Automation of finite element aided design of induction motors using multi-slice 2D models

D.R. Griffiths
FR-HiTEMP Limited, Fareham, UK, and
J.K. Sykulski
EPE, School of ECS, University of Southampton, Southampton, UK

Abstract

Purpose – To develop a practical design tool employing a general purpose electromagnetic finite element (FE) software package to perform automated simulation and performance analysis of induction motors in a design and optimisation process.

Design/methodology/approach – Recent publications identified a suitable approach in applying 2D finite-element analysis to 3D problems. This, together with other similar work carried out on brushless DC motors, set out a framework for program development. Performance of the program was validated against practical test data.

Findings – Finite-element analysis-based design tools can be realistically employed within a design office environment and are capable of providing solutions within acceptable time scales. Such tools no longer require user expertise in the underlying FE modelling method. The multiple slice technique was employed to model skew in three-phase induction motors and it was established that a four-slice model provides a good balance between accuracy and speed of computation.

Research limitations/implications – Program development was based on one commercial FE software package and comparison with practical test data was not exhaustive. However, the approach outlined confirms the practical application. Future work could consider alternative approaches to optimisation.

Practical implications – Computing hardware and commercially available 2D FE software have developed sufficiently to enable multi-slice techniques and optimisation to be employed in the analysis and design of machines.

Originality/value – This paper provides a practical illustration of how commercial electromagnetic software can be employed as a design tool, demonstrating to industry that such tools no longer need to be bespoke and can realistically be used within a design office.

Keywords Finite element analysis, Computer aided design, Electric machines, Induction, Optimization techniques, Skewness

Paper type Research paper

1. Introduction

Performing a full 3D transient finite element (FE) analysis, however desirable, often requires significant levels of computational effort to the extent that its use within the design office environment may be unacceptable. The alternative 2D analysis is known to provide solutions within a reasonable time scale, the drawback being its inability to model important 3D effects, such as skew. Research performed since early 1990s has introduced various techniques associated with the treatment of skew within the

The authors would like to thank Vector Fields Ltd for their work in providing 3D analysis results.

COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering
Vol. 25 No. 2, 2006
pp. 309-319

0332-1649
DOI 10.1108/03321640610648998

2D environment (Williamson *et al.*, 1995; Ho and Fu, 1997; Ho *et al.*, 1999; Tenhunen and Arkkio, 2001; Gyselinck *et al.*, 2001; De Gersem *et al.*, 2002; Lai and Roger, 2002). The approach employed is often being driven by the level of available processing capabilities and it is evident from this work that the most popular methods exploit a multi-slice technique using a number of slices in the axial direction.

The increase of available processing power provided by desktop PCs is encouraging and more widespread use of FE analysis as a design office tool is now realistic; however, its application still often remains the province of the specialist. Moreover, contemporary 2D FE commercial software now has the facility to incorporate directly the effects of skew – in an approximate fashion – through the use of multi-slice models, a capability previously requiring the development of bespoke routines.

Within the community of machine designers, available commercial FE packages are often considered more an analysis rather than a design tool, typically requiring the user to have background knowledge of FE methods as well as considerable design expertise. This paper reports on a development where commercial 2D FE analysis software OPERA (Vector Fields Ltd, 2002) has been integrated, together with Matlab and Excel and without any modifications, into a design system for induction motors. The resulting package has been configured so that it introduces the capability to model skew and removes – through the use of parametric input data together with charting and numerical output facilities – the requirement for the operator to have any skills in FE analysis.

2. Multi-slice 2D model

Model generation defining the machine geometry and magnetic properties is achieved through multiple calls to OPERA-2d, the complete model being stored as an “op2” data file. Model construction commences with the stator, with the specified number of slices to model the rotor skew, followed by the rotor – a sequence that, by default, creates a model having sequentially numbered regions.

The basic physical geometry of the motor, such as the number and dimensions of slots and poles, provides the input to the automated program. As is the case for the motor discussed here, due to the combination of stator and rotor slots, the periodic boundary conditions facility available within OPERA-2d cannot always be exploited.

