Electrical Machines Computer Simulation by Using Circuit-Field Models

Ioan-Adrian VIOREL, Loránd SZABÓ and Ilinca TOMESCU

Abstract: *The high performance personal computers (PCs) made possible an impressive development in the domain of the electric machines mathematical models. The circuit-field models become more sophisticated and are used more frequently in computing the electric machines characteristics. In the paper a personal point of view concerning the state of the art and the trends in this domain is presented.*

Key words: *electric machines, circuit-field models*

1. Introduction

The personal computers (PCs) had a dramatic impact on the humanity and particularly on the engineering domain. All R&D engineers, and not only, are fully dependent on PCs and the way of doing their work was totally changed compared with what happened only 20 or 30 years ago. By using PCs and the more and more advanced existing computer packages, everybody from the R&D put a very high stress on computer simulation avoiding in this way expensive prototyping and testing.

Nowadays, the models become more sophisticated taking fully into account some specific aspects which thirty years ago one could only dream about. Today, everybody can develop his own programs or can use commercially available packages. In the following paper a personal point of view will be presented concerning the way one should use and/or develop complex coupled models in the domain of electric machines.

Electrical machines models can be of circuit or circuit-field type, both of them fully considering the change of the rotor position, if necessary, due to the rotor movement.

Circuit models consist of voltage equations, flux-current equations and eventually of functions that describe the inductance variation versus of magnetizing current and/or rotor position, if necessary.

The machine parameters, mainly the inductances, are obtained usually by testing the machine. No dimensions are known or necessary, as are not known the air-gap topology, flux patterns, rotor and stator windings or any data obtained during design stage of the machine.

Circuit-field models are based mainly on analytical or numerical solving of the field problem associated with the machine topology and currents or/and permanent magnets pattern. The circuit-field model consists of adequately modified voltage equations and a flux linkage calculation procedure, the entire model being solved based on an iterative technique.

A circuit-field model requires the knowledge on the machine dimensions, air-gap topology, flux and current patterns, rotor and stator windings.

It means that a circuit-field model can be applied only within the machine design procedure since only then all the required data are known.

2. Circuit-field model evolution

In machine design and operating analysis the circuit-field models (CFM), were used

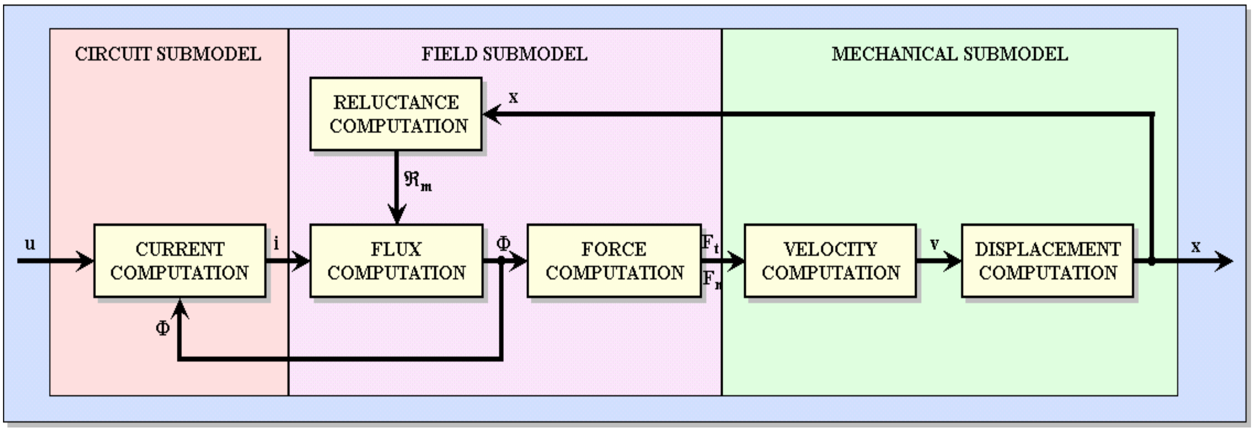

Fig. 1. The block diagram of CFM based on a MEC for linear stepper motor.

from the very beginning, but only later they got this very specific name.

It is mostly in connection with the 2D finite element or finite differences calculations of the magnetic field for the machines design.

