The U.K. Magnetics Society

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Developments In Electromagnetic CAD for Industrial Applications
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Computer Aided Design of Brushless Servo Motors

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Introduction

This paper describes the design process commonly employed by the authors on electric motor design. The flow diagram of the process followed is shown in Fig 1. Starting with the design aims, ideally several possible solutions will be identified. During the implementation stage the best available design tools are used firstly to gain a thorough understanding of the problem and secondly to optimise the design. Typically, several software tools will be used at this stage, ranging from simple spreadsheet programs to sophisticated analytical and numerical CAD packages. CAD tools should be used to study the electromagnetic, mechanical and thermal design aspects. The three areas of design are interrelated and iteration between the individual disciplines is required to obtain optimum design. For instance, in order to calculate the thermal rating of an electric motor, an iterative process between the motor losses and temperature distribution throughout the motor is required.

This discussion will be mainly focused on the electromagnetic design aspects. To highlight the typical use of CAD on electric motor, a design example will be presented. The design example addresses the use of circumferentially offset surface permanent magnets to eliminate cogging torque in a sinusoidal brushless permanent magnet (BPM) motor.

Design Aims

The design aims are detailed below. One of the main requirements of a high performance AC servomotor is minimum torque ripple. This requires the motor to possess a good back-emf waveform (sinusoidal in case of sinewave motor) and low cogging torque.

A further requirement of the example specification was for a large torque/volume by the use of a non-overlapping concentrated winding technique [1]. This winding type commonly involves the use of a segmented stator lamination. In such cases this prevents the use of stator skew. The non-overlapping winding technique also limits the number of slot and pole number combinations available.

A 12-slot 8-pole motor with a segmented stator construction and a sinusoidal drive were chosen as the pre-requisites for the design example used in this paper.

Possible Solutions

The identification of possible solutions is a important part of the design process. The number of suitable solutions identified depends largely upon the ingenuity and experience of the design team.

For the design aims described above the following possible solutions have been identified:

- skewed magnets
- shaped magnets and/or shaped tooth profile (graded airgap)
- special magnetising pattern
- circumferentially offset magnets
- magnet arc selection

The optimum solution will probably involve a combination of the above techniques. The combination of circumferentially offset magnets to give minimum cogging with the magnet arc selected to give a sinusoidal back-emf has been chosen as a design example in this paper.

It is noted that the 12-slot 8-pole construction is in the family of Slots/Poles = 1.5 motors. Contrary to common belief, it is possible to achieve a reasonably constant torque without skew in a squarewave current driven motor of this type. The important design parameter is the magnet arc in this case. However, when driven by sinusoidal currents, a skew of 1/2 slot pitch is usually required to obtain a good sinusoidal back-emf and low cogging torque.

Analytical Design

The design example used in this paper poses quite a difficult problem as the theory of circumferentially offset magnets is not well known. Indeed at the start of the project it was not known if it was possible to reduce the cogging to a reasonable level using this technique. The technique could not be investigated using the available specialist motor design packages as none of them allowed for circumferentially offset magnets. A general purpose calculation package was required such that the offset theory could be investigated. FEA could have been used, however the time required to develop the theory (many runs with differing magnet offsets) seemed to be inappropriate at this early stage of the design.

Spreadsheet & General Purpose Mathematical Packages

Spreadsheets and general purpose mathematical packages such as Mathcad and Matlab are useful as they feature straightforward input of design equations and plotting of resulting graphs.

The offset magnet theory was investigated using Mathcad[1]. The first task was to calculate a cogging waveform for one pole of a typical 12-slot 8-pole motor. This was done using the electromagnetic finite element analysis (FEA). This was then converted into time domain using a Fourier series representation. The total cogging torque for the whole motor can be calculated by the sum of the all eight individual cogging waveforms. A single parameter per pole is used to offset the individual cogging waveforms, i.e. the circumferential offset angle that the particular magnet is rotated. The resulting cogging waveform is plotted instantaneously. If none of the magnets are offset then the total cogging waveform has the same shape as the cogging for one pole, but has eight times the magnitude. The desired aim is to find the eight optimum offset angles that give minimum cogging. After much deliberation, the resulting offset strategy adopted is detailed below:

- For each half motor, magnets are offset by the angles 1 & 2 defined in Fig 2. The aim is to have four equally spaced individual pole cogging waveforms per half motor as shown in Fig 3. When the four waveforms are added together a half motor cogging waveform is obtained. The result is shown in Fig 3. It has a much lower magnitude than the individual pole cogging torque and it is symmetrical above and below the zero torque axis.
- The two half motor cogging waveforms are then cancelled by offsetting one group of four magnets by Angle 3 shown in Fig 4 (1/2 period of half motor cogging waveform). The two half motor cogging waveforms and the resulting total cogging waveform are shown in Fig 5.