Automated model construction procedures often result in poor mesh generation, thus the program attempts to overcome such associated difficulties by basing the model construction on a single half slot to achieve a balanced mesh and – to prevent conflict between geometry and the automated assignment of elements – the program also matches the size of the model to the number of elements employed. This modelling technique is particularly efficient in the most sensitive regions, e.g. tooth tips. Figure 1 shows a segment of regions used in the model construction for a typical machine.

Multi-slice models require a fully modelled air gap as OPERA-2d’s own automated facility “RMGap” cannot be applied in such cases. With the air gap between rotor and stator fully defined by the user it must also be sufficiently refined to permit repositioning of the rotor as demanded by the rotor skew. Ideally, the air gap should be modelled with an odd number of regions: 3, 5, etc. In implementing this, three layers of elements were considered insufficient to achieve a smooth mesh in the radial direction, whilst five layers increased the number of regions used in the model, a condition preferably avoided as OPERA has a limit on the permitted number of regions that can be used in any one model. A compromise was achieved by selecting four regions in the air gap (Figure 2).

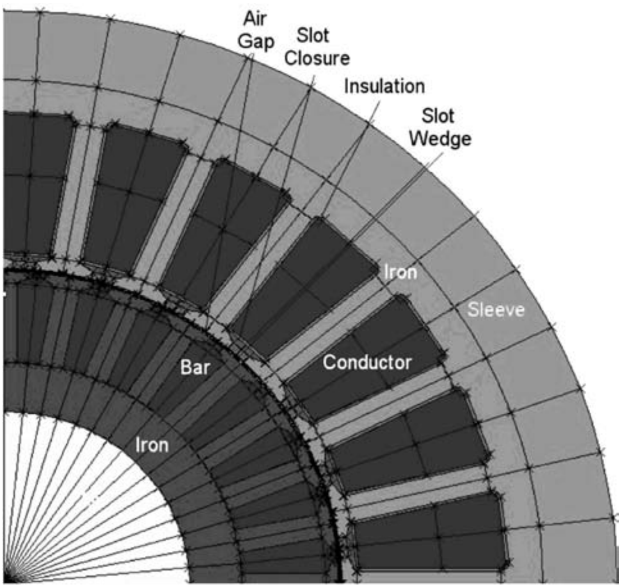

Figure 1.
Overall geometry of a typical machine

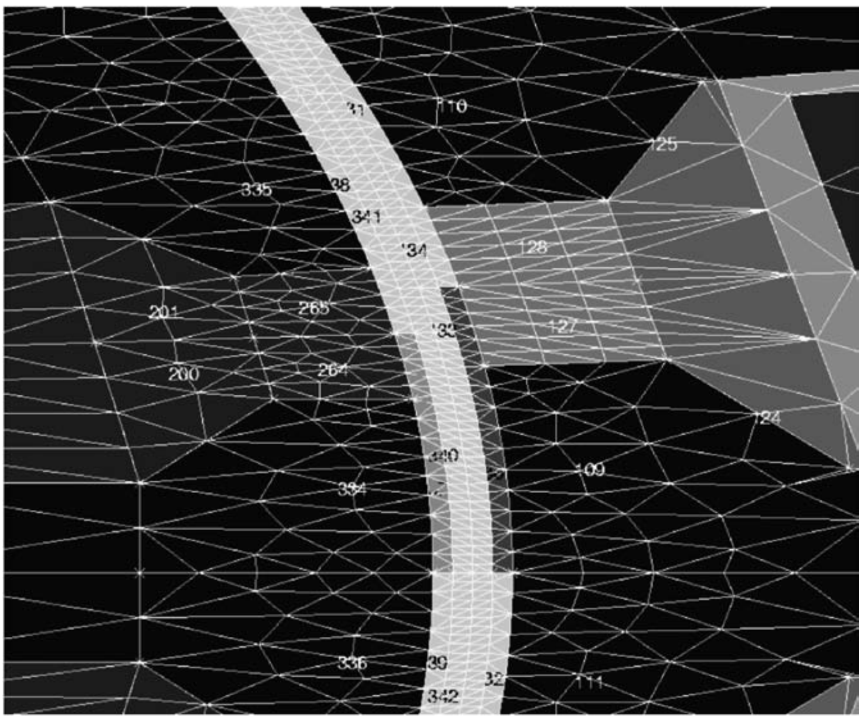

Figure 2.
Air gap detail

The number of elements in either of the two central air gap regions between the stator and rotor is derived as a function of the number of slots in the stator and rotor. By doing so the elements at the interface between the stator and rotor will automatically correspond to each other and this will be maintained provided any rotation of the rotor is controlled and limited to that permitted by a single element. Therefore, the number of steps required in order for any simulation to achieve a slot pitch rotation is directly dependant on the level of mesh refinement in the air gap region.