Some of the first papers published, which clearly introduced the CFM concept are [1, 2, 3] even not all in the same manner. In [1], with a latter extension [4], the CFM concept, based mainly on magnetic equivalent circuit (MEC) and a step by step procedure to consider multiple armature reactions, is applied to induction motor.

A general 2D concept of CFM is defined in [2] since [3] is particularly focused on a specific linear machine introducing a complete circuit-field-mechanical model based on a MEC concept, Fig. 1.

A further extension of the CFM defined for that variable reluctance permanent magnet linear motor [5] allows its control strategy determination and proves once more the versatility and the usefulness of such approach.

In fact, the CFMs were intensive applied for the steady state and/or transient analysis of the induction motor.

A lot of very important developments were published in this domain as [6, 7, 8, 9, 10, 11] for example.

Beginning with the very consistent work of Arkkio [6] and continuing with some other specific developments [7, 8, 9] for instance, the results obtained were impressive.

It is quite interesting to figure out that the domain trends pointed in [10, 11] were quite accomplished and largely overrun by the nowadays results.

An interesting way of defining a model which couples the magnetic field analysis with circuit and kinematics modeling to study the steady-state and transients of a brushless motor is presented in [12].

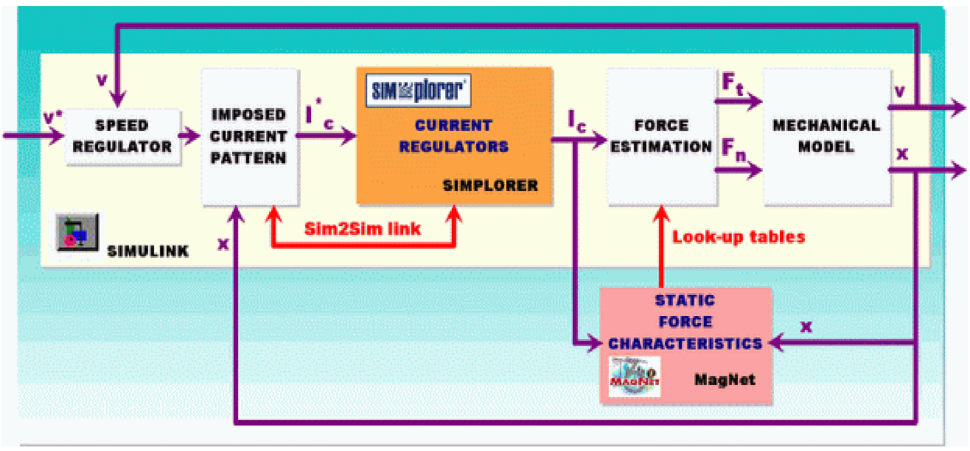

Fig. 2. The CFM for a system with variable reluctance linear motor built by using three different computer programming environments.

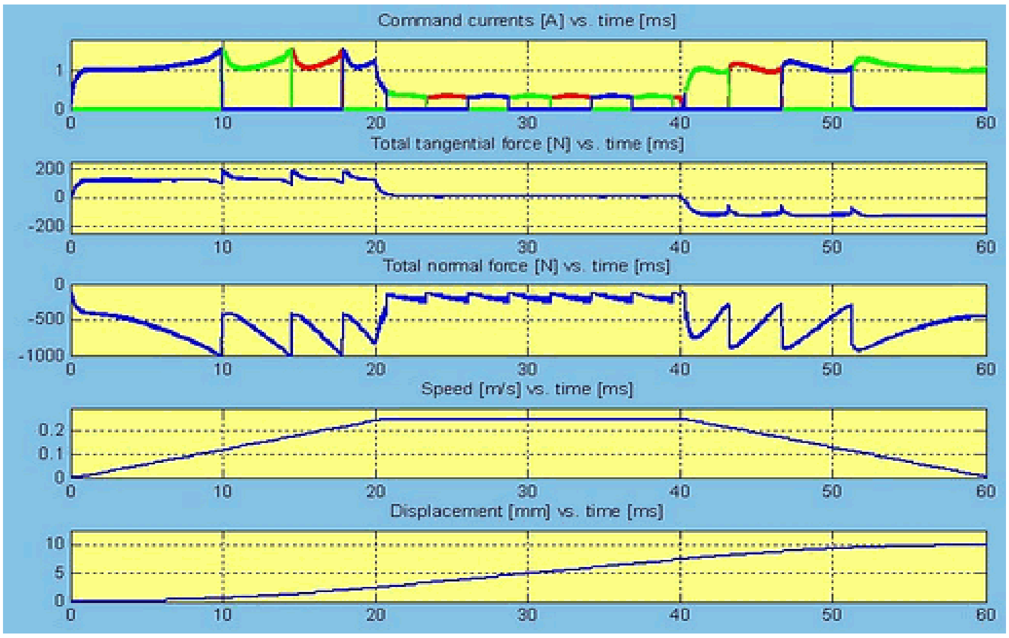

Fig. 3. Results obtained by employing the complex CFM presented in Fig. 2.

