An Integrated Design Environment for Electric Machines

Volume 1 of 2

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B. Eng. (Hons)

Submitted in fulfilment of the requirements for the Degree of PhD by published work

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March 2017

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Volume 1

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Abstract

In this essay I describe an original and sustained contribution to the methodology of research and design of electric machines, during a period of fundamental change in the technology itself; from pen and paper methods of design to a wholly computer-based methodology. This is paralleled by an even more dramatic transformation in analytical and numerical methods in engineering. The technological changes have arisen mainly in the growth of electronics, in connection with variable speed drives but also in new magnet and other materials.

The SPEED (Scottish Power Electronics and Electric Drives) Laboratory was founded in 1986 by Professor TJE Miller, to promote knowledge transfer between the University of Glasgow and a consortium of companies from the electric machine industry. A symbiotic relationship between Professor Miller and the author has arisen in the development of what the Laboratory is now principally known for: the SPEED software. In establishing this group, Professor Miller brought an international reputation in electrical machines theory and experience in writing FORTRAN programs for calculating the characteristics of motors. On joining the Laboratory in 1987, alongside a basic knowledge of motors, I brought a more specialised capacity in software design and development. This complementarity of roles and expertise has been a significant factor in the success of subsequent development over 27 years, enabling us to achieve more than either would have been able to do individually.

My major contributions are summarized as follows:

1. Initial implementation of the software: making the necessary engineering compromises and development to shoe-horn the code within the constraints of the early PC platform. This was a significant milestone in the genesis of SPEED. As the PC was becoming cheap and therefore ubiquitous, this direction enabled me to put design for electric machines

on the desktop of every engineer in the consortium, numbering over 1500 in 2011.

2. The hardware and software platform of the PC has evolved at a rapid pace since the early development outlined above. My ongoing research and development has progressed in parallel enabling the SPEED software to grow into a *software suite* rather than functioning as individual programs. At each stage I have extended the capabilities and sophistication of the software while retaining the key attributes of speed and cost-effectiveness.

3. Contribution to research within the University of Glasgow through support of PhD and post-doctoral work and in the general research community through contributions to a wide range of technical papers as listed in the references of this essay.

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Acknowledgements

Firstly I would like to acknowledge and thank the companies that made up the SPEED Consortium, for supplying funding over the last 25 years and for providing valuable feedback on software design and usage. I would also like to thank my colleagues, past and present for their support and encouragement and especially to Prof. TJE Miller. His continued faith in the use of PCs for designing electrical machines has driven our long collaboration.

I owe an immense amount to all my other co-authors especially to Calum Cossar, Prof. David Staton, Prof. Dan Ionel, Dr. Mircea Popescu and Prof. David Dorrell but also to the many other colleagues and collaborators referred to in this essay.

Finally I would like to thank my wife Helen, for all her encouragement.

1. Introduction

This essay describes my role in the development of the SPEED software system – a suite of programs for the analysis and design of electric machines. The SPEED (Scottish Power Electronics and Electric Drives) Laboratory, founded, in 1986, by Professor TJE Miller, was based in the School of Engineering at the University of Glasgow until its acquisition in 2011 by CD-adapco, a multinational company specialising in engineering simulation software. More recently CD-adapco itself was acquired by Siemens PLM, a computer software company specializing in 3D & 2D Product Lifecycle Management (PLM) software. Although the SPEED software continues to evolve in new directions within the broader scope of an integrated simulation package, this essay, and the related literature focuses on the initial 25 year period of development. During this period, SPEED was structured around a consortium which, in 2011, consisted of over 60 industrial member companies in over 100 sites around the world. Each member had access to the SPEED software and other research performed in the Laboratory. The software was also available to non-members from a number of global distributors. It continues to be the most widely used specialist electric machine design software in the world.

The architecture of SPEED is original, unique and solely my invention. It consists of multiple programs for various electric machine types. The first PC-SRD (1987) was for Switched-reluctance motors (see [1, 2]), and was soon followed by PC-BDC (1989) for brushless-DC motors (see [3, 4]), which became increasingly popular at that time with the growing availability of modern power electronics. Later, classical induction machines (PC-IMD) and commutator motors (PC-DCM) (see [5-7]) were added. The immediate purpose of the SPEED system can be defined as calculating useful results rapidly and then focusing on their interpretation with the minimum of distractions.

By incorporating finite-element analysis (FEA) in SPEED we have contributed significantly to making this important method a matter of routine during the process of electric machine design. The two methods by which SPEED accomplishes this are not only extremely effective but also unique in their field; namely, the "GoFER" and the "embedded solver". The finite-element module used in SPEED was developed in collaboration with its original author, Mircea Olaru (see [8-11]). The linking of SPEED to FEA, i.e. the transfer of geometrical, electrical and material information into a numerical analysis program is of increasing importance but is time-consuming and error prone. The methods, developed by the author, to perform these tasks have led to a huge productivity gain in terms of reducing the time required to achieve a useful and reliable result. More recently the simplicity and reliability of these links have opened up an entirely new and unique merger of classical machine design theory and numerical field computations by means of the *embedded solver*, where the operation of the FEA is hidden from the user (see [12, 13]).

1.1. The Papers

The papers accompanying this essay rarely refer to the "SPEED software". This is in accordance with normal protocol in archived journal and refereed conference publications. Some early papers (in particular, see [1, 2, 4, 5, 7, 14]) describe the architecture and the theory behind the software but later papers increasingly focus on developments that take the software into new areas or improve the accuracy for specific machine types. These include line-start motors (see [15-17]), iron loss computations (see [18-22]), multi-phase machines (see [23]), super-conducting machines (see [24]), and thermal aspects of design (see [25-28]). All of these, except for the thermal studies (which have less emphasis on electromagnetics), combine theory, software coding and FEA. Taking iron loss as an example (see [22]), this requires a time-based waveform of flux-density and a set of loss coefficients. The SPEED software calculates these waveforms from equivalent-circuit analysis or numerical FEA and the steel databases contain the loss coefficients. As the program performs its calculation, a stage is reached where the iron loss is calculated so it is clear where any new methods can be inserted. The whole body of software can then be used to assess rapidly and straightforwardly the new code as many test cases can be tried out with ease.

2. Software Architecture

2.1. Historical perspective

Although computers have long been used to aid electrical machine design, it was not until the late 1980s that the possibilities of a comprehensive design capability came into view. As an example, the first non-Government owned IBM mainframe in Denmark was purchased by Grundfos A/S to improve its induction motor designs. Grundfos's design program was based in part on the work of C.G. Veinott, one of the pioneers whose books and software were widely used throughout the industry until the turn of the century. Veinott's induction motor program is typical of programs from this era. It was written in FORTRAN, ran on mainframe or mini-computers with teletype displays and was sold as source code for adaptation to company needs (or computing hardware). Input and output were by means of text files and there was little, if any, visualisation or facility for interactive design. Finite-element analysis was essentially unknown outside specialist physics laboratories.

The development of desktop computing brought about by the relatively cheap, widely available IBM PC and compatible personal computers in the mid-1980's, revolutionised this. In 1987, Professor Miller needed to migrate engineering code for a particular electric machine design calculations to enable the software to run on the PC platform. This original FORTRAN code ran on the Electrical Engineering Department's GEC 4180 mini-computer, at the University of Glasgow, as a suite of separate programs. These were linked by text-based data files for input and output. One program produced a drawing of the lamination cross-section based on a given input file. The main "engineering[1]" program performed the analysis on the input files and produced output files containing a "design sheet" and tables of graph data. These could either be displayed as plots

[1] What we now refer to as "Real engineering" or RE, as opposed to "Software Engineering", or SE which refers to all the aspects of programming that do not directly relate to the motor design equations.

(by running a separate graphing program) in the case of graph data, or in a text editor for the design sheet (see Figure 1).

