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Design Optimization of Single-sided Axial Flux Permanent Magnet Machines by Differential Evolution

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***Abstract*—In this paper, a design optimization approach for single-sided axial flux permanent magnet (AFPM) machines using a differential evolution algorithm for is presented. The objectives of the design optimization are to maximize the output torque per unit cost (Nm/$) and maximize the efficiency. A paremetric 2-D FEA model of an AFPM is built. A sensitivity study of design variables is carried out to determine the correlation between the design variables and the objectives, enabling the removal of insignificant design variables. Design constraints including geometrical and operating limits are considered. A total of five independent variables are employed in the optimization process. The optimization result is compared with a prototype design and results verified by 3-D FEA simulations.**

***Index Terms*—axial flux permanent magnet (AFPM) machines, design optimization, differential evolution, sensitivity study.**

I. Introduction

Axial flux permanent magnet (AFPM) machines have gained much attention because of their disc shaped structure and low volume, which make them suitable for traction systems such as in hybrid vehicles [1].

Much work has been done concerning machine design optimizations. In [2], [3], an analytical procedure for the design of a surface mounted PM machine using binary genetic algorithm in order to optimize a single objective function of material cost is proposed. In [4], [5], a multi-objective optimization of a 48 slot/4 pole IPM motor with three barriers per pole is presented. The objective is both optimizing the torque and the saliency to obtain a good performance in sensorless control. The optimization is carried out using an FEA model and a binary genetic algorithm. A weighted sum method is used,thus the multi-objective function reduces to a single objective problem. In [6], the optimization design of an IPM motor is presented using an FEA-based multi-objective genetic algorithm (MOGA). In [7], the author includes rotor losses in the optimization process an additional cost function. In [8], first a global search MOGS is carried out first. After that one solution machine is selected manually from the Pareto front on the basic of its performance, for a local search.

The implementation of a differential evolution algorithm in electrical machine design optimization has been studied recently in [9]–[16]. Most of this work focuses on radial flux permanent magnet machines. In [9], a multi-objective optimization for an IPM motor based on the differential evolution and finite element model is presented. The objective is to minimize active volume and while maximizing the power output in the flux weakening area. In [10], an optimal design practice for an IPM machine with a modular stator structure based on finite element analysis (FEA) and different evolution is discussed. Both a single and a multi-objective of maximize the torque and minimum THD of back EMF process is implemented. In [11], an automated machine design process with differential evolution techniques is proposed to maximum the torque and efficiency. In [12], [13], a bi-objective optimization of a PM machine with 11 parameter variables using computationally efficient-FEA and differential evolution, to minimize torque ripple and maximize the torque per unit volume is presented. Four different machine topologies are evaluated by comparing their Pareto-optimal design sets. In [14], a multi-objective optimization of a surface PM motor with 5 variables is used to minimize of total weight and maximize a goodness function, which is defined as torque per root square of losses at rated load. The results using differential evolution(DE) is compared with results using the response surface(RS) method. It is shown that DE has a better capability for dealing with a large number of candidate designs. In [15], an optimal design by differential evolution of a surface PM machine with 8 variables and the objective of minimzing the cost of active materials per unit efficiency is presented. Stopping criteria for the DE algorithm are discussed based on both the solution space and thedesign space. In [16], a combined design of Design of Experiments and DE is implemented for the optimization of a 12 slot,8 pole, spoke type ferrite permanent magnet machines.

This paper will provide insights into the design optimization for axial flux machines by means of a multi-objective differential evolution algorithm. A sensitivity study of the design variables is studied. A total of five independent significant variables are employed in the design. Design objectives are to maximize the output torque cost(Nm/$) and efficiency. Optimization results are compared with a prototype design.

II. Parametirc FEA Model of Single-sided Axial Flux PM Machines

The flowchart of the whole optimization process is shown in Fig. 1.

The target machine used as a prototype integrated starter-alternator for hybrid vehicles. The rated torque is 22.8 Nm and the rated speed is 2800 rpm, corresponding to a output of 6.7 kW. The machine is designed to have a per-phase peak open circuit back EMF voltage of 148 V at rated speed. This prototype machine was previously designed by analytical calculation but not optimized.