In [13, 14, 15] results obtained by coupling different computer programming environments, as packages for finite element (FE) analysis and system simulation, to study on the CFM basis the steady state and transient behavior of the different electric machines are presented.

It is a long way from the simple CFM defined in [3] and the complex coupled programming packages, Fig. 2, used in [15] for quite the same purposes.

The results given in [15], Fig. 3, sustain the versatility and the potential accuracy of such an approach.

By now there are quite many commercial computer programs which solve simultaneously, with high accuracy, a CFM for different machines. They allow for steady-state and transient behavior analysis, as it is shown in [16, 17] for instance, Fig. 4, where a Flux2D finite element analysis is intrinsic coupled via a circuit model with Simulink to calculate the transient behavior of a brushless permanent magnet, Fig. 5, [16] and respectively of a double excited synchronous motor, Fig. 6 [17].

For the 120º commutation pattern of the switches, Fig. 7, the phase current of the PM brushless obtained by employing the above described CFM based package is shown in Fig. 8, [16].

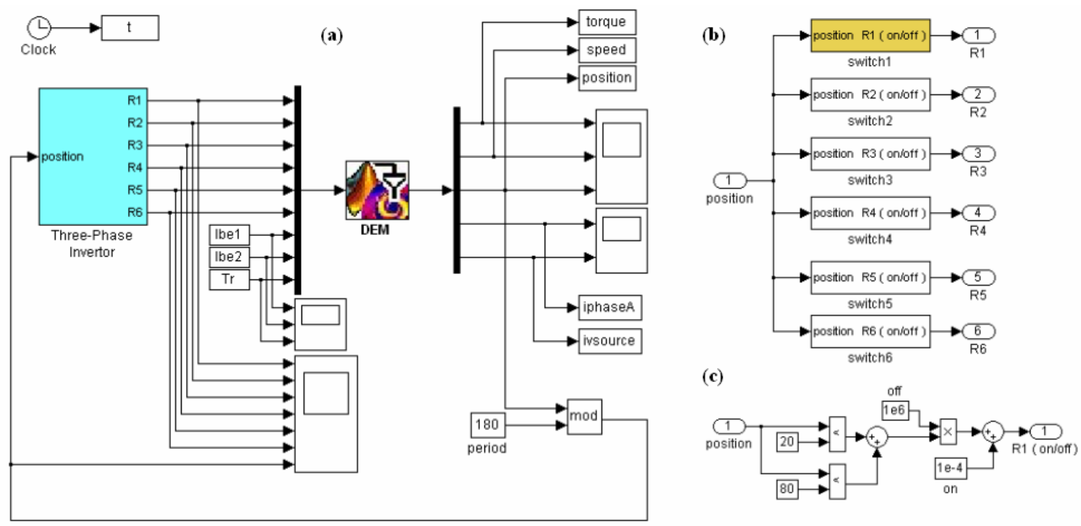

Fig. 4. Circuit –field model within FLUX 2D-FEM (DEM=double excited motor).

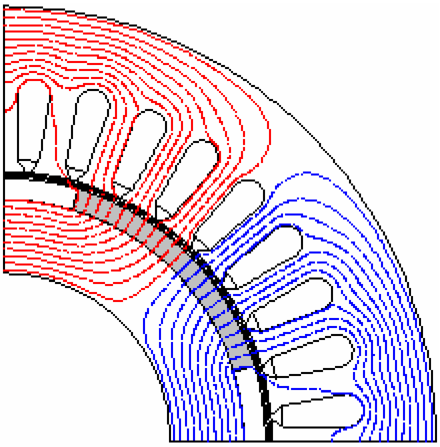

Fig. 5. Field lines distribution in the studied DC brushless motor.