3. Multi-slice 2D solver

The steady state AC solver was used for the analysis of a multi-slice induction motor model operating at steady state. Minimising computational effort is an important objective and thus the minimum number of linear elements required to achieve a desired high accuracy solution was employed. Typically, a model is set up with voltage driven coils and utilises the external circuit option available in OPERA to link each slice of the model. Lumped resistance and inductance values (external to the FE model) are included in the circuit definition to account for elements not catered for in the two dimensional model (e.g. end winding effects).

The motor simulation and optimisation (MSO) program, of which the motor simulation and performance analysis routine forms an integral part, provides fully automated control of the pre- and post-processing of the FE model. Whilst the graphical evidence of FE computation is visible during program execution, all processing associated with the analysis is performed in the background. This removes the burden from the operator to posses any in-depth knowledge of FE methods as all input and output data are related directly to the motor's easily identifiable parameters without the need for any reference to FE internal data structures. The overall program operation is depicted simplistically by the flow chart of Figure 3.

The simulation and performance component of the software is shown in greater detail in Figure 4. With the FE solver invoked from within the main Matlab controlling

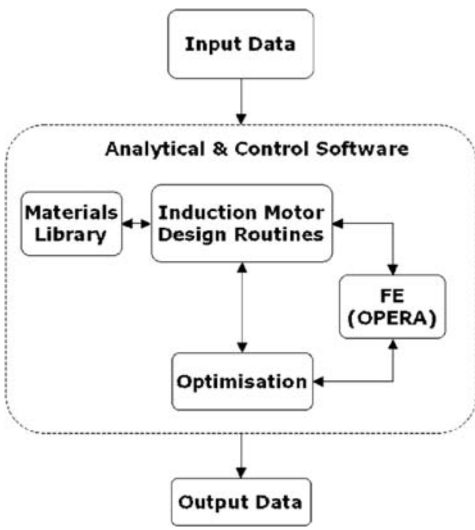

Figure 3.
MSO program

routine, the model is analysed for multiple rotor positions – as derived from the slot ratio – over one rotor tooth pitch. For each position of the rotor the standard OPERA-2d post-processor is used to extract information about stator peak currents per phase, rotor power loss, force, torque and rotor conductor peak current.