Even at this early stage the question of the most suitable programming language was a significant factor in planning the software, as it still is today. While FORTRAN was suitable for engineering calculations (including native complex number type), it was severely limited in the modularity needed to develop the software in different functional directions, and at the same time very inconvenient for the presentation of graphical data or the development of a GUI. Borland Turbo Pascal 3 (TP3) was an obvious choice as at the time it was closely tied to the PC platform, giving straightforward access to file handling, graphics and was orders of magnitude faster than the alternatives. In addition, I had several years' experience of using Pascal at undergraduate and in industry as part of a year's placement with IBM.

```
18th APR 1988 15:20    PC-SRD Glasgow University 1988            Ver 2.0
-----------------------------------------------------------------------------
PC-SRD. Sample
------------------------------------------------------------DIMENSIONS ( mm )
Rotor  RO    11.879
       R1    18.500      4.000   Poles   Arc   32.000°   Gap          0.250
Stator R2    30.500      6.000   Poles   Arc   28.000°   Stack Lgth 50.800
       R3    35.637
Stckng fact.  0.970         Steel : Losil 500/50
------------------------------------------------------------------WINDING DATA
Wire Dia.   = 0.629 mm    3 Phases       Turns/Pole         =     110
C/S. Areas  :
   1 Wire   = 3.108E-01 Sq.mm            Resistance/Phase = 2.163 Ohm
   Slot Cu  = 3.418E+01 Sq.mm            Temp. 75.000 °C
Slot fill     3.500E-01
M.L.T       = 1.467E+02 mm               Inductance/Phase = 5.556E-02 H Al
Lgth o/ends = 7.370E+01 mm                                = 7.379E-03 H Un
Copper wt.  =     0.267 kg                          Ratio =     7.529
------------------------------------------------------------------CONTROL DATA
Voltage             60.000                     Current Regulator setting
R.P.M             3000.000                                    1000.000 A
Turn-on angle       47.400 deg.                Duty Cycle       1.000
Turn-off angle      75.000 deg.                Transistor RQ    0.000 Ohm
Dwell angle   =     27.600 deg.                Transistor VQ    2.000 V
Stroke angle  =     30.000 deg.                Diode      VD    0.600 V
O/lap starts  =     30.000 deg. BTC            Phase freq. =  200.000 Hz
-------------------------------------------------------------------PERFORMANCE
Torque             =  2.113E-01 N-m          Efficiency       =     76.358%
Shaft Power        =  6.639E+01 W            kVA/kW(pk)       =     14.868
                                             kVA/kW(rms)      =      5.850
Losses: Copper  =  1.464E+01 W
        Iron    =  5.912E+00 W
        Windage =  0.000E+00 W               Deg. C / W       =      3.000
        Total    = 2.056E+01 W               Temp. rise       =     61.668 °C
CURRENTS =                    PEAK                 MEAN                 R.M.S
Winding                        3.591                0.954                 1.502
Transistor                     3.591                0.745                 1.413
Diode                          2.143                0.209                 0.510
DC Link (Supply)                                    1.609
DC Link (Capacitor)                                                       1.517
RMS current Density =   3118.934 A/SQ.in. =     4.834 A/SQ.mm.
------------------------------------------------------------------------------
----------------------------------------------------------SUPPLEMENTARY OUTPUT
WEIGHTS: Copper =     0.267 kg                  Inertia     = 2.589E-05 kg-m2
         Iron   =     0.896
         Total  =     1.163
Resistivity     = 8.197E-07 Ohm-m               Temp. fact  =    1.216
CPU             =     3.741                     ETF         =    1.277
PSlot           =     1.496                     PRS         =    2.245

IRON LOSSES      Eddy current                               Hysteresis
Rotor yoke      =     0.444 W                               =    0.243 W
Rotor poles     =     0.329                                 =    0.158
Stator yoke     =     2.530                                 =    1.224
Stator poles    =     0.671                                 =    0.313
Total           =     3.974                                 =    1.938
Sigma           =     0.280 psi

End of design
```

Figure 1: Design sheet from early version of PC-SRD

2.2. Translation and basic modules

The mechanics of translating FORTRAN to Pascal are fairly straightforward, with the exception of FORTRAN specific features such as native complex arithmetic (which fortunately these early programs did not use), so the RE (Real Engineering) code was transferred without undue complication. However, some areas were identified as needing further development to take advantage of the new platform and these are described in more detail below.

2.2.1. Graphical output:

On the mini-computer the drawing and graphing routines were handled by libraries of graphics routines which were not available for Borland Turbo Pascal 3 (TP3). In fact, TP3 had no general graphics routines at all, although it did have a graph plotting library that we used. In addition, the PC platform supported a variety of graphical screen resolutions which needed to be catered for, so I created a library of general routines based on the pixel based functions available in the IBM BIOS[2]. These were fast, utilising line-drawing routines such as Bresenham's algorithm and practical, taking floating point numbers, and automatically accounted for different aspect ratios. Although now commonplace, at that time these procedures were highly original. As they were under our full control, we were able to take immediate advantage of the recently introduced VGA graphics standard to produce high-resolution colour graphics (640x480, 16 colours).

2.2.2. Data Editors:

On the GEC mini-computer, data input was by means of a text editor, as was viewing the output. This was convenient, as the user could have a text terminal with the editor and a graphics terminal with the motor cross-section, or output graphs, and be able to see both simultaneously.

[2] The BIOS (Basic Input Output System) is a library of routines built into PCs

Figure 2: Early promotional shot of PC-SRD

In practice however, most PCs had only a single screen, so the cycle of load-edit-save-load-display-load-edit-save etc. took considerable time and was a distraction to the engineering process. To overcome this, I developed two editors: the *Cross-section editor* and the *Template editor* (or TED). The *Cross-section* editor is used when viewing the lamination cross-section and is now called the *outline editor* as it can be used to edit axial parameters. The *Template editor* is used for editing all the remaining (non-dimensional) parameters such as those for defining the electronic control and other simulation parameters. Both of these editors were based on a simple spreadsheet model with the data being arranged in grid form (a single column grid in the *Cross-section editor*) with the name of the parameter shown alongside its current value (which could be directly edited) and with the previous value shown above. Navigation around the grid was achieved by means of arrow keys.

2.2.3. Materials

*S*teel properties including magnetisation curves and loss parameters, and magnet properties including remanence and recoil permeability were other text-based inputs in the original program. For ease of use with a large number of material types to handle I wrote flat-file record based database handlers to store and edit these materials.

2.2.4. Outputs

For the output two viewer programs were written which allowed the user to scroll and print the *design sheet*, again using the arrow keys to navigate and to display graphical plots. The data displayed by both programs was produced by Professor Miller's RE code.

2.3. Original program structure

Building on the mini-computer model of separate programs for each major function, the first big step was to integrate them into a single program. As was common for programming languages in the 1980s, TP3 had a 64KB limit on the amount of code that could be in memory at one time, although it did have a facility for "chaining" or "overlaying" multiple programs. By ensuring that these chained programs all had an identical data segment it was possible for one program (sometimes called a module or unit) to alter the data and then load another program which could then access and use the same data. In this way it was possible to greatly speed up the program, mainly by eliminating the requirement of writing data to disk, which is orders of magnitude slower than writing to memory, but also by automating the linking of the programs through a main menu system such that the editors, analysis, graphs and design sheet output could all be accessed by single keystrokes. Today, this structure would be recognisable as an integrated development environment (or IDE) for motor design.

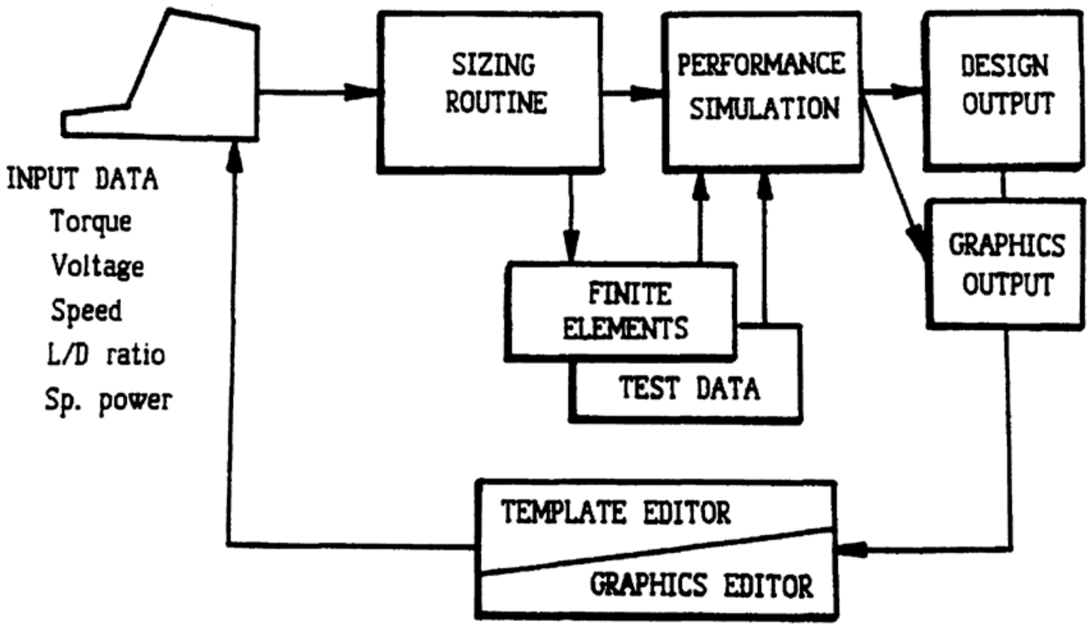

Figure 3: Structure of PC-SRD

At this point we had what can still be recognised as PC-SRD – an integrated program that allows the engineer to view and modify a lamination; set values for the electronic controller and the simulation; run an analysis; view the output graphs and design sheet; and iterate through all these operations quickly and efficiently.