Ideally the FEA model should be in 3-D to better evaluate the performances as in Fig. 2, however, due to the computation time, 2-D model is used in the optimal design with transient solution. The simulation results of 2-D FEA will be verified and compared with 3-D simulations.

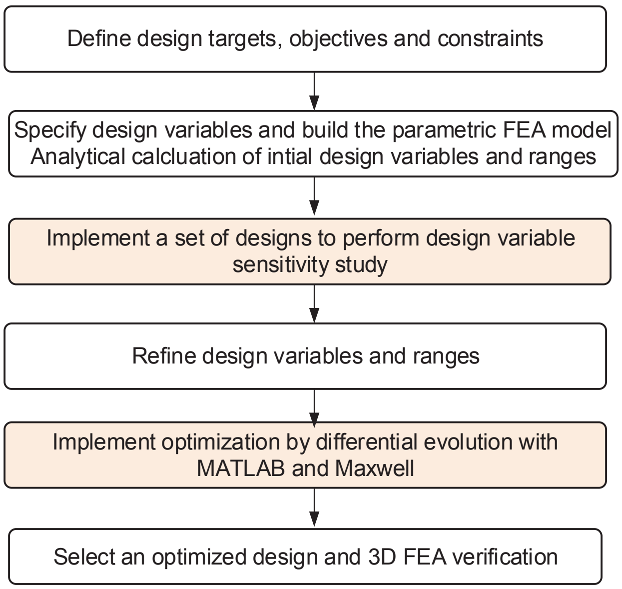

Fig. 1. Flow chart for the optimization process

The approach to model the AFPM in 2-D is to view the machine from the side. The geometry is a cylindrical cross-section taken at the average radius as shown in Fig. 2. Rotational motion is assigned to model it as a very small portion of a radial flux machine with a very large radius (e.g. 100 m). Depending on the number of slots and poles, only a fraction of the machine is modelled. For the 24 slot/22 pole machine, the 2-D model contains 12 slots and 11 poles. The symmetric multiplier is 2 with the master and slave boundary conditions applied.

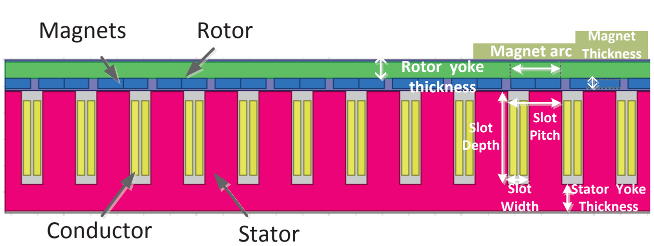

Fig. 2. 2D-FEA Model of a 24 slots/22 poles double layer winding AFPM

The 2D-FEA model of the machine is shown in Fig. 2. These seven variables are slot depth, slot width to slot pitch ratio, stator back iron thickness, magnet thickness, magnet arc to pole pitch ratio, rotor back iron thickness and split ratio, which is defined as the ratio of stator inner diameter to the stator outer diameter.

TABLE I
DESIGN VARIABLES AND RANGES

		Variables	Range	Unit
x1	Sd	Slot Depth	[25, 45]	*mm*
x2	K_{sw}	Slot Width Ratio	[0.3, 0.8]	
x3	T_{sy}	Stator Back Iron Thickness	[8, 20]	*mm*
x4	T_{mag}	Magnet Thickness	[3, 5]	*mm*
x5	K_{magarc}	Magnet Arc Ratio	[0.5, 0.9]	
x6	T_{ry}	Rotor Back Iron Thickness	[5, 15]	*mm*
x7	K_{Split}	Split Ratio	[0.5, 0.7]	

III. DESIGN OBJECTIVES AND CONSTRAINS

The purpose of the optimal design is to design a machine with high efficiency and low cost with a torque requirement of 22.8 Nm to guarantee the 6700 W output power.