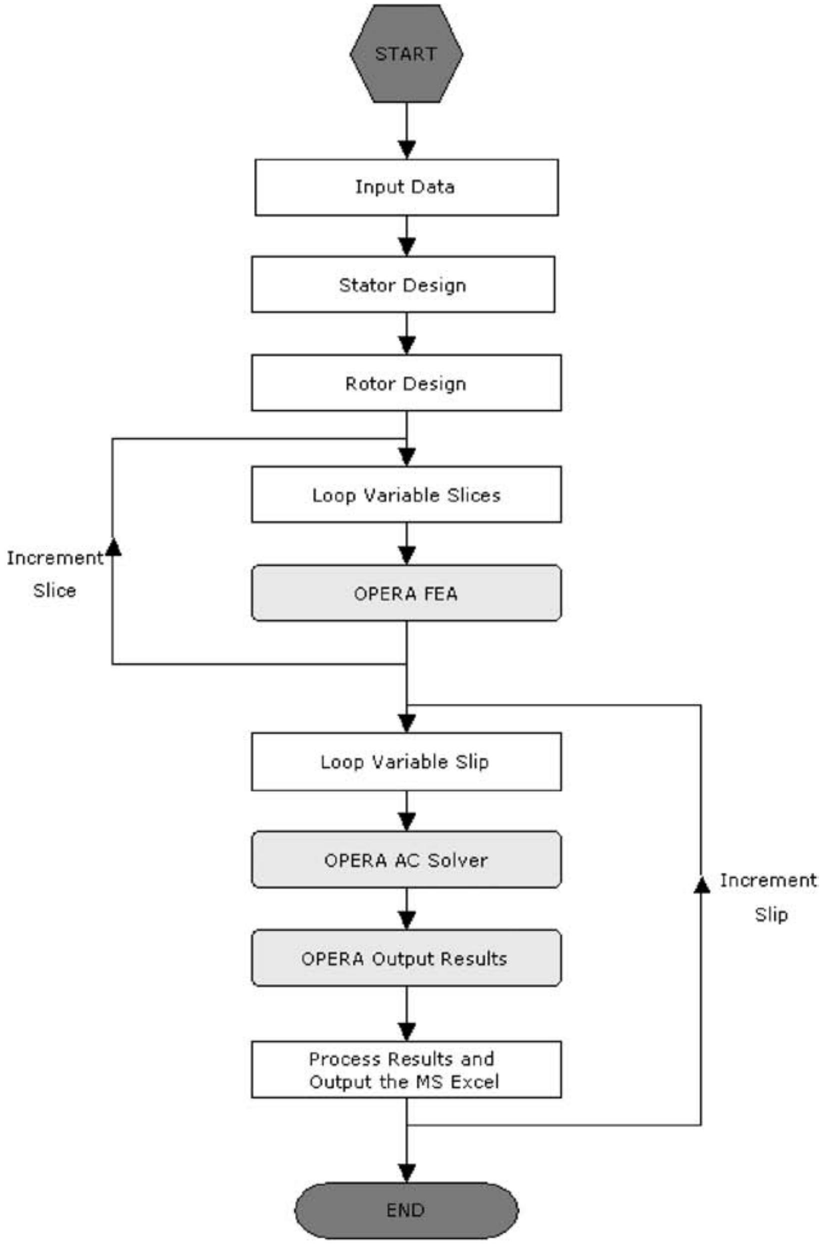

Figure 4.
Motor simulation and performance routine

With the completion of the analysis, control is returned to the core Matlab function where the output data files created by OPERA-2d are processed using Matlab's high-level programming language. Field plots can be viewed on the screen as the study progresses (Figure 5), or subsequent to the run, but this is not necessary although an available option.

For an efficient execution of the analysis, the results produced by OPERA-2d are averaged according to the number of slices in the model and number of rotational steps. The final result is combined with calculated losses for drag and exported to an MS Excel spreadsheet. These results can then be processed using the full range of charting functions available within MS Excel.

4. Optimisation

The optimiser is based upon the approach using response surface methodology (RSM) (Sykulski and Santilli, 1998; Al-Khoury and Sykulski, 1998; Pahner and Hameyer, 2000; Sykulski and Al-Khoury, 2000, 2001). The routine, shown in Figure 6, evaluates an objective function for a number of pre-determined cases and fits an interpolating function through the derived set of data points. The optimisation then uses this interpolation to reduce the number of necessary FE calls. The interpolating function, in this case a polynomial, has an order that can be specified between 1 and 5; usually cubic interpolation can be used as a good compromise between speed and accuracy of computation, with higher order polynomials only recommended if the objective function is known or expected to have a particularly complicated shape. The higher the order the more initial points are needed. The position of the initial points can be optimised as described in Sykulski and Al-Khoury (2000, 2001).

An optimum is found using a deterministic function that is available in the Matlab toolbox "Fmincon.m". In the minimum function calls approach (Sykulski and Al-Khoury, 2001), the number of initial points used is the theoretical minimum number that is required to fit the interpolating function. Using RSM reduces computing times