The above method is general and can be apply to motor with any pole and slot numbers. It is interesting to note that subsequent work on 6 pole motors showed that the reduced number of offsets available limited their ability to control the cogging torque.

Once the basic angles required to produce the minimum cogging had been identified, the next task was to size the motor for the required application. This was done using a combination of specialist motor CAD packages.

Specialist Motor CAD Packages

Three specialist analytical motor design packages are used by the authors, PC-BDC[2], Motor-CAD[3] and an in-house motor CAD package. The in-house software is not discussed here as it is not commercially available. These packages are especially useful for the initial design stages as their sophisticated user interfaces ease data input and their near instantaneous calculation speeds allow "what-if" scenarios to be run in real time.

The requirement for rapid calculation speed and ease of processing of the results does necessitate a reduction of accuracy compared to numerical analysis. However, when used in combination with numerical analysis the ability to "fine-tune" the analytical calculation algorithms leads to a powerful design environment both in terms of accuracy and design turn-around.

A limitation of dedicated design packages is that they can only be used to design motor types that have been in-built into the software. However, such packages have so many options and "adjustment factors" built in, that this situation occurs infrequently. Indeed for the design example given in the paper, none of the packages can model offset magnets, however this did not preclude their use in the design process. An equivalent skew was used instead of the offset magnets in their analysis.

PC-BDC was used to size the electromagnetic dimensions and estimate the losses. Motor-CAD was used to calculate the thermal performance of the motor. The losses and temperature are interrelated so there was some iteration between the two packages to obtain the optimum solution. Further subsequent iteration was required with the FEA software to fine tune the design. This step was especially useful as the specialist CAD could not directly model the offset magnets.

[1] Mathcad - general purpose mathematical package from MathSoft

[2] PC-BDC - software package for BPM motors developed by the SPEED Consortium at the University of Glasgow, UK

[3] Motor-CAD - electric motor thermal design software developed by Motor Design Ltd, UK (www.motor-design.com)

Fig 6 shows a PC-BDC a screen capture of the 12-slot 8-pole motor modelled in the paper. The current, emf & torque waveforms for the motor are shown in Fig 7. Fig 8 shows Motor-CAD radial and axial screen captures of the same motor, while Fig 9 shows the thermal transient behaviour of the motor.

Numerical Design

Numerical analysis has the advantage over specialist motor design software that it is not limited to the geometries built into the software. It is also more accurate, but only if correct data is input. A common area design that is often incorrectly input is the magnetisation pattern within the magnets. This is often assumed to be purely radial or purely parallel when in reality it may be a combination of the two. In such cases the magnetisation process should also be modelled.

Electromagnetic FEA

In the offset magnet example, the Flux-2d[4] FEA package was initially used to generate a cogging waveform for one pole of a general 12-slot, 8-pole motor. This was then used in the Mathcad analysis presented earlier.

Flux-2d was subsequently used after the initial PC-BDC/Motor-CAD/in-house-CAD sizing to check that the offset angles selected did give the minimum cogging. It was then used to select the magnet arc that produces the optimum sinusoidal back-emf waveform. Fig 10 shows a flux plot of the model used. Fig 11 shows the emf waveform with a magnet arc of 130 degrees. The FEA was also used to check the torque and iron losses calculations calculated by PC-BDC. This particular aspect was especially required in this case as the offset magnets were not directly modelled in PC-BDC (equivalent skew used instead). It is quite typical to iterate between the specialist motor design packages and FEA in order to "fine-tune" the design.

One potential problem with the offset magnet design is that there is a component of unbalanced magnetic radial pull which may lead to excessive noise and vibration. FEA can be used to calculate the unbalanced force and this input into a mechanical CAD package to analyse the deflections produced. This step has not been performed in this case. It is noted that the level of the unbalanced pull does reduce with pole number. The critical offset angle in terms of unbalanced pull is Angle 3 shown in Fig 4, its magnitude reducing as the pole number is increased. Experience with 6 and 8-pole rotors do show a benefit when moving to a 8-pole rotor.