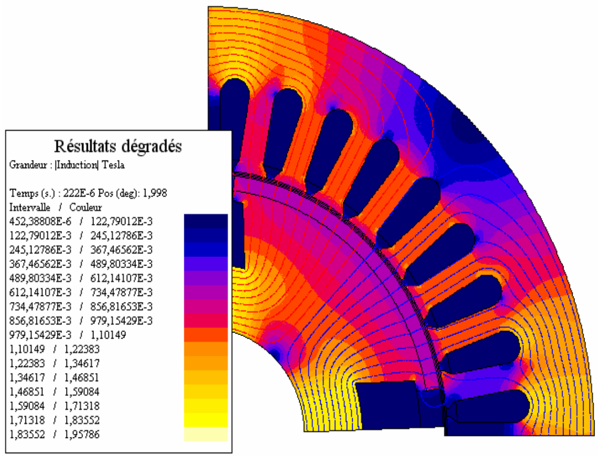

Fig. 6. The field lines and the flux density distribution in the DEM's core at no-load.

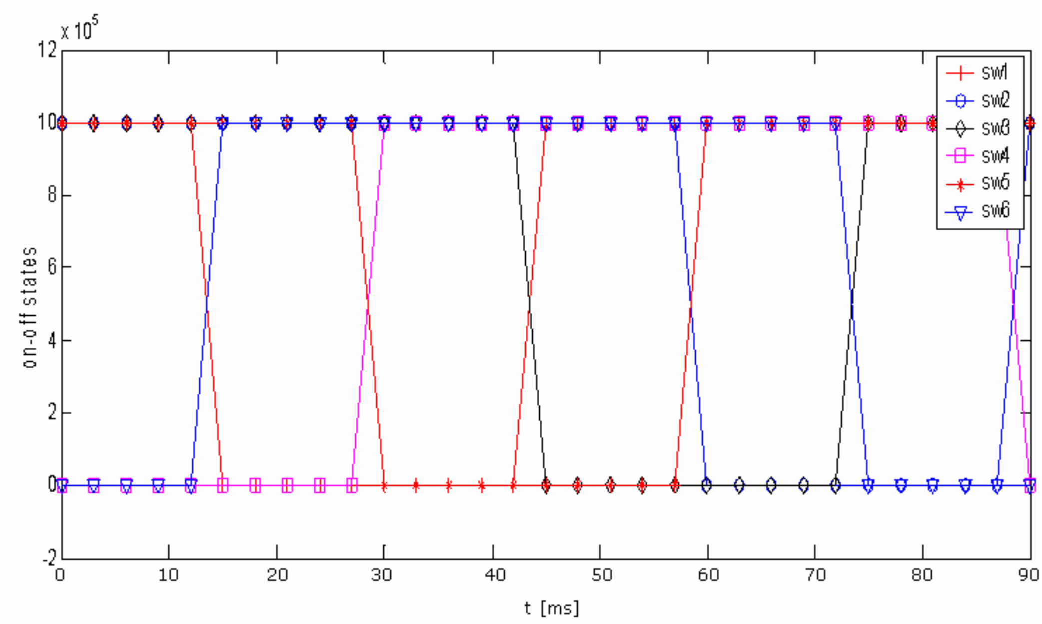

Fig. 7. Phase applied voltage for 120° commutation, DC brushless motor.

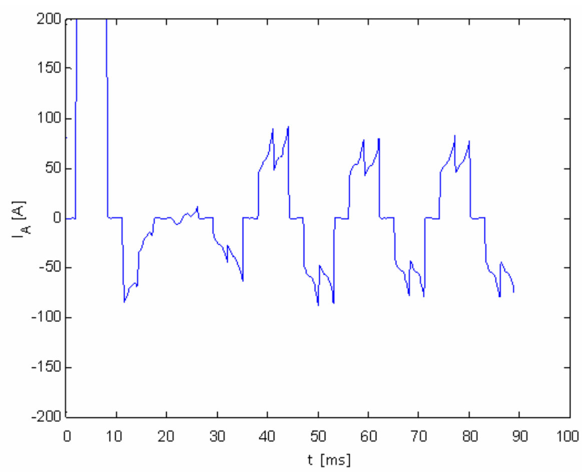

Fig. 8. Phase current variation versus time for a starting on regime, DC brushless motor.