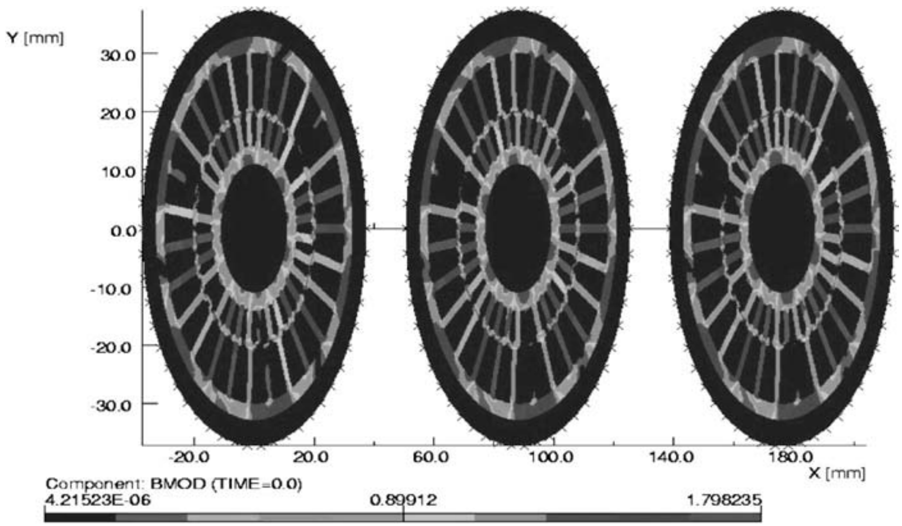

Figure 5.
Typical field plot for a three-slice model

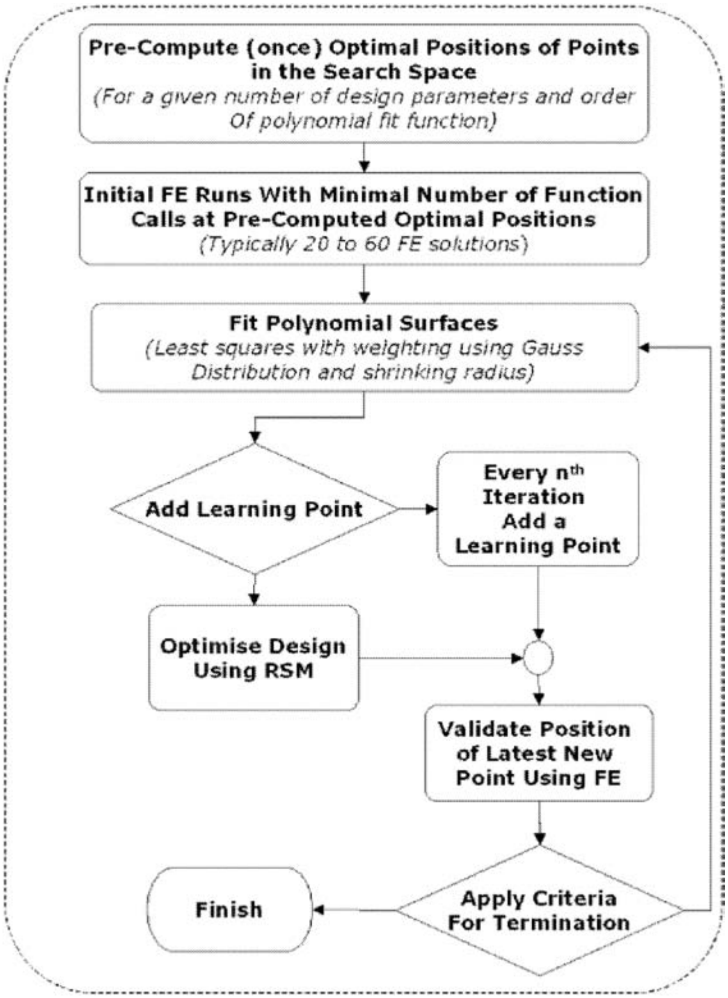

Figure 6.
Optimisation routine

dramatically, but care must be taken not to sacrifice accuracy. As the optimisation process proceeds, the number of points available for curve fitting increases and the estimate of the optimum position becomes more accurate. Thus it becomes appropriate to apply lower weighting to points far from the predicted optimum; this is achieved by applying exponential reduction so that on average, when a new point is added, one point will move outside the "important" region.

The optimiser includes the facility to carry out online learning, a feature that is intended to prevent the fit equations becoming ill conditioned; this procedure also goes some way towards preventing the optimiser from being trapped at a local minimum. A routine injects a random point that is some distance away from the current "optimum" position but within the multi-dimensional radius of the search space as traced by the optimiser. The curve fitting routines use the new point to produce a new fit that is then supplied to the optimiser to use in its predictions. Provided the learning point is sufficiently away from any local minima, which the optimiser is tracking, the consequential predictions from the optimiser will ensure that the forecast, following the learning point addition, will divert the optimiser away from the "obvious" direction and thus ensuring that it widens the search space to include any other minima.