Thermal CFD

Typically CFD is not used in main stream electric motor design because of complications associated with modelling such complex structures as electric motors, and the high cost in terms of time required to define and calculate a solution. CFD can however be of benefit when used to model individual components of a motor and the data then used to "fine-tune" the model used in lumped circuit packages such as Motor-CAD [2].

Prototypes & Testing

The use of sophisticated CAD packages to design motors can lead to a reduction in the number of prototypes required. The use of CAD also gives the designer a greater understanding of the mechanisms at work within the motor so making it easier to obtain an optimum solution. The use of prototypes to "fine-tune" the specialist motor CAD packages has been found to be of great benefit in the past. It is noted that the prototypes built using this offset magnet technology have demonstrated a larger audible noise level than traditional motors, however, actual levels cannot be quoted as more testing is required.

Conclusions

The design method used by the authors has been demonstrated using a real motor design problem, i.e. the requirement for low levels of torque ripple in a 12-slot 8-pole sinusoidal BPM servomotor having no skew. The solution chosen was to use circumferentially offset magnets to minimise cogging and to select that magnet arc to achieve a sinusoidal back-emf waveform. A potential problem of unbalanced magnetic radial pull has been identified. The design example demonstrated the use of several CAD packages, with much iteration, to achieve an optimum design.

References

[1] Staton, D.A.: Permanent Magnet Motor CAD: Thermal Design Aspects. Developments in the Manufacture and Use of Permanent Magnets, UK Magnetics Society Seminar, 8 Nov. 2000, Birmingham

[2] Staton, D.A.: Thermal Analysis of Naturally Ventilated Servo Motor Housings. 5th International Flotherm User Conference, Paris, 16-19 Sept. 1996.

[4] FLUX software from Cedrat, France (www.cedrat.com)