2.4. The framework evolves

PC-SRD was followed by programs for other machine types as summarised below.

Table 1. SPEED Software: Program Development

Program	Year introduced	Machine types
PC-SRD	1987	Switched-reluctance machines
PC-BDC	1989	Brushless machines
PC-DCM	1992	PM commutator machines
PC-IMD	1993	Induction machines
PC-SREL	1994	Synchronous reluctance machines
PC-SLD	1999	Fast acting solenoids
PC-WFC	1999	Wound-field commutator machines
PC-LPM	2002	Linear PM machines
PC-AXM	2005	Axial gap machines

All these programs follow the core architecture shown earlier in Figure 3

2.4.1. Developing a Structured Approach

This, now large body of code, required a much more structured approach compared with the relatively ad hoc approaches of early versions of PC-SRD. Primarily this was achieved by creating a software library of routines commonly used in each of the separate motor design programs. For example, the code to provide the editor functionality is essentially the same in each of the programs – only the data it accesses is different. To this end the editor code deals in an abstract view of the data, only ever accessing it via one of the many Get* routines or the Set* routines[3]. This also had the additional benefit of making unit conversions easy to implement, which was important as a large part of the user

[3] This technique was first implemented in an experimental version of PC-BDC for the Apple Mac but later re-used in all subsequent SPEED programs.

base was located in the USA where, even today, Imperial units are still widely used.

2.4.2. Separation of RE & SE

Another important feature of the developing architecture was the deliberate separation of the RE (Real Engineering) and SE (Software Engineering) domains. With clearly defined and easy access points for engineers working on machine design theory to add parameters and calculations, work could be carried out independently of a specialist software developer. In particular, [12, 15-17, 23, 24] benefit from this code structure which allowed research developments to be implemented in a fully functioning user interface and immediately available to researchers and end users in a familiar manner.

2.4.3. Compiler development

One of the main facilitators in the process of achieving code reuse was the introduction of newer versions of Turbo Pascal. The first of these was TP4, which borrowed the concepts of "units" from Modula-2 (via Apple's Object Pascal) and eliminated the need for chaining separate executable modules. Later versions, specifically TP5.5, brought Object Oriented Programming and the graphics and printing routines were rewritten to take advantage of that. Finally (at the end of the DOS era), Borland Pascal 7 (BP7) brought the ability to access large amounts of memory albeit with a 64KB limit on individual data structures.

2.4.4. Limitations

This 64KB limitation necessitated the removal of certain features such as *ranging* i.e. the simple repetition of calculations with varying parameters, as the data arrays became too large. Another more serious limitation was the internal compiler limits which restricted the size of programs that could be debugged and browsed - even though they were able to compile and run without problems. In 1995, Borland introduced Delphi, first in a 16 bit version then soon after Windows 95 was released, a 32 bit version - Delphi 2. With Delphi 2, these limitations became a thing of the past.

2.5. Windows framework

The separation of RE and SE concerns not only benefited RE development. It also allowed the author to experiment with the development of versions of the SPEED software for MS Windows. A number of prototypes were investigated, written in MS Visual Basic and Borland Pascal for Windows (BPW) but with the arrival of Borland Delphi, described above, the ease of use and an extremely high degree of code compatibility made the choice straightforward.

2.5.1. Code reuse

An important aspect of the migration to Windows was the reuse of exactly the same RE code that had previously been developed and compiled in BP7, underlining the continuity of development and execution that was so important to the RE community of developers and users. In addition, there were the advantages of developing in BP7 which, at that time, was familiar to the principal engineers and faster to develop in. Also, there were facilities in BP7 that were required in tracking changes to parameters which could occur in what was now tens of thousands of lines of code. For these reasons the use of BP7 continued long after it was technically obsolete, but without hindering the development of the Windows versions. This was achieved by means of *conditional compilation*, which required special comments in the source code. These are interpreted at compile-time to control which sections of code that are actually compiled. Code dealing with the DOS user-interface could be omitted from the Windows version and vice versa. Similarly, parts of the code that due to size limitations would have crashed the BP7 compiler could be omitted from the DOS version.

2.5.2. Development environment

For the engineers who have worked on the calculating facilities within the SPEED software, there is the ability to develop without the need to know how the entire Windows user interface actually works. As is usual in interactive (or production) software, this framework dwarfs the amount of code involved in calculating the actual numbers[4]. The benefits of this functionality for an engineer experimenting and developing new code and theory are many. There is the rich functionality of editors, graphics and charting facilities. There are the built-in file handling (database type) functions, standardised input and output methods and a clear structure for modifications. Finally, there are the specialised functions which allow an engineer simple access to highly complicated functionality; an example being *EmbeddedFEA_Getpsi* in PC-BDC (see [12]). With this single procedure call an engineer is able to get the flux-linkage from any given PC-BDC machine with any excitation or at any rotor position. This will be described in more detail later.

2.5.3. Windows Architecture

Structurally, the Windows code follows the same pattern as the original DOS program of a *cross-section editor*, a *template editor*, *analysis options*, *graphs* and *design-sheet viewer*. In addition, the multi-windowed nature of Windows means that the separate editors or results viewers must be kept in sync with each other. This is done by means of a message based procedure in the main program module, which receives notifications of changed parameters and in turn passes these on to all the other windows. The same Get* and Set* routines are used as in DOS and the same (although Windows specific) *editor* routines are used, not just between the different programs, but in multiple places in each program. For example the outline, template and winding editors, the harmonics editor, the match FE windows and the I/O units selector all use the same basic parameter editor.

2.5.4. Design process flexibility

Although the basic structure is the same as for the DOS version, the use of multiple windows and the possibility of rapid switching between them leads to a framework which can be used by different engineers in different ways. This is fundamentally different from the template based design programs, common with

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[4] In "The Mythical Man Month" Fred Brooks estimates that there is nine times more work involved moving from a first working program to a finished product.

FEA packages, where the design process is driven step-by-step through a linear sequence of dialogs to get a final result. The flexibility of SPEED is crucial as there is no single correct way to design an electric machine. As SPEED covers multiple disciplines - electromagnetic, electrical, mechanical, control, thermal and manufacturing – each engineer has a different set of priorities and goals and the SPEED architecture allows almost infinite customisation to achieve this.

2.5.5. Linking

Additional features in the Windows versions include *custom template editors* and *output windows* but there are two significant features which the Windows platform aided. The first of these is the ability to transfer geometric and material information to finite-element analysis (FEA) programs and the second feature is the means by which the SPEED software can be linked to other Windows programs enabling SPEED to be integrated into a companies' design tool chain or to automate repetitive tasks. The former feature is based on a program neutral geometry file format (GDF) that I developed and the latter uses Windows COM (ActiveX) as the means to expose program functionality in a standard way.

3. GDF to FEA procedure

While the rationale behind the development of the GDF process is given in a later section describing PC-FEA, the program function and architecture is described here. For a given machine geometry, specific geometric vertices or node co-ordinates are calculated from the relevant set of named parameters as documented in the SPEED Manuals. These nodes are used in both the cross-section editor for the display of the motor and in the RE code where they are used to determine weights, inertias, widths and distances as necessary for the magnetic equivalent circuit calculations. In routines, very similar to the drawing routines, closed shapes - called sub-domains in PC-FEA – are constructed from the nodes by concatenating lines and arcs. Internally, lists of unique nodes and unique lines and arcs are maintained to ensure the integrity of the finished data file. This avoids a common error in FEA front-ends which is calculating the same point in two different ways at different times resulting in minute differences in the points used. When these points are transferred to the FEA package it can lead to either holes in the mesh, overlapping sub-domains or other “mysterious crashes”. Ensuring data integrity at the construction stage leads to a much more successful FEA process.