5. Multi-slice 2D results

Figure 7 shows, for a typical model, how the torque varies with rotor angular position. This highlights the need for averaging torque results over the rotor tooth pitch and illustrates the importance of selecting a suitable elemental step of the rotor in order to avoid any detrimental impact on results.

A family of performance curves, for the same example machine as in Figure 7, shows that as the number of slices increases, the variation between the results produced decreases (Figure 8).

The accuracy aspect of modelling is demonstrated here with the estimation of torque. The greatest difference exists between the two- and the three-slice models. Variation between three and four slices is significantly less, whilst variation between four and five slices is reduced even further. It is doubtful – due to the marginal differences in results obtained for four and five slices – if performing an analysis with five slices is computationally justifiable or advantageous; a four-slice model appears to be the best choice. Discrepancies between test and simulated results can be attributed to model deficiencies in neglecting iron losses, those associated with interbar currents, as well as temperature and end-winding effects which can have an impact on the impedance of the stator and rotor electrical circuits. In addition, a deviation in magnetic properties of the stator and rotor laminations, and thus between the B-H characteristics used in modelling and manufacturer supplied material data, could also have contributed to the errors in the torque predicted by the program.

The MSO program software was installed and run on a 2.4 GHz machine with 1 GB of RAM. Preparation, solution and post processing times vary with the model

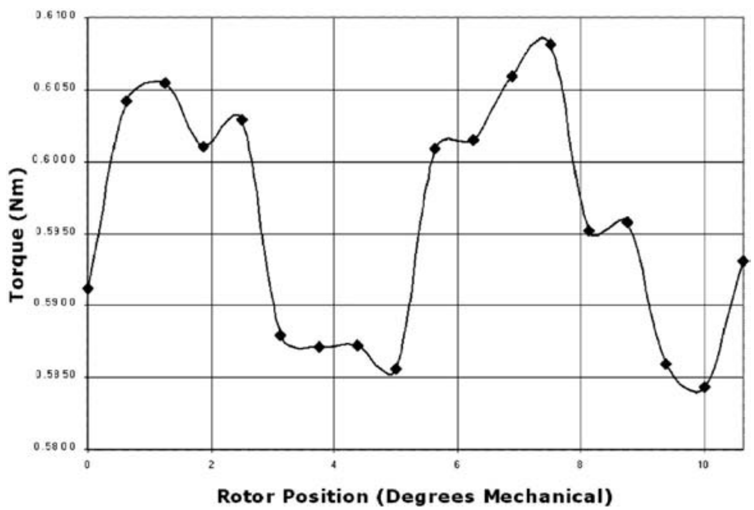

Figure 7.
Variation of torque with rotor angular position

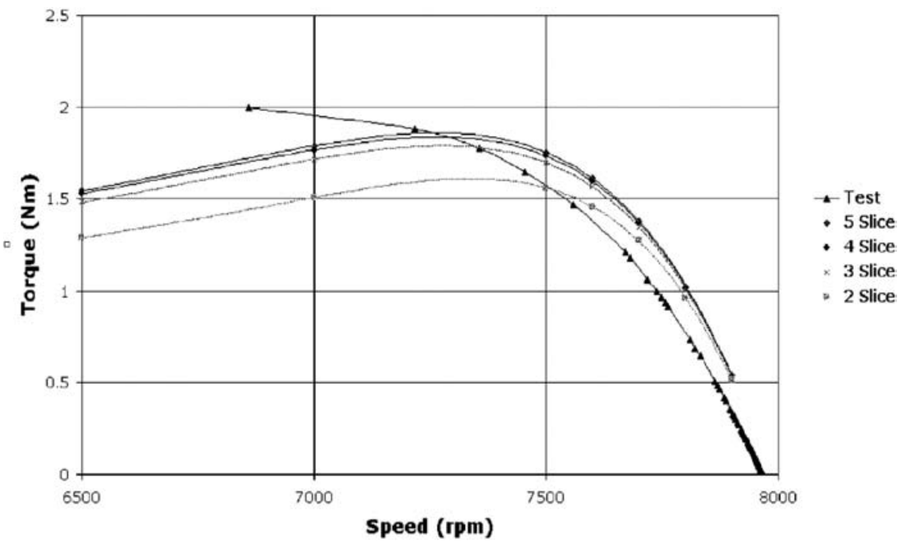

Figure 8.
Torque/speed characteristics for 2-5 slice models

complexity and do so approximately linearly with the number of slices modelled. Those obtained for the test case are given in Table I.