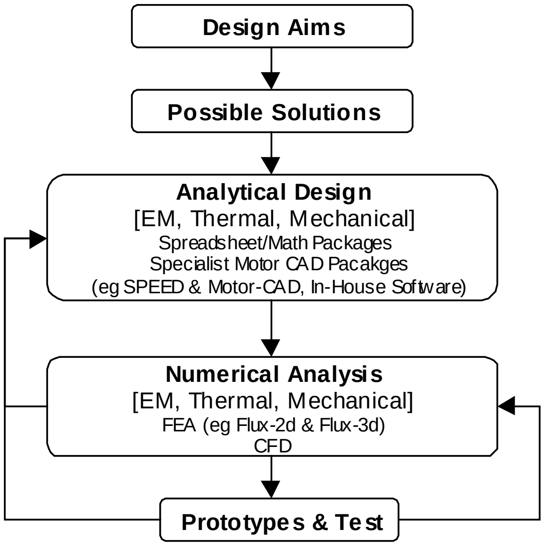

Fig 1: Flow diagram of design process used by authors

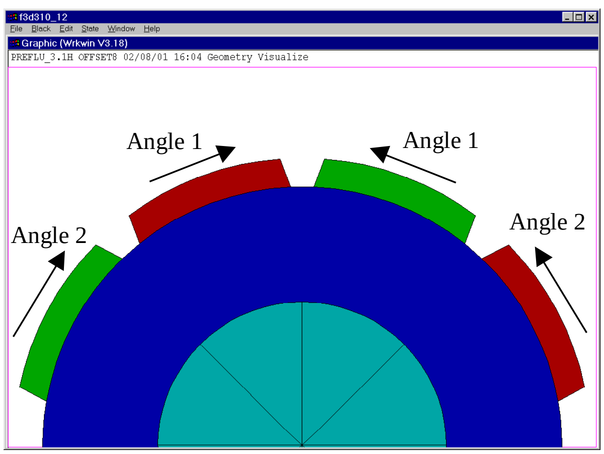

Fig 2: Offset angles used for half motor individual magnets

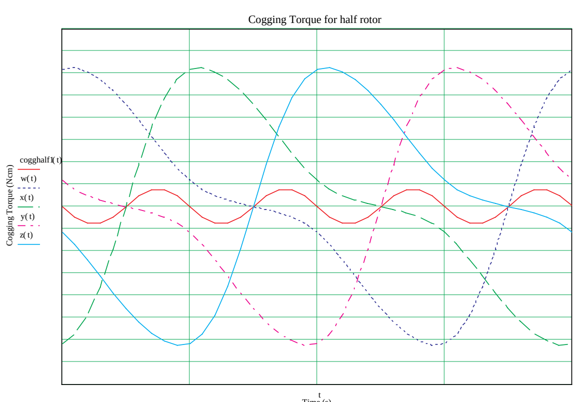

Fig 3: Cogging waveform for half motor with offset magnets

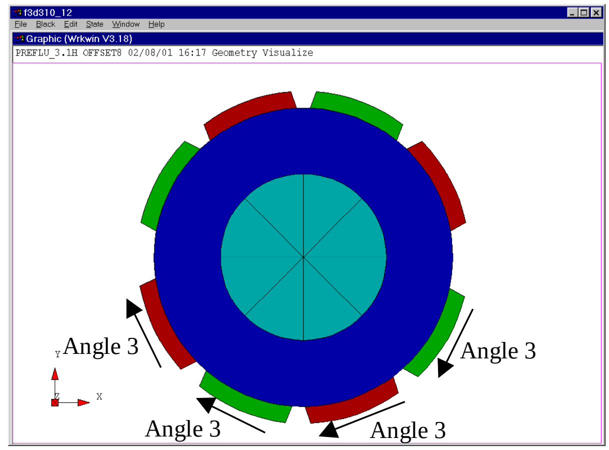

Fig 4: Offset angle used for half motor magnet group

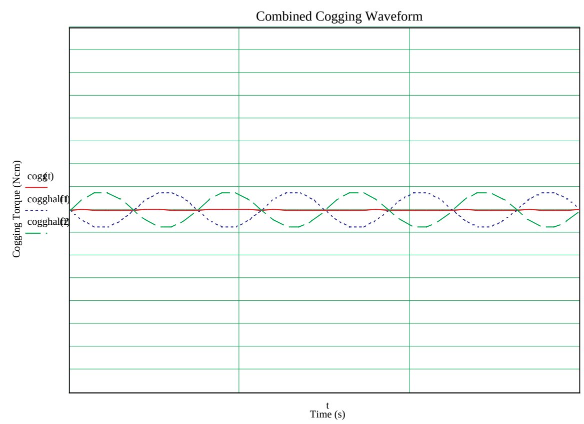

Fig 5: Cogging waveform for two half motors + total cogging

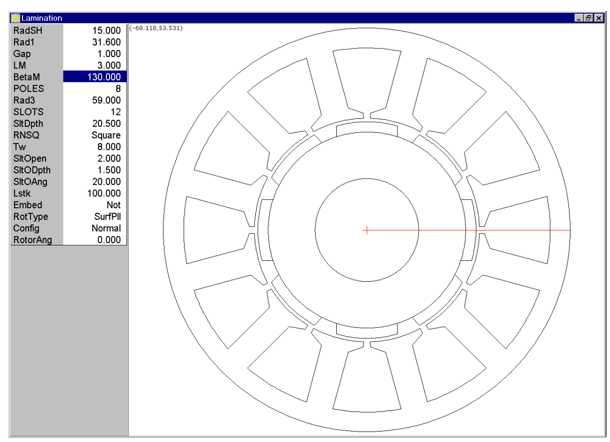