All the SPEED programs have this basic geometry transfer capability but most, PC-BDC especially, have pre-defined FEA procedures which can be automated using suitable FEA packages such as PC-FEA, Infolytica’s Magnet, JSOL’s JMag and others. These procedures are known as GoFERs, (Go to Finite Elements and Return) with the R being very important. I wrote the first PC-FEA GoFERs to perform specific engineering calculations whilst removing the usual error-prone manual drudgery normally associated with them. By making them simple and quick to run, the actual process of running the FEA package becomes almost invisible and the engineer is able to focus more closely on the interpretation of the results.

Table 2. Most used PC-BDC GoFERs	
Bgap distribution	in this a single open-circuit calculation is performed and a plot of the radial B field in the air-gap obtained
Btooth waveform	in this multiple open-circuit calculations are performed and at each step a value for the radial B field in a stator tooth obtained
i-psi calculation	in this multiple on-load calculations are performed with the stator current distribution being kept synchronised with the rotor position. At each step values of flux-linkage in all phases are obtained

As these GoFERs are often performed dozens of times during the design process, to simplify where possible, they use information already in the PC-BDC data file such as the drive type and the winding layout (if required). In each of the cases listed above the GoFER dialog provides additional options such as the solution domain to be passed to FEA and in the case of 1 and 2 the location of the B measurement. For 3, the FEA package also needs to know the stator current waveform and this is defined in the same terms as PC-BDC itself i.e. a peak current, ISP, and a phase advance angle, gamma or Th0. The actual current waveform calculated by a PC-BDC dynamic simulation, including chopping, could also be used. In addition, some control is given to the PC-FEA solver to allow the user to adjust the mesh density and the solver tolerance.

The “R” part of the GoFER comes when using PC-BDC’s Match FE facility where the adjustment factors for the magnetic equivalent circuit can be used to compare the finite-element calculation with the internal one. This is an example of the linking of a powerful external tool in both directions, a relatively unusual (but extremely productive) concept.

The benefits of using a GoFER are largely ones of speed and improved accuracy in the design calculation but more importantly it removes a whole set of error-prone activities. These include building the mesh, assigning material properties, assigning excitation and ensuring it is maintained relative to the rotor position, setting boundary conditions and other problem definition parameters. Once the FEA problem has been correctly posed and solved there still remains the problem of extracting useful engineering results from what is essentially an array of vector potentials. Flux-densities can generally be calculated using built-in FEA functions but to calculate the flux-linkage of a phase-winding, it is necessary to combine the vector potentials from multiple sub-domains together with knowledge of the winding layout in order to get a final answer. The i-psi GoFER automates this process too and writes the results to a file for comparison with PC-BDC’s internally calculated values.

4. Embedded FEA solver

Notwithstanding the great productivity gains obtained with the GoFER process, even more remarkable gains can be achieved by embedding the entire finite-element process in the RE code. In the piece of sample PC-BDC code shown below (which has had minor edits for clarity) the embedded PC-FEA solver puts a complete finite-element calculation at the disposal of the RE developer with a single function call.

```
id := -ISP * sin(gamma);
iq := ISP * cos(gamma);
ParkInverse(id,iq,0,Theta,iph1,iph2,iph3);
EmbeddedFEA_Getpsi(Params,Common,OPD,Count,
                   Theta,iph1,iph2,iph3,TRUE,
                   psi,Result);
Lq := psi.q/iq + (Lendt + Lext);
Ld := psi.d/id + (Lendt + Lext);
```

In this simplified example we pass a rotor position and three phase currents to the FE solver and get, in return, the flux-linkages in the *d* and *q* axes which are then used to calculate inductances for the time-stepping circuit solver in PC-BDC. What is maybe not explicitly made clear in the code sample is that the call to *Embedded_Getpsi()* handles almost every geometry available in PC-BDC, every winding configuration, all materials and all this information is automatically transferred during a similar single line set up call and of no direct importance to the engineers working in the code and they can concentrate on design equations and circuit solving.

Not only does this empower the RE developer with a much more accurate method than the traditional methods used previously, it also dispenses with the need to compare the finite-element results and adjust the traditional methods, or even to execute the traditional methods at all. When an embedded solver is both sufficiently robust and fast, it becomes possible to restructure the RE calculation to be altogether more effective, and to do calculations that were not even possible before.

In the Wound-Field Commutator program (PC-WFC) a similar call is used to calculate the variation of flux-linkages (and hence inductances) with respect to field, armature and commutating currents so that inductance matrices can be set up to have a full dynamic model of commutation to aid performance and brush life calculations.

5. Linking via ActiveX

In Windows, the most common means of inter-process activity is based on the Component Object Model (COM) often known by its earlier name of ActiveX. An ActiveX program contains a binary resource that describes the functionality the program is providing in terms of software "objects". This object specification is loaded into the Windows registry where other programs can find it and link to it. A typical example, for SPEED users, would be using MATLAB, Excel or Python to run multiple cases of a machine simulation, essentially doing multi-dimensional ranging, or optimisation beyond the built-in capabilities of the software.

To accomplish this I decided to write several objects that would allow control of the application (*AppAutomation*) and a complex object (*AppDesign*) that gave access to the parts of the SPEED software related to a specific design including separate objects for the windings and FEA GoFERs.

AppAutomation, has functions such as *CreateNewDesign*, *Quit* and parameters such as *Visible* and *VersionNumber* whose functions are simple to understand.

AppDesign is a much richer object giving access to the *Get** and the *Set** functions used internally to provide edit capabilities for the design data file. For simulation purposes, each program is different, but methods such as *DoDynamicSimulation* in PC-BDC and *DoSteadyStateAnalysis* in PC-IMD are typical of the functions provided. These functions map directly to the menu items under each program's Analysis menu. *AppDesign,* in PC-BDC and PC-IMD also provides a function for returning a *Winding* object which allows simple read and write access to the winding information – conductor location, number of turns, slot-fills etc. Similarly, GoFER related objects including *BDCGoFERIPSI* allow the i-psi GoFER process to be fully automated and *ElementsTable* which gives access to the post-processing of iron-loss data resulting from a GoFER run.

Using the SPEED ActiveX models customers have written their own in-house design and optimisation programs and integrated them into their design processes in a way that would not be possible otherwise. The ability to automate the edit-simulate-results cycle to synthesise designs to their customers, suppliers or manufacturing requirements allows for much faster time to final design. The ability to treat the SPEED software as a black-box has also led to novel uses such as [29] where inductance, resistance and other parameters for a fictitious machine are extracted from PC-IMD and then used to analyse a completely different topology of machine than is covered in the basic program. In addition several third parties also now sell add-on utilities to the SPEED software to automatically generate efficiency maps and other optimised design tools[30, 31].

6. Software Development

As the size of the SPEED software, the numbers of programs, the number of developers working on the code and the number of users depending on the software has increased, a large amount of effort has had to be spent on managing the software. This has been done mainly through the use of splitting the code into program specific projects sharing a library of common code, as described earlier, but the use of commercial software to simplify and manage the process has also increased.

6.1. Software management tools.

A shared library brings with it its own problems, specifically breaking changes i.e. a change in a library function that requires changes to the calling program.

This is achieved by comparison tools, some built in-house, but also commercial packages such as Acronis Merge. Build tools such as VSoft FinalBuilder are used to verify that the entire code-base is syntactically valid (although it may still not work) and work is on-going into automated testing. Back up and source code sharing is performed at a local level using individual ZIP files but code management software such as Borland's TeamSource and StarTeam are used to provide more secure facilities. In particular, StarTeam is used to provide, secure internet (remote) access to the code for each developer and includes facilities for merging and branching the code. This makes it possible to track the changes made to individual files and see what changes were made (and for what reason), as well as to reconcile files modified by different developers at the same time.

6.2. Company Specific Versions

While providing benefits for both SPEED and the individual organisations, company-specific software versions present another major complication, especially when combined with source code agreements in place with a small number of consortium member companies. The solution we use to facilitate this is to use the conditional compilation techniques (originally used to separate the DOS and Windows interface code), to separate the company specific code and place the proprietary or commercially sensitive material into separate units in a separate folder. In this way it is not possible for one company to compile another company's versions even with their own source code.