Solution times for optimisation runs are longer and less predictable, although the optimal design is usually achieved within 20-60 FE solutions. The optimisation convergence process, shown here by Figure 9 for a typical optimisation run, has been carried out for efficiency (with constrained torque) in terms of three design parameters: stack length, outer radius of the stator back iron and radial slot depth of the stator.

As can be seen in Table I, the time required to solve a single step rotation in OPERA-2d is 28 min:24 s (177,410 elements) for the five-slice model; this should be compared with 23 h:25 min required for a single OPERA-3d solution (1,800,000 elements) on a 2.4 MHz machine with 1.5 GB RAM, although additional OPERA-3d cases at different frequencies or excitations can be solved in approximately 13 h per case, by employing a coil field scaling technique. Thus savings in computing times by using the multi-slice 2D model are considerable without noticeable sacrifice in accuracy. Moreover, some of the previously identified possible sources of errors apply also to 3D modelling.

Results obtained from a full 3D analysis (using currents predicted by the 2D model to make the comparison meaningful) are shown in Figure 10 against the 2D model predictions (only the most important part of the torque speed curve is shown). The 2D and 3D predictions show quite reasonable correspondence. Further work is underway

Model type	Nodes No. off	Elements No. off	Solution time per step rotation h:min:s
2 slice	35,592	70,964	0:11:47
3 slice	53,388	10,6446	0:17:36
4 slice	71,184	14,1928	0:24:00
5 slice	88,980	17,7410	0:28:24