Two objectives are considered to maximize the torque cost (Nm/\$) and the efficiency:

$$
\begin{aligned}
&\text{maximize}: \\
&f1 = \frac{T_{em}}{C_{Mag} + C_{Steel} + C_{Copper}} \\
&\text{maximize}: \\
&f2 = \frac{P_{output}}{P_{output} + P_{statorloss} + P_{rotorPMloss} + P_{copperloss}}
\end{aligned}
\tag{1}
$$

in which, $C_{Copper}, C_{Steel}, C_{Mag}$ are the cost of used copper, steel and magnets. The unit costs used for copper, steel and magnets are 10\$, 1\$ and 100\$ per kg. P_{output} is the output power,$P_{statorloss}$ is the stator core loss, $P_{rotorPMloss}$ is the eddy current loss in rotor back iron and magnets, $P_{copperloss}$ is the copper loss.

There are some geometry constrains. The stator outer diameter is fixed at 196 mm, and the airgap is fixed at 1 mm. Current density is fixed at 4.1 A/mm^2 to ensure equal thermal capability. The maximum stator tooth and back iron flux is 1.5 T.

There are two operating limits. The per phase peak open circuit back EMF is 148 V. The output torque should be 22.8 Nm at the rated condition. During the optimization process, for each design with randomly generated geometry parameters, first the number of turns per phase needs to be adjusted to match the back EMF requirements. The output torque of the design should be not be either too small or too large for a fair comparison, it should be within the range of 22 Nm to 24 Nm to meet the power requirements.

IV. DESIGN VARIABLES SENSITIVITY STUDY

In order to see how the design variables affects the performance as measured by design objectives, a set of designs are produced for comparison. Generally the design of experiment (DOE) approach is utilized during the process. However, in this case, by setting the design variables using DOE, the desired output torque could not be guaranteed to be in the acceptable range. Thus a set of designs which could meet the requirement are randomly generated.

Then a neural network is used to generate the prediction profile to predicting the relationship between the design variables and the objectives. A set of 800 suitable designs were generated and the resultant objective functions plotted in Fig. 3. and Fig. 4.

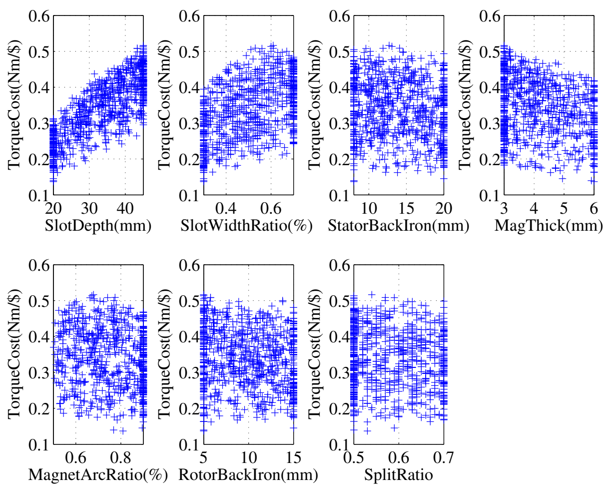

Fig. 3. Design Variables vs TorqueCost (Nm/$)

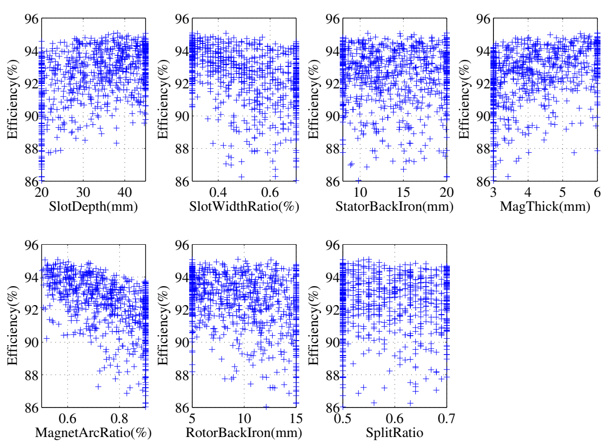

Fig. 4. Design Variables vs Efficiency

The Spearman's rank correlation coefficient is a statistical measure of the influence between the input variables and the outputs [15]. The value is from -1 to 1. Higher absolute value means strong correlations. A positive value indicates an increase in input will cause an increase trend in that output; a negative value indicates a decrease trend. Values closer to zero mean weak correlations. From Fig. 5 and Fig. 6, it could seen that stator back iron and rotor yoke back iron have consistantly less influence on these two objectives. From Fig. 7, it indicates that the changes of stator back iron and rotor back iron has a very low influence on the design objectives. This is reasonable since stator back iron and rotor back iron does not have any direct influence on the electric and magnetic loading.