Fig 6: PC-BDC - radial cross section of 12-slot 8-pole motor

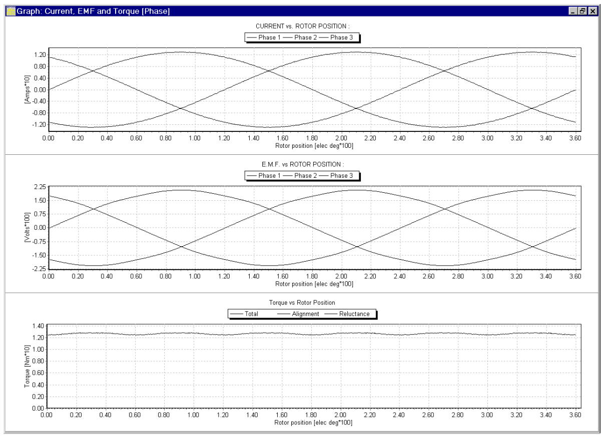

Fig 7: PC-BDC - prediction of rated current, emf & torque

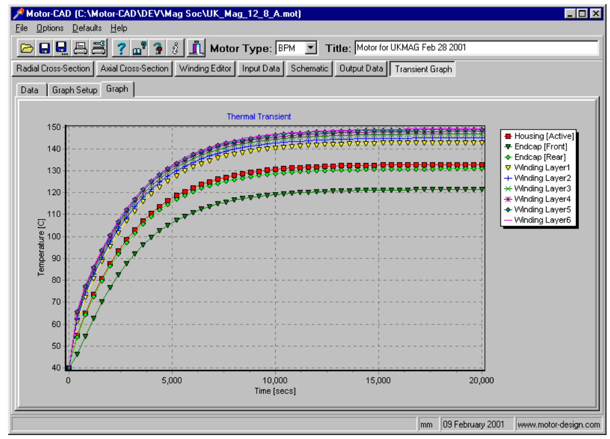

Fig 9: Motor-CAD - thermal transient with full-load

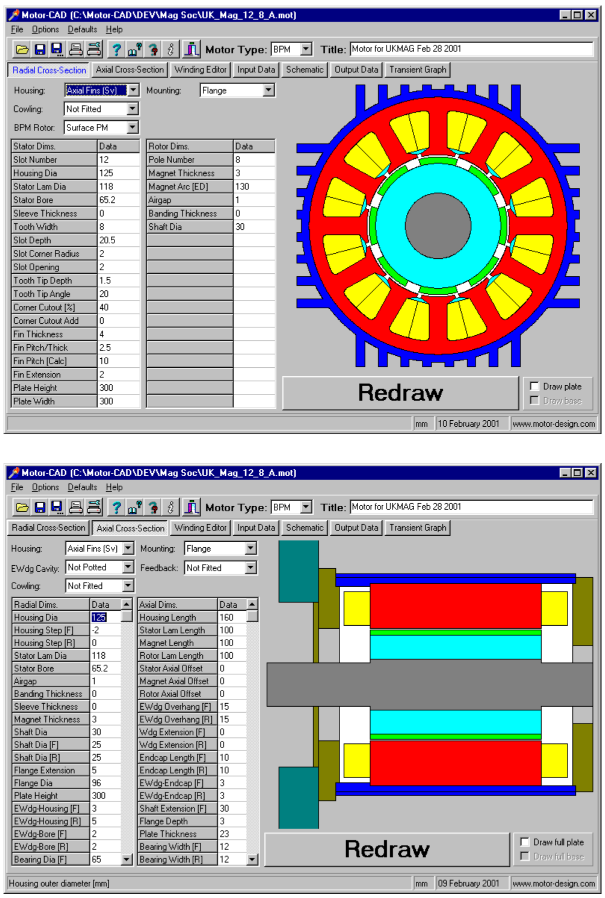

Fig 8: Motor-CAD - radial & axial screen cross-section

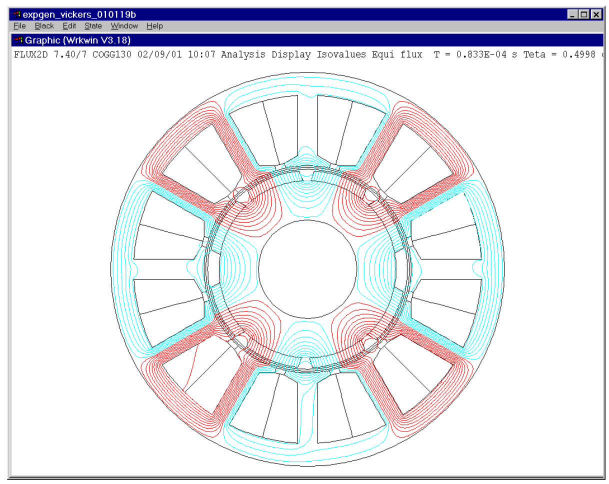

Fig 10: Flux-2d - offset magnet motor flux plot

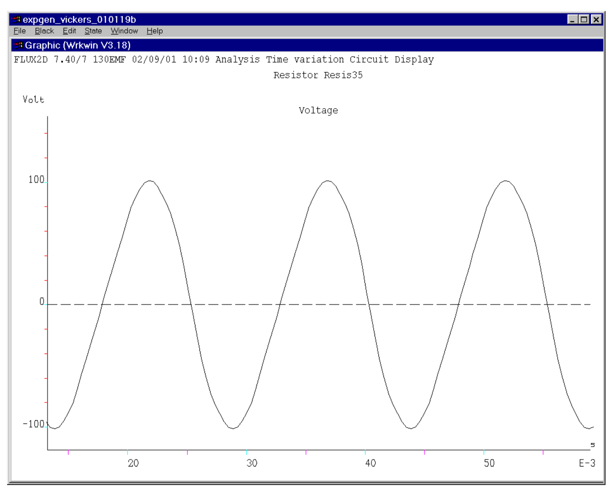

Fig 11: Flux-2d - back emf prediction