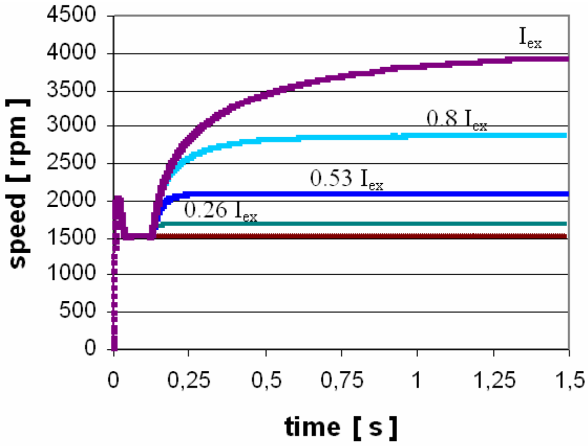

Fig. 9. Speed vs. time for different values of the excitation current, DEM.

In the second case, double excited synchronous machine, the speed versus time characteristics, calculated with the same package are given in Fig. 9 [17] for different values of the excitation current.

3. Electrical machines design and circuit-field models

The gap between the simple MEC proposed in [1] for instance and the complex programming packages available today for solving CFMs is extremely large, but the improvement of the programming packages was sustained by the impressing impetus in the field of personal computers (PCs). The PCs structure was changed quite dramatically during the last 20 years and in the same time the performances of the components and of the entire ensemble were steadily improved, maintaining or even decreasing the price. One thing remains quite the same as at the beginning, a more sophisticated programming package costs more and requires larger computer time for solving a certain application based on a CFM. Therefore still the usual question "is worth doing it this way?" remains valid.

Let explain everything on an example since it might be easier to understand what would be pointed out in this short discussion. As an example a designing procedure for a double salient motor, switched reluctance motor (SRM) or a double salient permanent magnet motor (DSPMM) for instance, will be considered.

Basically this procedure should start with a preliminary sizing which allows for key dimensions calculation and machine performance evaluation.

The next step consists on applying a numerical magnetic field computation method such as FEM for example, in order to bring the preliminary geometry near to optimum. The machine steady-state and dynamic characteristics can be obtained by using FEM analysis.

Usually it follows a thermal analysis, which can be done via different methods such as building a thermal equivalent circuit or employing a FEM analysis computing package containing a part dedicated to the temperature distribution calculation.

Another step should be devoted to vibration and noise prediction. It implies usually a calculation of the 2D resonant modes that allows the determination of the force magnitudes and frequencies.

The steady state and transient behavior of the drive system, including the machine, the supply source and the controller, must be simulated. This simulation is of great importance and it should help the designer in taking his final decision considering the possibility to use the designed motor in the specific considered application.

A CFM can be useful in almost all the above presented design steps, even in the thermal analysis if the circuit-field model is extended with an adequate thermal model.

When an extended computing package, as the one developed by CEDRAT for example and used in the above discussed applications [16, 17] and in a lot more, is employed, usually it is based on a CFM for the considered machine, the second and the last step of the designing procedure are coupled together.

The main question concerns the costs and the computing time. If a much simpler CFM is used, as the one proposed in [18] for SRM model, based on the motor air-gap variable permeance calculation [19], then the

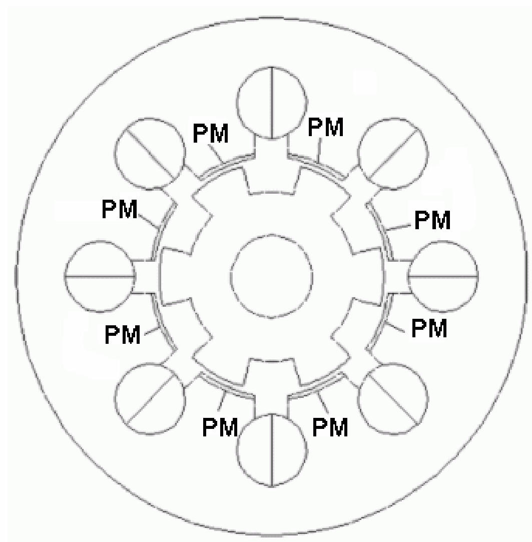

Fig. 10. Cross-section of a DS machine with the PM placed on the stator poles' face in the air-gap.

computing time is drastically shortened, the program can be developed or adapted easily by the user and it does not require a very performing PC.

The flowing chart of the program, developed for a double salient air-gap permanent magnet (DSAGPM) machine, Fig. 10, is given in Fig. 11.