Based on these observations, only five variables are considered for the optimization, which are Sd, K_{sw}, T_{mag}, K_{magarc}, T_{ry} and K_{Split}.

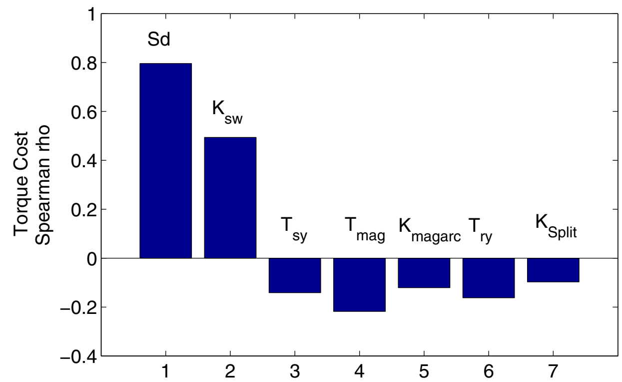

Fig. 5. Sensitivity study for TorqueCost

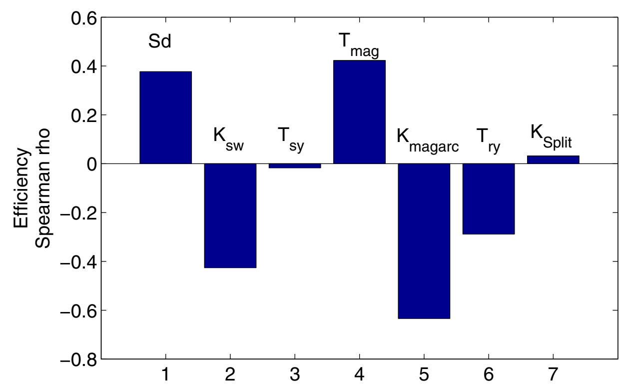

Fig. 6. Sensitivity study for Efficiency

V. Differential Evolution and Optimization Results

A. Differential Evolution

The differential evolution algorithm is selected to perform the optimization since it has been shown that DE is far more efficient and robust than particle swarm optimization and other evolutionnary algorithms [17]. The population size for the differential evolution is 17, the generation size is 6, which leads to total of 102 designs. Cr is 0.7122, Fr is 0.6301, these parameters are defined in [18]. In this optimization, the number of designs is limited due to computation time.

B. Optimization Results

Fig. 8 shows the optimization results and the plotted Pareto front. A chosen optimized, labeled M1,a solid purple dot, is selected. The solid blue dot is the reference prototype machine.

