	997	995	994	991
P_{shaft} [W]	19021	37924	57078	75064
slip [%]	0.3	0.5	0.6	0.9
P_{loss} measured directly [W]	3249	3896	4772	6296
$P_{RI^2,1}$ [W]	354	578	968	1553
P_{core} [W]	1774	1728	1660	1527
$P_{RI^2,2}$ [W]	60.4	198	355	705
$P_{w,fr}$ [W]	910	910	910	910
P_{stray} from eq.(4) [W]	151	482	879	1601
P_{shaft}/P_{rated} [%]	**25.4**	**50.6**	**76.1**	**100.1**
Efficiency Direct [%]	**85.4**	**90.7**	**92.3**	**92.3**
Efficiency using IEEE-112. Linear regression coefficient. Slope: 2.802 10^{-3} Correlation: 0.99				
$P_{stray\ corr}$ [W]	93	371	843	1466
$P_{loss\ corr}$ [W]	3191	3785	4736	6161
$P_{shaft\ corr}$ [W]	19079	38035	57114	75199
P_{shaft}/P_{rated} [%]	**25.4**	**50.7**	**76.2**	**100.3**
Efficiency IEEE-112 [%]	**85.7**	**90.9**	**92.3**	**92.4**
Efficiency using IEC 34-2				
P_{stray} [W]	93	151	253	407
P_{loss} [W]	3191	3565	4146	5102
P_{shaft} [W]	19079	38255	57704	76258
P_{shaft}/P_{rated} [%]	**25.4**	**51.0**	**76.9**	**101.7**
Efficiency IEC 34-2 [%]	**85.7**	**91.5**	**93.3**	**93.7**
Efficiency using JEC				
P_{stray} [W]	0	0	0	0
P_{loss} [W]	3098	3414	3893	4695
P_{shaft} [W]	19172	38406	57957	76665
P_{shaft}/P_{rated} [%]	**25.6**	**51.2**	**77.3**	**102.2**
Efficiency JEC [%]	**86.1**	**91.8**	**93.7**	**94.2**

Table 4 makes the comparison for manufacturer 1 between the efficiency value given in the catalogue and the measured IEEE and IEC values.

Table 5 gives the results for manufacturer 2. For manufacturer 2 results from IEC and IEEE were equal within the limits of measurement accuracy.

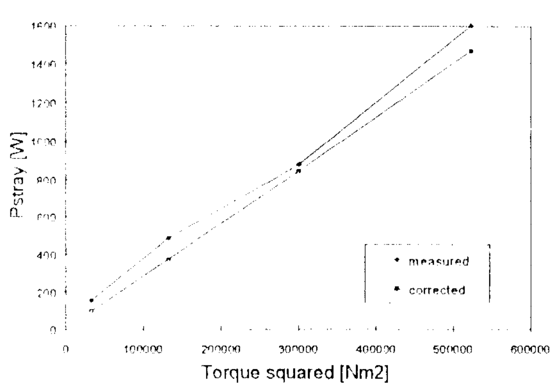

Fig 4. Stray load losses versus torque squared

TABLE 4
RESULTS FOR MANUFACTURER 1 (6 POLE 75 KW)

Load		100 % load	75 % load	50 % load
IEC Catalogue		94.7	94.7	92.7
Motor 1	IEC	93.7	93.3	91.5
	IEEE	92.4	92.3	90.9
Motor 2	IEC	93.9	93.6	92.3
	IEEE	92.6	92.6	91.8
Motor 3	IEC	93.7	93.2	91.9
	IEEE	92.3	92.2	91.2

TABEL 5
RESULTS FOR MANUFACTURER 2 (6 POLE 75 KW)

Load		100 % load	75 % load	50 % load
IEC Catalogue		94.7	94.7	93.6
Motor 1	IEEE	93.3	93.7	92.9
Motor 2	IEEE	93.2	93.4	92.5
Motor 3	IEEE	93.5	93.8	93.0

C Discussion of the measurement results

The results clearly show that at rated load for manufacturer 1, there is a difference up to 2.5 percent between the catalogue values and the values according to IEEE 112 and up to 1 percent between the measured IEC and the catalogue IEC values. For manufacturer 2, the difference is 1.4 between measured IEC and IEEE values and the catalogue value. However, having the same catalogue efficiency, the motors of manufacturer 2 deliver a higher mechanical output. All motors were brand new and have been loaded for several hours before testing. The temperature of the windings was the same and also the environmental temperature did not change.