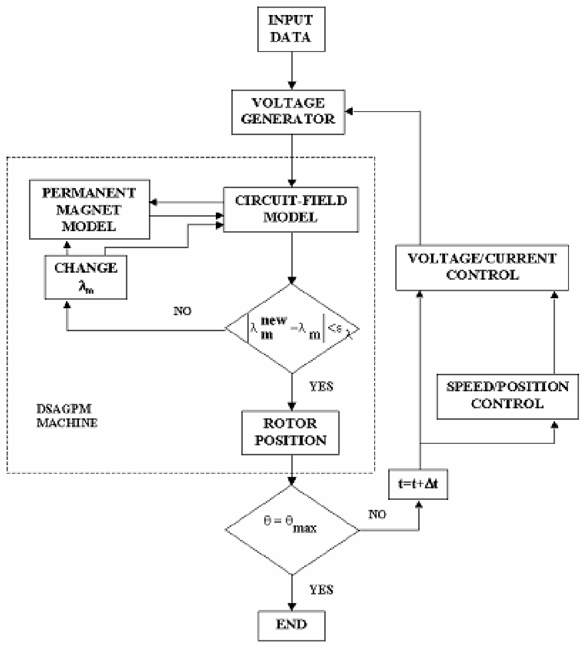

Fig. 11. The block diagram of the program.

The MEC which constitutes the base of the flux calculation is given in Fig. 12 [20].

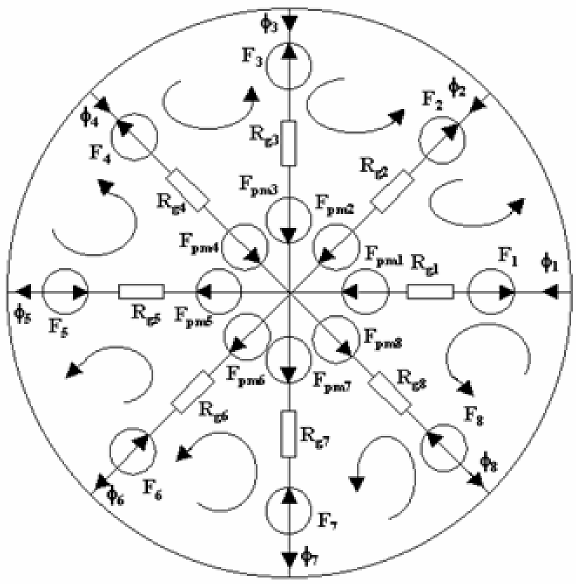

Fig. 12. Sample DS machine magnetic equivalent circuit (MEC).

Such a program can offer the possibility to calculate the transient and steady-state characteristics, as the ones shown for a sample DSAGPM motor in Fig. 13 [20] and would be very useful for the sizing step of the design procedure.

Considering that the magnetic field calculation via a 2D-FEM analysis is quite compulsory within a designing procedure, a way to improve the calculation of a SRM's characteristics, via a quite similar to above