Table I.
Preparation, solution and post processing times

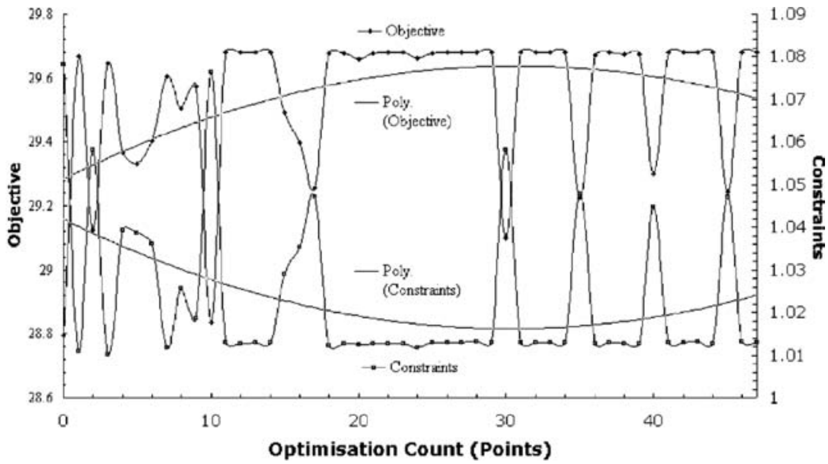

Figure 9.
Typical optimisation run

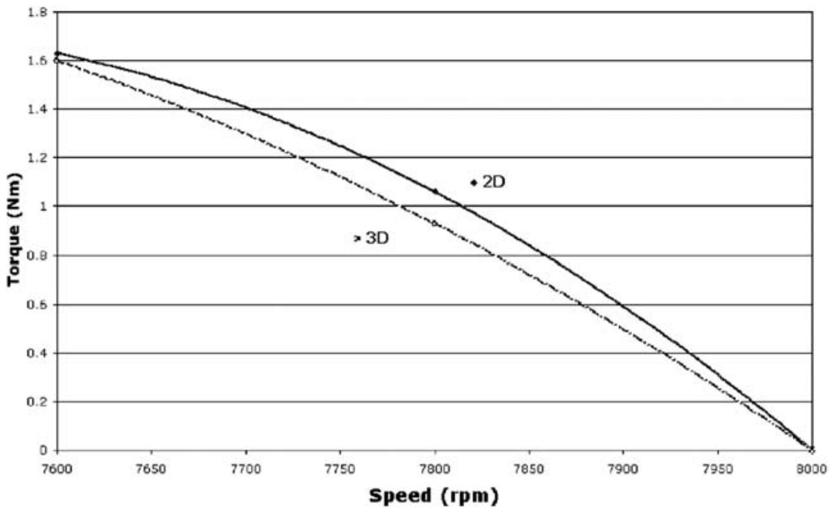

Figure 10.
2D and 3D results compared

using voltage driven coils in 3D to help validate the trends seen in 2D models when skew is applied to the rotor.

6. Conclusions

The paper describes an induction motor finite-element analysis-based design tool that is suitable for design office use. The program can provide solutions within acceptable time scales and removes the need for the user to have expertise in the underlying FE modelling technique. The approach makes use of the commercial software package OPERA-2d and adopts a multiple slice technique to model skew in three-phase induction motors, without recourse to bespoke FE analysis software. The results demonstrate that the use of a four-slice model achieves a good balance between accuracy in the modelling of skew and speed of computation.

References

Al-Khoury, A.H. and Sykulski, J.K. (1998), "Automation of finite element aided design of brushless PM motors", *Proceedings of ICEM'98, Istanbul, Turkey, 2-4 September*, pp. 614-8.

De Gersem, H., Hameyer, K. and Weiland, T. (2002), *Skew Interface Conditions in 2D Finite Element Machine Models*, Technische Univeritat Darmstadt, Dept. Electrical Engineering and Information Technology, Computational Electromagnetics Laboratory (TEMF), Darmstadt.

Gyselinck, J.J.C., Vandevelde, L. and Melkebeek, J. (2001), "Multi-slice FE modelling of electrical machines with skewed slots – the skew discretization error", *IEEE Transactions on Magnetics*, Vol. 37 No. 5, pp. 3233-7, pt. 1.

Ho, S.L. and Fu, W.N. (1997), "A comprehensive approach to the solution of direct – coupled multislice model of skewed rotor induction motors using time-stepping eddy-current finite element method", *IEEE Transactions on Magnetics*, Vol. 33 No. 3, pp. 2265-73.

Ho, S.L., Fu, W.N. and Wong, H.C. (1999), "Direct modelling of starting process of skewed rotor induction motors using a multi-slice technique", *IEEE Transactions on Energy Conversion*, Vol. 14 No. 4, pp. 1253-8.

Lai, H.C. and Roger, D. (2002), "Comparison of 2D and 3D finite element modelling results of a skewed induction machine", Power Electronics, Machines and Drives Conference Publication No. 487.

Pahner, U. and Hameyer, K. (2000), "Adaptive coupling of differential evolution and multiquadrics approximation for the tuning of the optimization process", *IEEE Transactions on Magnetics*, Vol. 36 No. 4, pp. 1047-51.

Sykulski, J.K. and Al-Khoury, A.H. (2000), "A system for interactive design and optimisation of brushless PM motors", *COMPEL*, Vol. 19 No. 2, pp. 664-8.

Sykulski, J.K. and Al-Khoury, A.H. (2001), "Minimal function calls approach with on-line learning and dynamic weighting for computationally intensive design optimisation", *IEEE Transactions on Magnetics*, Vol. 37 No. 5, pp. 3423-6.

Sykulski, J.K. and Santilli, M. (1998), "A procedure for magnetic design and optimisation of permanent magnet brushless DC motors", *COMPEL*, Vol. 17 Nos 5/6, pp. 749-56.

Tenhunen, A. and Arkkio, A. (2001), "Modelling of induction machines with skewed rotor slots", *IEE Proceedings Electrical Power Applications*, Vol. 148 No. 1, pp. 45-50.

Vector Fields Ltd (2002), *OPERA-2d Reference Manual*, Vector Fields, Oxford.

Williamson, S., Flack, T.J. and Volschenk, A.F. (1995), "Representation of skew in time-stepped two-dimensional finite-element models of electrical machines", *IEEE Transactions on Industrial Applications*, Vol. 31 No. 5, pp. 1009-15.