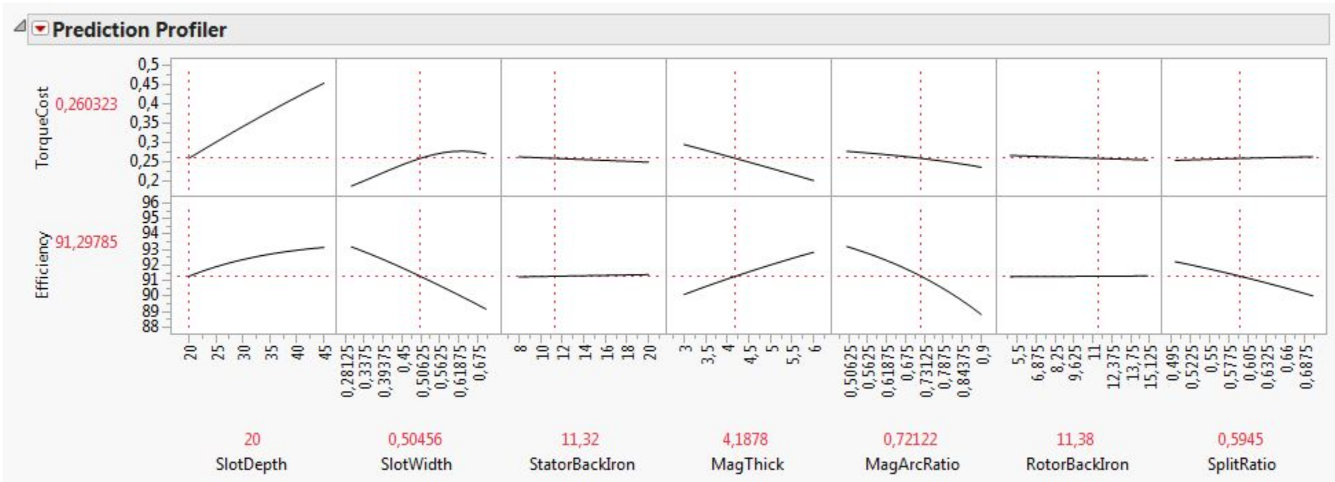

Fig. 7. Prediction profiler for design variables vs design objectives

It can be seen that the torque/cost (Nm/$) is improved, the cost is reduced by 17 % and the efficiency is improved by 2 %.

From the Table II, it can be seen that in the optimized design, the slot depth is increased, and magnet arc ratio is decreased compared to the initial design. The previously presented sensitivity study indicates a larger slot depth and a smaller magnet arc leads to better designs, while the other three variables, slot width, magnet thickness, and split ratio have conflicts with these two objectives, which requrie compromise.

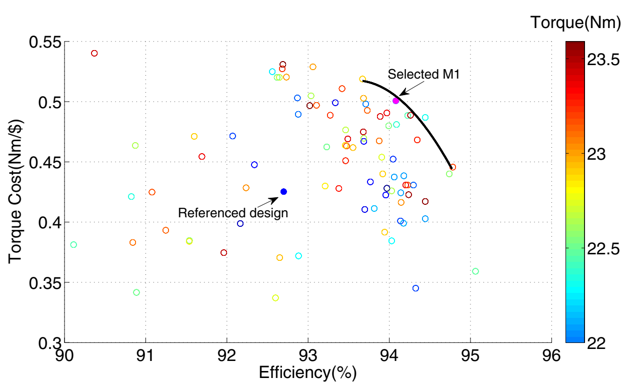

Fig. 8. Optimization results

C. Verification by 3-D FEA Simulations

The results of optimized design resulting from 2-D FEA simulations are verified by 3-D FEA simulations to more accurately evaluate the performance.

The 3D simulation results for open circuit phase back EMF at 2800 rpm is about 148 V, which meets the requirement, is shown in Fig. 10 and rated torque in Fig. 11 is 22.23 Nm which is in the design range.

From Table III, comparing the simulation results obtained using both 2-D and 3-D FEA model, it can be deduced that it is sufficient to use 2-D FEA to perform the optimization process which greatly reduces the computation time.

TABLE II
OPTIMIZATION RESULTS

	Variables	**Initial Design**	**Optimized-M1**	*Unit*
x1	Slot Depth	35	41.67	*mm*
x2	Slot Width Ratio	0.3918	0.374	-
	Slot Width	8	7.46	mm
x3	Magnet Thickness	4	3.0	*mm*
x4	Magnet Arc Ratio	0.85	0.616	-
x5	Split Ratio	0.5918	0.555	-
	Stator Inner Diameter	116	110	mm
	Performance	**Initial Design**	**Optimized-M1**	*Unit*
	Torque Cost	0.4253	0.5007	*Nm/$*
	Efficiency	92.38 %	94.08 %	-
	Max Tooth Flux	1.33	1.10	T
	Max Back Iron Flux	1.07	0.86	T
	Copper Loss	95.67	112.48	W
	Stator Core Loss	180.15	153.24	W
	Rotor and PM Loss	274.98	143.87	W
	Output Torque	23	22.2	Nm

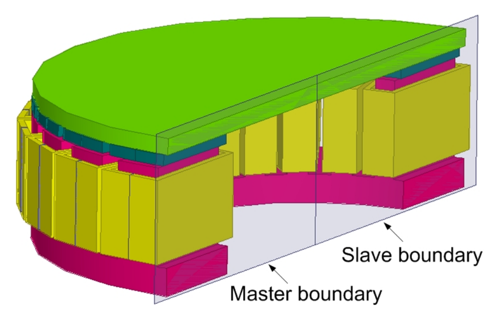

Fig. 9. 3D-FEA Model of a 24 slots/22 poles double layer winding AFPM

VI. CONCLUSION

In this paper, a design optimization approach using a differential evolution algorithm for single-sided axial flux permanent magnet (AFPM) machines is implemented. A design variables sensitivity study is used first to analyzing the correlation