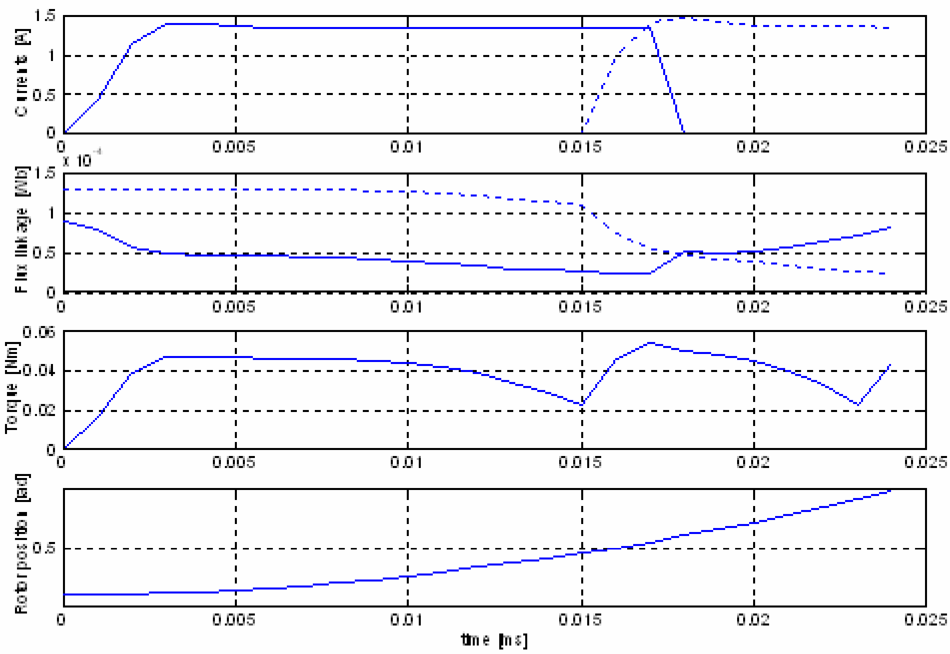

Fig. 13. Sample DS motor with PM in the stator dynamic characteristics for initial angle α_o=π/12, voltage step angle α_{step}=π/12, overlap angle α_{ov}=π/48, load torque T_s=0.002 Nm.

presented program based on CFM, was proposed in [21].

The approach presented in [21] combines the results obtained by 2D-FEM analysis on a given rotor position and the simplified CFM, based on a MEC similarly to the one shown in Fig. 12.

The developed program fills up the gap between the FEM-computed field at different rotor position by calculating the current value for the next step.

The results are obtained for a motor fed with ideal square-wave voltage on each phase [21].

The iterative magnetic flux calculation considering the 2D-FEM obtained results is given in Fig. 14 and the SRM's characteristics calculated with and without employing the 2D-FEM support are presented in Fig. 15 and Fig. 16 respectively [21].

It is quite a good example which shows how using some easy to be obtained field values by solving magneto-static problems via a 2D-FEM commercial package, a simple CFM based program cam be extended and improved.

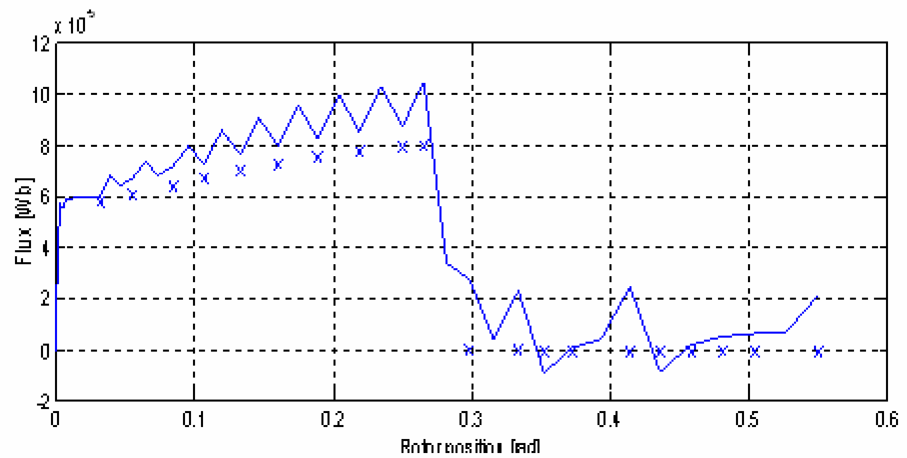

Fig. 14. Iterative flux calculation with 2D-FEM support (× FEM calculated values).