VI. Conclusions

It has been shown that the efficiency value of an induction motor is not unequivocal, but depends on the standard used. The European IEC and the Japanese JEC standard almost always overestimate the efficiency. According to IEC and JEC, motors from different manufacturers have the same efficiency, while in fact, there are differences, that are determined by the stray load losses. The extend of these losses depends on the design of the machine and the quality of the manufacturing process. The value is higher than the 0.5 percent of IEC or the zero percent of JEC. All this leads to the conclusion that one should work towards a worldwide uniform standard for the testing of electrical machines.

Due to the constant improvement in the accuracy of measurement equipment and especially of torque transducers, the indirect method should whenever possible be abandoned in favor of the direct method as IEEE 112 - B

VII. Acknowledgment

The authors are grateful to the Belgian "Fonds voor Wetenschappelijk Onderzoek Vlaanderen" for its financial support of this work and the Belgian Ministry of Scientific Research for granting the IUAP No. P4/20 on Coupled Problems in Electromagnetic Systems. The work is sponsered by Electrabel Laborelec.

VIII. References

[1] "IEEE Standard Test Procedure for Polyphase Induction Motors and Generators," *IEEE Std 112-1996*, IEEE Power Engineering Society, New York, NY.

[2] "Rotating electrical Machines - Methods for determining losses and efficiency of rotating electrical machines from tests," *IEC Std 34-2:1972*.

[3] W. Nürnberg, R. Hanitsch, *"Die Prüfung elektrischer Maschinen,"* Springer-Verlag, 1987.

[4] *"Handbook of electric motors"*, ed. by Richard H. Engelmann, William H. Middendorf, Marcel Dekker Inc, 1995.

[5] F. Taegen, R. Walczak, "Experimental verification of stray losses in cage induction motors under no-load, full-load and reverse rotation test conditions," *Archiv für Elektrotechnik*, Vol 70, pp 255-263, 1987.

[6] F. Taegen, R. Walczak, "Eine experimentell überprüfte Vorausberechnung der Oberfelder von Käfigläufermotoren," *Archiv für Elektrotechnik*, Vol 66, pp 233-242, 1983.

[7] A.A. Jimoh, R.D. Findlay and M. Poloujadoff, "Stray losses in induction machines: Part I, Definition, Origin and Measurement," *IEEE Trans.on Power Apparatus and Systems*, Vol. PAS-104, No. 6, pp 1500-1505, June 1985.

[8] N. E. Nilsson, " A comparison of ANSI and IEC standards for power station polyphase induction motors," *IEEE Transactions on Energy Conversion*, VOL. 11, No. 3, pp 500-507, September 1996.

[9] Gerald G. Gray, Walter J. Martiny, " Efficiency testing of medium induction motors, a comment on IEEE Std 112-1991, " *IEEE Transactions on Energy Conversion*, VOL. 11, No. 3, pp 495-499, September 1996.

IX. Biographies

Bruno Renier received the M.S. degree in electrical engineering in 1995 from the Katholieke Universiteit Leuven, Belgium. Since September 1995 he is working at the research group Electrical Energy of Prof. R. Belmans at the same university. His interests are focused on the use and implementation of electrical machines and drives. Currently, he is working towards a Ph.D. degree on the influence of field and time harmonics on the losses in squirrel cage induction motors.

Kay Hameyer (M' 1995) received the M.S. degree in electrical engineering in 1986 from University of Hannover, Germany. He received the Ph.D. degree from University of Technology Berlin, Germany, 1992. From 1986 to 1988 he worked with the Robert Bosch GmbH in Stuttgart, Germany, as a design engineer for permanent magnet servo motors. In 1988 he became a member of the staff at the University of Technology Berlin, Germany. From November to December 1992 he was a visiting professor at the COPPE Universidade Federal do Rio de Janeiro, Brazil, teaching electrical machine design. In the frame of a collaboration with the TU Berlin, he was in June 1993 a visiting professor at the Université de Batna, Algeria. Beginning in 1993 he was a scientific consultant working on several industrial projects. From 1993 to March 1994, he held a HCM-CEAM fellowship financed by the European Community at the Katholieke Universiteit Leuven, Belgium. Currently he is professor for numerical field computations with the K.U.Leuven and a senior researcher with the F.W.O.-V. in Belgium, teaching CAE in electrical engineering and electrical machines. His research interests are numerical field computation, the design of electrical machines, in particular permanent magnet excited machines and numerical optimization strategies. Dr. Hameyer is member of the International Compumag Society.

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