7. Finite element analysis

In the mid-to-late 1990's a considerable effort went into linking SPEED software with third-party commercial FEA software, specifically Vector Fields' Opera-2D, Infolytica's MagNet and Cedrat's Flux-2D which were all in common use with consortium members. The techniques we used to develop this functionality were generally specific to each particular FEA package and motor design program, and hence the amount of code was growing exponentially. The code was not inherently re-usable or particularly stable due to the changes the FEA companies made to their programs. This stability issue, in particular, plus the fact that we wanted more control over the internal workings of the FEA tool led to the commissioning of a FEA program, called PC-FEA. With the original architecture, supporting this would require writing PC-FEA specific modules for every SPEED program which would be a significant amount of work. The solution I devised to address this was the GDF as outlined above and shown in more detail in the diagram below.

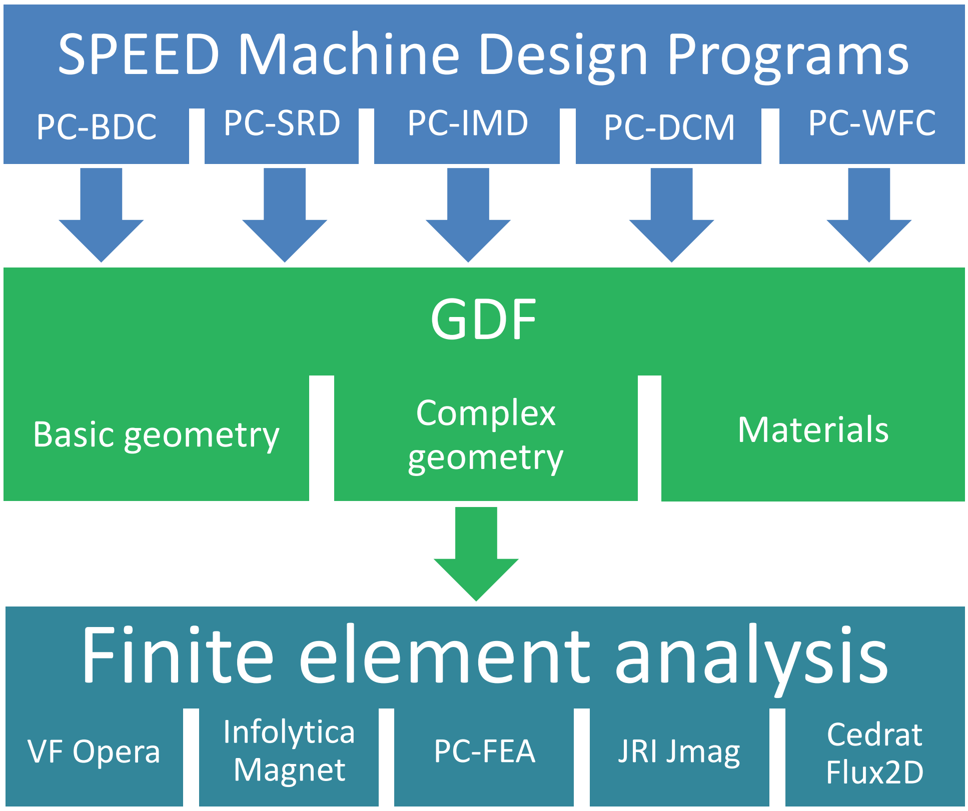

Figure 4: Structure of GDF transfer

The GDF library files provide facilities for handling arrays of nodes, lines, arcs, sub-domains and the properties associated with each one e.g. boundary types for nodes, lines and arcs, and material properties (including excitation) for sub-domains.

The geometry specific portions of the code only need to be written once in each program and thereafter all the FEA packages are supported automatically. In addition, if a new FEA program requires support it only needs to be written to read GDF files not PC-BDC or PC-SRD files. This has been done independently by the commercial companies JSOL, IES and Vector Fields. Other example translations of the GDF are to DXF for loading into FEA packages that are not compatible with GDF files and directly into AutoCAD and CorelDraw (both via ActiveX).

The development of PC-FEA was carried out by Mircea Olaru in Bucharest with localisation and additional interface work programmed by the author in Glasgow. The ability to alter the code means a rapid turnaround in addressing bugs, and also permits changes to be made to the interface and even in internal functions (e.g. the co-energy function) in a way that would be extremely difficult if not impossible in a commercial package.

8. Post University

As mentioned in the introduction, the SPEED Laboratory was acquired by CD-adapco in 2011 and Siemens in 2016. Since the initial acquisition the Author has been the main developer involved with integrating the SPEED software into CD-adapco's development process and team.

- The SPEED distribution is now created automatically on servers in the Lebanon, NH offices. Source code is downloaded from a git repository onto a build machine and configured to set date, version number and licensing then compiled, combined with support files and documentation, compressed and uploaded to a hosting site for customer download.

- The pace of technical development has slowed due to the retirement of Professor Miller and an increased focus on work linking to STAR-CCM+ and other CD-adapco programs. This stability has enabled a lot of work on consolidating and rationalising the SPEED software.

- The GDF file format has been re-implemented as an XML format (xGDF) to ease the creation of readers the first of which was for STAR-CCM+, CD-adapco's finite-volume based CFD program. The 3D aspects of geometry have been improved considerably to facilitate this and losses, in the form of a 2D heat-map can be calculated using PC-FEA and imported to the CFD study to accurately calculate temperatures.

- In recent months STAR-CCM+ has added the capabilities of a 2D and 3D electromagnetic finite-element solver and work is on-going to extend the GoFER concept to use this to include end-effects in the standard calculation.

In 2013, The University of Glasgow submitted the SPEED Laboratory as a case study to the Research Excellence Framework (REF 2014 [32, 33]) for assessing the quality of research in UK higher education institutions. This submission was widely reported and helped contribute to its position as the top Engineering institution in Glasgow and the West of Scotland, and one of the leading Engineering institutions nationally.

9. Conclusions

In this essay I have explained my role in the development of the SPEED software and, in broad terms, the academic papers which it both originated and contributed to. In the first section I have outlined the historical precedents of the SPEED software and how its architecture has developed to take advantage of new features of the Windows platform. I have shown how, as the platform became more capable, that features such as FEA first became automated and then routine and finally integrated into the main engineering calculations. I have described the functionality provided by the software architecture that has enabled researchers to develop motor theory in an easy to use framework.

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[48] T. J. E. Miller and M. McGilp, "High-speed PC-based CAD for brushless motor drives," in *EPE '91. 4th European Conference on Power Electronics and Applications*, Firenze, Italy 1991, pp. 435-9.

[49] T. J. E. Miller and M. McGilp, "Software for choosing the best brushless motor," in *Drives and Controls Magazine*, 1990, pp. 115-116.

[50] T. J. E. Miller and M. McGilp, "Nonlinear theory of the switched reluctance motor for rapid computer-aided design," *IEE Proceedings Electric Power Applications* vol. 137, pp. 337-347, November 1990.

[51] T. J. E. Miller and M. McGilp, "Sizing software for electrical machines," in *IEE Colloquium on Heavy Current CAD Applications*, London, 1989, pp. 6/1-6/5.

[52] T. J. E. Miller and M. McGilp, "PC CAD for switched reluctance drives," in *Third International Conference on Electrical Machines and Drives (Conf. Publ. No.282)*, London, UK 1987, pp. p 360-6.

12. Awards

[1] IEEE Industry Applications Society 2008 First Prize Paper Award for D. Ionel, M. Popescu, C. Cossar, M. I. McGilp, A. Boglietti, and A. Cavagnino, “A general model of the laminated steel losses in electric motors with PWM voltage supply,” in *Conference Record - IAS Annual Meeting (IEEE Industry Applications Society),* Edmonton, 2008

[2] IEEE Industry Applications Society 2006 Third Prize Paper Award for C. Cossar, T. J. E. Miller, M. Popescu, M. McGilp, and M. Olaru, “A new on-line torque estimator for brushless permanent magnet motor drives: Validation through the i-ψ diagram,” in *Conference Record - IAS Annual Meeting (IEEE Industry Applications Society)*, Tampa, FL, 2006, vol. 4, pp. 1657–1662.