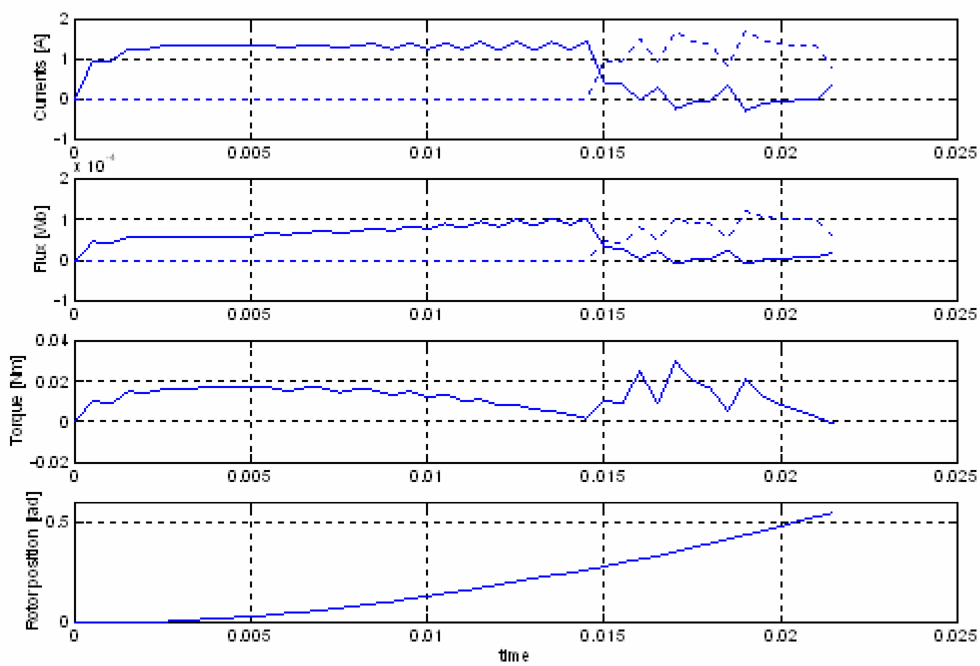

Fig. 15. SRM's transient, with FEM calculation.

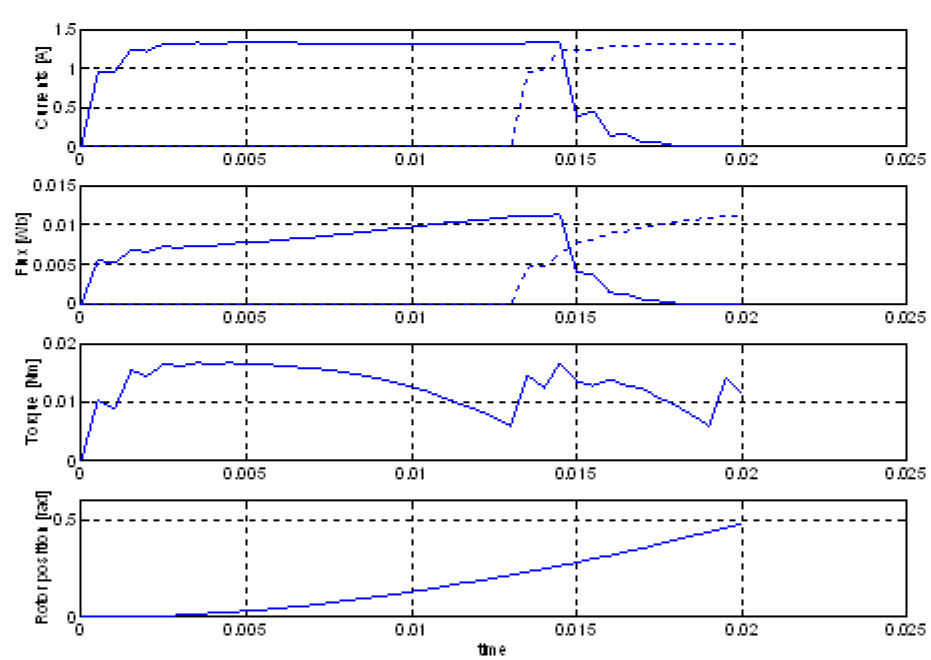

Fig. 16. SRM's transient, no FEM calculation.

4. Conclusions

A simple computer program based on CFM developed in MATLAB as is the one presented in [20] for example, can be quite easily extended to allow the losses calculation once the air-gap flux and the phase current values are known. It means that such a program can be of real use not only in the sizing part of a design procedure, but in thermal analysis and in drive simulation as well.

When an optimized design is the target then such programs, as that presented above, should be extremely useful since it will take definitely much less time to check, for different variants, the steady-state and transient characteristics with this sort of simple programs than by using complex programming packages as is the one used in [16, 17].

Considering all the developments presented above and the trends in the field the following conclusions look like coming up quite naturally:

- In the nearest future the commercial available program packages based on a coupled circuit-field-movement-thermal models will became more powerful, but will require in the same time more performing PCs, will consume more CPU time and will have a higher cost.
- Quite simple programs, based on extended coupled models, included or not in a larger CAD environment, will play quite an important role in electric machines design and in their characteristics calculation.
- Definitely the sizing step from a design procedure, and many times not only this step, can be based on quite simple CFM developed with or without the 2D-FEM analysis support.
- The simpler CFM based programs will have an improved accuracy and will become easily adaptable for different machines structures, enlarging their applicability and versatility.

As an overall conclusion it has to be said that the researchers in this field should cope with the actual tendencies and try to use their own programs together with the existing commercial ones.

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