TABLE III
OPTIMIZATION RESULTS

Results Comparision	**2-D FEA**	**3-D FEA**	*Unit*
Open Circut Phase Back EMF (peak)	153.5	148.6	V
Rated Torque	22.64	22.23	Nm
Torque Ripple	3.97 %	2 %	
Stator Core Loss	153.24	161	W
Rotor and PM Loss	143.87	132	W

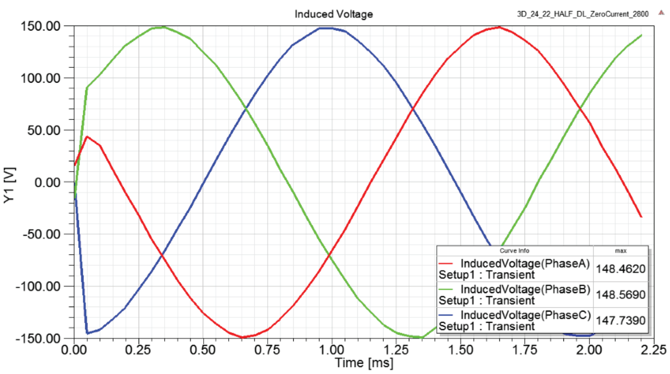

Fig. 10. Open circuit phase back EMF at 2800 rpm

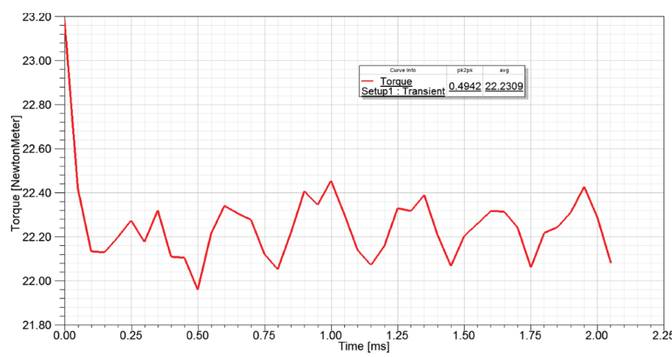

Fig. 11. Rated torque at 2800 rpm

between design variables and design objectives. This provides insights into the design optimization of axial flux machines.

In the future, the relation between each design variables for the target back EMF and torque requirements will be investigated in details. The machine optimized has fixed slot/pole numbers. The broad concept of an optimized machine should include different slot/pole combinations. The number of slots and poles will be included in the final work.

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VII. BIOGRAPHIES

Xu Yang(S’07) received the B.S. degree in electrical engineering from Wuhan University, Wuhan, China in 2007, the M.S degree from the Polytechnic Institute of New York University in 2009 and the Ph.D. degree from University of Univerisity of Nebraska-Lincoln in 2013.

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Dean Patterson (F'07) was born in Adelaide, South Australia. He received the Ph.D. degree from the University of Adelaide.

In 1984, he went to what was to become the Charles Darwin University in the northern Australian city of Darwin. He set up the four-year undergraduate degree program, a graduate degree program, and the established a research focus in the area of solar and alternative energy. He developed a high performance electric traction system for solar powered vehicles. In 2001, he moved to the USA, to the University of South Carolina as a Research Professor, working on the electric ship program of the US Navy, and in 2004, he was invited to the University of Nebraska-Lincoln, to help set up courses in Energy Studies. His spin-off company from the Charles Darwin University, specializing in very high efficiency electric machines, was bought in 2006 by FASCO, who were more recently acquired by Regal Beloit. He now divides his time between the company and the university. He is the author of more than 100 technical papers.

He has been very active in the IEEE Power Electronics Society, having served as its president 2003, 2004.

Jerry Hudgins (F'04) received the Ph.D. degree in electrical engineering, in 1985, from Texas Tech University, Lubbock, TX.

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Dr Hudgins was the President of the IEEE Power Electronics Society(PELS) for the years of 1997 and 1998 and President of the IEEE Industry Applications Society(IAS) for 2003.