[3] IEEE Industry Applications Society 2006 First Prize Paper Award for T. J. E. Miller, M. Popescu, C. Cossar, M. I. McGilp, M. Olaru, A. Davies, J. Sturgess, and A. Sitzia, "Embedded finite-element solver for computation of brushless permanent-magnet motors," in *Conference Record - IAS Annual Meeting (IEEE Industry Applications Society)* , Tampa, FL, 2006, 44(4):1478 - 1485.

[4] IEEE Industry Applications Society 2002 First Prize Paper Award for M. Popescu, T. J. E. Miller, M. I. McGilp, G. Strappazzon, N. Trivillin, and R. Santarossa, “Line start permanent magnet motor: single-phase starting performance analysis,” in *Conference Record of the 2002 IEEE Industry Applications Conference. 37th IAS Annual Meeting*, Pittsburgh, PA 2002, vol. 4, pp. 2499–2506.

[5] IEEE Industry Applications Society 2001 First Prize Paper Award for K. F. Rasmussen, J. H. Davies, T. J. E. Miller, M. I. McGilp, and M. Olaru, "Analytical and numerical computation of airgap magnetic fields in brushless permanent-magnet motors," in *Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting*, Phoenix, AZ, 1999, pp. 104-109.

[6] The IEE John Hopkinson Premium for T. J. E. Miller and M. McGilp, "Nonlinear theory of the switched reluctance motor for rapid computer-aided design," *IEE Proceedings on Electric Power Applications* vol. 137, pp. 337-347, November 1990.

Appendix 2:
Letters of permission and statements of contributions to submitted papers from co-authors

Submission of PhD by published work:

An Integrated Design Environment for Electric Machines

Malcolm Iain McGilp

March 2017

CONTRIBUTION TO PAPERS

The essay *An Integrated Design Environment for Electric Machines* describes the development of SPEED software architecture and features that formed my primary contribution to the submitted papers listed in Appendix 1. This body of work was written and published over a 25-year period. During that time the software was first created and subsequently developed into a world leading machine design program.

Programming for the research involved the development of custom versions of the software, providing different sets of functions and flexibility. Through the collaborative nature of the multi-authored papers, theory and programming developed together. Additional contributions varied in response to the focus and requirements in each case. The body of published work broadly falls into 4 distinct 'classes of contribution'. These are set out below, and link to more detailed descriptions by principal co-authors in their Letters of permission and statements of contributions to submitted papers, which forms the following part of this section.

1. Describing software and theory

Contributions in this category of papers cover early published work centring on the structure of the software and original methods of calculation. The first of these is [50], in which I programmed and evaluated several methods for calculating the unaligned inductance in a switched reluctance motor. The outcome is a method that is still used in PC-SRD today and which compares surprisingly well with FEA.

These early publications describe the software directly, and typically describe the main features and framework, such as [51-52] for switched-reluctance motors and [44; 46-49] for brushed and brushless permanent magnet motors. Carrying out machine design on a desktop computer was a new activity in the late 1980's and although the functionality and features described in the papers may seem basic from a contemporary perspective, they were breaking new ground at the time.

2. Integrating new theory into the software

Once SPEED software became established, papers focused on the new theory that was being implemented. An early example of this class of paper is [42], which focuses on the PC-SRD framework, that had the capacity to integrate original theory (by TJE Miller) in order to add new abilities. My development of this aspect of the architecture is described in the accompanying essay. These papers report on the subsequent improvements in accuracy and speed of calculation.

Other major areas of focus include: *Induction machines* [10], [28], [33], *Brushless permanent magnet machines* [37-38] and, more specifically, *Line-start motors* [11], [15], [24-26], [32] and [34-35]. For these papers my work primarily involved implementing and refining algorithms, towards improving functionality across all programs. Dr. Keld Rasmussen describes this aspect in his letter outlining contribution:

> *Malcolm McGilp contributed in bringing the theory into practical use. He implemented the algorithms into the Delphi based motor design program WBDC, where he linked it together with related motor design theory. Most importantly, he managed to link the theory into a visualisation that enabled motor designers, that do not have the deep theoretical knowledge of the paper, to bring the theory into practical use.*

This is echoed by Prof. Dan Ionel, who writes:

> *Mr. McGilp brought original contributions to the methodology of research and design of electric machines. Such contributions include the implementation of the SPEED software, associated mathematical models, and the development of the suite of programs that enabled the modern design of electric machines of many different types.*

A more general improvement to the machine design software has been the implementation of improved iron loss models [12-13], [2] and [30-31]. For these I not only re-implemented the models in a faster form, (they were developed in MATLAB and Excel by my co-authors) I also wrote methods that used PC-FEA to calculate losses on an element by element basis allowing much more accurate calculation. More recently, collaborations with Motor Design Limited has led to greater emphasis on co-simulation with thermal analysis [6], [9], [19-21]. These papers utilise the automation capabilities of the SPEED software and the simulation architecture to iterate between electromagnetic and thermal analysis to investigate the thermal effects of losses on performance.

3. Further developments of software architecture: Application and improvement of FEA

Advances in analysis capabilities, enabled by the use of FEA in the software, are examined in, for example, [35-36] and [39]. In these papers, I developed an approach to take advantage of the geometry transfer capabilities I implemented in SPEED to enable analysis of almost any of the many hundreds of available machine topologies and either use directly the FEA results or automatically adjust the internal calculations. The open architecture of SPEED made it possible for me to also implement this with other commercial FEA programs [38].

Papers [16-17], [22], [27] [29] and [33] each exploit the benefits of the SPEED framework to improve the design of machines, mainly by means of speed of setup but also by using the pre-defined FE calculations provided by the GoFERs.

A further advance is what became known as the *embedded solver,* see for example [7]. With this method, the process of setting up the FEA calculation and interpreting the results became completely removed from the user. As detailed in the essay, this utilises my work in geometry transfer, and I achieved the necessary speed by setting up and executing the FEA by means of automation. This led to a step-change in fidelity and accuracy alongside unprecedented speed of calculation.

In relation to the application and improvements which define this class of paper, Prof. Miller noted that:

> *It is easy to take these aspects for granted, but they did not happen by accident. ... In terms of research originality I would mention Mr. McGilp's work in developing original methods for extremely rapid finite-element analysis of electric machines.*

4. Electronic controllers

My work on the Flexible Controllers, designed by Calum Cossar, involved developing a GUI (first in DOS and later in Windows) to provide an easy to use interface for setting controller parameters and later logging of measurements and internal calculations. This was the basis of a number of papers [40] and [45] which describe the controller and its uses in machine testing in the laboratory. Later papers [8], [14], and [23] demonstrate extensions to this GUI, in some cases using automation to provide real time comparison of measured and calculated values.

Conclusion

My contribution to SPEED and these papers has been distinct, as author and architect of the software. It has played a vital and innovative role in enabling machine theory to be put into practice on the engineering desktop. It has been sustained; spanning more than two decades at the University of Glasgow, and continues within Siemens PLM. Over this period, working within interdisciplinary teams has achieved more than each author could have individually.

Letters of permission and statements of contributions to submitted papers from co-authors

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Appendix 3: **Curriculum Vitae**

Submission of PhD by published work:

An Integrated Design Environment for Electric Machines

Malcolm Iain McGilp

March 2017

Curriculum Vitae **Malcolm I McGilp**

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An Integrated Design Environment for Electric Machines

Volume 2 of 2

Malcolm Iain McGilp

B. Eng. (Hons)

Submitted in fulfilment of the requirements for the Degree of PhD by published work

School of Engineering

College of Science and Engineering

University of Glasgow

March 2017

	Papers	Citation Count*		
		S	WoS	GS
[1]	K. W. Klontz, T. J. E. Miller, M. I. McGilp, H. Karmaker, and P. Zhong, "Short-Circuit Analysis of Permanent-Magnet Generators," *IEEE Transactions on Industry Applications,* vol. 47, pp. 1670-1680 12 May 2011. https://ieeexplore.ieee.org/document/5766739/	28	15	39
[2]	D. Ionel, M. Popescu, C. Cossar, M. I. McGilp, A. Boglietti, and A. Cavagnino, "A General Model for Estimating the Laminated Steel Losses Under PWM Voltage Supply " *IEEE Transactions on Industry Applications,* vol. 46, pp. 1389-1396, July-August 2010. https://ieeexplore.ieee.org/document/5464360/	46	33	53
[3]	T. J. E. Miller, M. I. McGilp, and K. W. Klontz, "Approximate methods for calculating rotor losses in permanent-magnet brushless machines," in *IEEE IEMDC Electric Machines and Drives Conference*, Miami, FL, 2009, pp. 1-8 https://ieeexplore.ieee.org/document/5075175/	11	7	15
[4]	T. J. E. Miller and M. I. McGilp, "Analysis of multi-phase permanent-magnet synchronous machines," in *ICEMS Electrical Machines and Systems International Conference* Tokyo, 2009, pp. 1-6. https://ieeexplore.ieee.org/document/5382988/	0	0	16
[5]	T. Miller and M. I. McGilp, "Unified theory of superconducting and PM synchronous machines " in *ICEMS Electrical Machines and Systems International Conference* Tokyo, 2009, pp. 1-5. https://ieeexplore.ieee.org/document/5382829/	0	0	2
[6]	D. Staton, M. Popescu, C. Cossar, M. McGilp, S. Omori, and T. Kurimoto, "Analytical Thermal Models for Small Induction Motors," in *ICEM 18th International Conference on Electrical Machines*, Vilamoura, Portugal, 2008 https://ieeexplore.ieee.org/document/4800139/	0	0	0
[7]	T. J. E. Miller, M. Popescu, C. Cossar, M. I. McGilp, M. Olaru, A. Davies, J. Sturgess, and A. Sitzia, "Embedded finite-element solver for computation of brushless permanent-magnet motors," *IEEE Transactions on Industry Applications,* vol. 44, pp. 1124-1133, 2008. http://eprints.gla.ac.uk/4546/	23	13	7
[8]	C. Cossar, M. Popescu, T. J. E. Miller, M. I. McGilp, and M. Olaru, "A general magnetic-energy-based torque estimator: validation via a permanent-magnet motor drive," *IEEE Transactions on Industry Applications,* vol. 44, pp. 1210-1217, 2008. http://eprints.gla.ac.uk/4545/	7	4	8
[9]	A. Boglietti, A. Cavagnino, D. A. Staton, M. Popescu, C. Cossar, and M. I. McGilp, "End Space Heat Transfer Coefficient Determination for Different Induction Motor Enclosure Types," *IEEE Transactions on Industry Applications,* vol. 45, 2008. https://ieeexplore.ieee.org/document/4957502/	36	21	51
[10]	M. Popescu, T. Miller, M. McGilp, and C. B. Rasmussen, "Effect of MMF Harmonics on Single-Phase Induction Motor Performance – A Unified Approach," in *IEEE Industry Applications Conference, 42nd IAS Annual Meeting* New Orleans, LA, 2007. https://ieeexplore.ieee.org/document/4347932/	4	1	6
[11]	M. Popescu, T. Miller, M. McGilp, D. M. Ionel, and S. J. Dellinger, "A Unified Approach to the Synchronous Performance Analysis of Single and Poly-Phase Line-Fed Interior Permanent Magnet Motors," in *IEEE Industry Applications Conference, 42nd IAS Annual Meeting* New Orleans, LA, 2007. https://ieeexplore.ieee.org/document/4347780/	5	2	8

[12]	M. Popescu, T. Miller, D. M. Ionel, S. J. Dellinger, and R. Heidemann, "On the Physical Basis of Power Losses in Laminated Steel and Minimum-Effort Modelling in an Industrial Design Environment," in *IEEE Industry Applications Conference, 42nd IAS Annual Meeting*, New Orleans, LA, 2007. https://ieeexplore.ieee.org/document/4347768/	7	3	7
[13]	D. M. Ionel, M. Popescu, M. I. McGilp, T. J. E. Miller, S. J. Dellinger, and R. J. Heideman, "Computation of core losses in electrical machines using improved models for laminated steel," *IEEE Transactions on Industry Applications,* vol. 43, pp. 1554-1564, 2007. http://eprints.gla.ac.uk/3840/	95	68	121
[14]	C. Cossar, M. Popescu, T. J. E. Miller, and M. McGilp, "On-line phase measurements in switched reluctance motor drives " in *EPE'07 12th European Conference on Power Electronics and Applications*, Aalborg, 2007. https://ieeexplore.ieee.org/document/4417358/	0	0	1
[15]	M. Popescu, T. J. E. Miller, M. I. McGilp, G. Strappazzon, N. Trivillin, and R. Santarossa, "Torque behavior of one-phase permanent magnet AC motor," *IEEE Transactions on Energy Conversions,* vol. 21, pp. 19-26, 2006. http://eprints.gla.ac.uk/2834/	18	14	31
[16]	M. Popescu, D. Dorrell, and M. McGilp, "Instantaneous electromagnetic torque/force estimation in electrical motors using the finite element method- a review," in *ICEM 17th International Conference on Electrical Machines*, Crete, 2006.	0	0	1
[17]	T. J. E. Miller, M. Popescu, C. Cossar, and M. I. McGilp, "Performance estimation of interior permanent-magnet brushless motors using the voltage-driven flux-MMF diagram," *IEEE Transactions on Magnetics,* vol. 42, pp. 1867-1872, 2006. http://eprints.gla.ac.uk/3436/	25	23	26
[18]	D. M. Ionel, M. Popescu, S. J. Dellinger, T. J. E. Miller, R. J. Heideman, and M. I. McGilp, "On the variation with flux and frequency of the core loss coefficients in electrical machines," *IEEE Transactions on Industry Applications,* vol. 42, pp. 658-667, 2006 http://eprints.gla.ac.uk/3438/	108	84	142
[19]	D. G. Dorrell, D. A. Staton, and M. I. McGilp, "A Combined Electromagnetic and Thermal Approach to the Design of Electrical Machines," in *ICEMS Electrical Machines and Systems International Conference*, Nagasaki, 2006.	0	0	0
[20]	D. G. Dorrell, D. A. Staton, and M. I. McGilp, "Design of Brushless Permanent Magnet Motors - A Combined Electromagnetic and Thermal Approach to High Performance Specification," in *IEEE Industrial Electronics 32nd Annual Conference* Paris, France, 2006 https://ieeexplore.ieee.org/document/4153644/	3	0	12
[21]	D. G. Dorrell, D. A. Staton, J. Kahout, D. Hawkins, and M. I. McGilp, "Linked Electromagnetic and Thermal Modelling of a Permanent Magnet Motor," in *Power Electronics, Machines and Drives Conference*, Dublin, 2006 https://ieeexplore.ieee.org/document/4123580/	0	0	28
[22]	D. G. Dorrell, M. Popescu, and M. I. McGilp, "Torque Calculation in Finite Element Solutions of Electrical Machines by Consideration of Stored Energy," *IEEE Transactions on Magnetics* vol. 42, pp. 3431-3433 2006. https://ieeexplore.ieee.org/document/1704650/	0	7	15
[23]	C. Cossar, T. J. E. Miller, M. Popescu, M. McGilp, and M. Olaru, "A New On-Line Torque Estimator for Brushless Permanent Magnet Motor Drives: Validation through the i-psi/ Diagram," in *IEEE Industry Applications Conference, 41st IAS Annual Meeting*, Tampa, FL, 2006. https://ieeexplore.ieee.org/document/4025446/	1	1	1

[24]	M. Popescu, T. J. E. Miller, M. McGilp, G. Strappazzon, N. Trivillin, and R. Santarossa, "Asynchronous performance analysis of a single-phase capacitor-start, capacitor-run permanent magnet motor," *IEEE Transactions on Energy Conversion,* vol. 20, pp. 142-150, March 2005. https://ieeexplore.ieee.org/document/1396093/	31	18	40
[25]	M. Popescu, T. J. E. Miller, M. McGilp, F. J. H. Kalluf, C. A. da Silva, and L. von Dokonal, "Effect of Winding Harmonics on the Asynchronous Torque of a Single-phase Line-start Permanent Magnet motor," in *IEEE Industry Applications Conference, 40th IAS Annual Meeting*, Hong Kong, 2005 http://eprints.gla.ac.uk/2854/	16	12	19
[26]	M. Popescu, T. J. E. Miller, C. Cossar, M. I. McGilp, G. Strappazzon, N. Trivillin, and R. Santarossa, "Comparative study of starting methods for a single-phase permanent magnet synchronous motor," *European Power Electronics and Drives Journal,* vol. 15, pp. 48-56, January-March 2005.	0	0	1
[27]	M. Popescu, D. M. Ionel, T. J. E. Miller, S. J. Dellinger, and M. I. McGilp, "Improved finite element computations of torque in brushless permanent magnet motors," *IEE Proceedings Electric Power Applications* pp. 271- 276, 2005 https://ieeexplore.ieee.org/document/1425283/	26	14	37
[28]	M. Popescu, D. M. Ionel, S. J. Dellinger, T. J. E. Miller, and M. McGilp, "Analysis and Design of a Two-Speed Single-Phase Induction Motor With 2 and 18 Pole Special Windings," *IEEE Transactions on Energy Conversion,* vol. 20, pp. 62-70, March 2005. https://ieeexplore.ieee.org/document/1396083/	5	3	6
[29]	T. J. E. Miller, M. Popescu, M. McGilp, and C. Cossar, "Computation of the voltage-driven Flux-MMF Diagram for saturated PM Brushless Motors," in *IEEE Industry Applications Conference, 40th IAS Annual Meeting*, Hong Kong, 2005 http://eprints.gla.ac.uk/2855/	7	2	13
[30]	D. Ionel, M. Popescu, T. J. E. Miller, M. McGilp, S. J. Dellinger, and R. J. Heidemann, "Factors Affecting the Accurate Prediction of Core Losses in Electrical Machines," in *IEMDC Electric Machines and Drives Conference*, San Antonio, TX, 2005. https://ieeexplore.ieee.org/document/1531555/	7	0	7
[31]	M. Popescu, C. Cossar, T. J. E. Miller, and M. McGilp, "Iron loss modelling and effects in salient pole magnet synchronous motors a review," in *ICEM 16th International Conference on Electrical Machines*, Cracow, Poland, 2004, p. 6.	0	0	0
[32]	T. J. E. Miller, M. Popescu, C. Cossar, M. McGilp, G. Strappazzon, N. Trivillin, and R. Santarossa, "Line-start permanent-magnet motor single-phase steady-state performance analysis," *IEEE Transactions on Industry Applications* vol. 40, pp. 516-525, March-April 2004. http://eprints.gla.ac.uk/2836/	41	26	72
[33]	D. M. Ionel, M. Popescu, M. McGilp, T. J. E. Miller, and S. J. Dellinger, "Assessment of torque components in brushless permanent magnet machines through numerical analysis of the electromagnetic field," in *IEEE Industry Applications Conference, 39th IAS Annual Meeting*, Seattle, WA, 2004, pp. 1715-1722. https://ieeexplore.ieee.org/document/1510812/	54	40	2
[34]	M. Popescu, T. J. E. Miller, M. I. McGilp, G. Strappazzon, N. Trivillin, and R. Santarossa, "Line start permanent magnet motor: Single-phase starting performance analysis," *IEEE Transactions on Industry Applications,* vol. 39, pp. 1021-1030, July-August 2003. http://eprints.gla.ac.uk/2921/	54	34	72
[35]	T. J. E. Miller, M. Popescu, C. Cossar, M. McGilp, and J. A. Walker, "Calculating the interior permanent-magnet motor," in *IEMDC Electric Machines and Drives Conference* Madison, WI, 2003, pp. 1181-1187 https://ieeexplore.ieee.org/document/1210390/	14	2	19

[36]	T. J. E. Miller, M. I. McGilp, and M. Olaru, "Finite elements applied to synchronous and switched reluctance motors," in *IEE Seminar on Current Trends in the Use of Finite Elements in Electromechanical Design and Analysis*, London, UK, 2000, pp. 3/1-3/4. https://ieeexplore.ieee.org/document/843240/	0	0	5
[37]	K. F. Rasmussen, J. H. Davies, T. J. E. Miller, M. I. McGilp, and M. Olaru, "Analytical and numerical computation of airgap magnetic fields in brushless permanent-magnet motors," in *IEEE Industry Applications Conference, 34th IAS Annual Meeting.*, Phoenix, AZ, 1999, pp. 104-109. https://ieeexplore.ieee.org/document/799937/	50	41	0
[38]	T. J. E. Miller, M. I. McGilp, D. A. Staton, and J. J. Bremner, "Calculation of inductance in permanent-magnet DC motors," *IEE Proceedings Electric Power Applications,* vol. 146, pp. 129-137, March 1999. https://ieeexplore.ieee.org/document/766188/	26	15	41
[39]	T. J. E. Miller, M. McGilp, and A. Wearing, "Motor design optimisation using SPEED CAD software," in *IEE Seminar on Practical Electromagnetic Design Synthesis*, London, 1999, pp. 2/1-2/5. https://ieeexplore.ieee.org/document/757901/	2	0	12
[40]	L. Kelly, C. Cossar, T. J. E. Miller, and M. McGilp, "The SPEED Laboratory Flexible Controller: A tool for Motor/Drive Performance Evaluation and Optimised Product Development," in *Drives and Controls Conference*, Telford, 1999.	0	0	0
[41]	T. J. E. Miller, D. M. Ionel, M. I. McGilp, P. Brown, and M. Olaru, "Integrated CAD software for motor/drive design," in *Proceedings of Drives and Controls Conference*, Telford, UK 1998, pp. 48-52.	0	0	0
[42]	T. J. E. Miller, M. Glinka, M. McGilp, C. Cossar, G. Gallegos-Lopez, D. Ionel, and M. Olaru, "Ultra-fast model of the switched reluctance motor," in *IEEE Industry Applications Conference, 33rd IAS Annual Meeting*, St. Louis, MO, 1998, pp. 319-326 https://ieeexplore.ieee.org/document/732313/	17	5	37
[43]	D. M. Ionel, M. V. Cistelecan, T. J. E. Miller, and M. I. McGilp, "A new analytical method for the computation of air-gap reactances in 3-phase induction motors," in *IEEE Industry Applications Conference, 33rd IAS Annual Meeting*, St. Louis, MO, 1998, pp. 65-72. https://ieeexplore.ieee.org/document/732260/	5	4	12
[44]	D. A. Staton, M. I. McGilp, and T. J. E. Miller, "Interactive computer aided design of permanent magnet DC motors," *IEEE Transactions on Industry Applications,* vol. 31, pp. 933-940, July-August 1995 https://ieeexplore.ieee.org/document/298927/	6	5	0
[45]	C. Cossar, P. C. Kjaer, M. McGilp, T. J. E. Miller, and S. Colby, "Design and Function of a flexible controller for switched reluctance drive development," in *International Power Electronics Conference*, Yokohama, 1995, pp. 518-522.	0	0	0
[46]	D. A. Staton, M. I. McGilp, T. J. E. Miller, and G. Gray, "DC machine teaching experiments," in *EPE '93. 5th European Conference on Power Electronics and Applications*, Brighton, UK, 1993, pp. 35-40 https://ieeexplore.ieee.org/document/265076/	0	0	6
[47]	D. A. Staton, M. I. McGilp, T. J. E. Miller, and G. Gray, "High-speed PC-based CAD for motor drives," in *EPE '93. 5th European Conference on Power Electronics and Applications*, Brighton, UK, 1993, pp. 26-31. https://ieeexplore.ieee.org/document/264965/	0	0	16
[48]	T. J. E. Miller and M. McGilp, "High-speed PC-based CAD for brushless motor drives," in *EPE '91. 4th European Conference on Power Electronics and Applications*, Firenze, Italy 1991, pp. 435-9	0	0	0

[49]	T. J. E. Miller and M. McGilp, "Software for choosing the best brushless motor," in *Drives and Controls Magazine*, 1990, pp. 115-116.	0	0	0
[50]	T. J. E. Miller and M. McGilp, "Nonlinear theory of the switched reluctance motor for rapid computer-aided design," *IEE Proceedings Electric Power Applications* vol. 137, pp. 337-347, November 1990. https://ieeexplore.ieee.org/document/62457/	151	116	260
[51]	T. J. E. Miller and M. McGilp, "Sizing software for electrical machines," in *IEE Colloquium on Heavy Current CAD Applications*, London, 1989, pp. 6/1-6/5. https://ieeexplore.ieee.org/document/197786/	0	0	1
[52]	T. J. E. Miller and M. McGilp, "PC CAD for switched reluctance drives," in *Third International Conference on Electrical Machines and Drives (Conf. Publ. No.282)*, London, UK 1987, pp. p 360-6	0	0	13

*** Times cited in Scopus, Web of Science and Google Scholar databases**
where more than one version of the paper is listed on the database, the citation figures have been amalgamated