METHODOLOGICAL CONSIDERATIONS OF DRIVE SYSTEM SIMULATION, WHEN COUPLING FINITE ELEMENT MACHINE MODELS WITH THE CIRCUIT SIMULATOR MODELS OF CONVERTERS.

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Abstract
The paper discusses the issues with - and provides an overview of - the available methods for drive system simulation when the electrical machine is modeled by the finite element method (FEM) and the converter with the control is modeled by a circuit simulator. The main emphasis is placed on the necessity and accuracy of the simulation of the interaction between the subsystems: the electrical machine, the power electronics and the control logic.

1. INTRODUCTION

A typical drive system consists of an electrical machine, power electronics and a control intelligence, usually integrated into the converter. Fig 1 shows a simplified structure of a drive system with the interacting components.

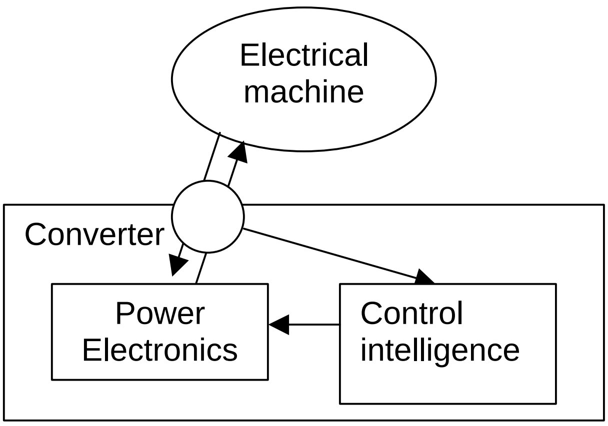


Fig.1 Schematic structure of a drive system. Interaction between the sub systems is represented by arrows.

The direction of the arrows indicates, which system has a direct effect on the other. In this schematic diagram it is supposed that measuring the voltages and currents at the connecting terminals between the electrical machine and the converter terminal, provides all the information needed for the control:

- currents for e.g.: power/torque feedback
- voltage output from the converter e.g. flux/speed feedback

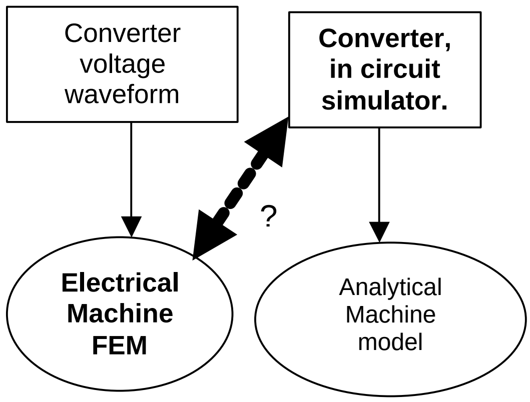
From this schematic figure one can conclude, that there is a mutual influence between the electrical machine and the converter, and the outcome of this mutual coupling is the input for the control intelligence.

1.1 Conventional design of components

The conventional design of the components involves accurate modeling of the component, which is the object of the design and optimization, while utilizing reduced models for the other components. Traditionally it has been an acceptable approach. However in modern drive systems it is becoming increasingly difficult to define the error made by reduced modeling and usually it is only after an in depth analysis, when such conclusion can be made. It is becoming a paradigm of system simulation, that in order to be able to determine whether one needs accurate system simulation or not, accurate system simulation is required.

2. TRADITIONAL DRIVE SYSTEM MODELS

Electrical machines fed from frequency converters are commonly analyzed by providing proper voltage waveform for the 2D FEM model of an electrical machine, while ignoring the effect what the machine has on the drive circuit. Control systems are also often analyzed in connection with only partially accurate analytical machine models. Fig2. shows these common ways of simulation, from the electrical machine point of view Fig.2. a, and from the converter point of view: Fig. 2. b.



a, b,

Fig 2. a, Drive system from the machine point of view.
b, Drive system from the converter point of view.
In these methods the mutual interaction is not modeled.

Both of the above mentioned approaches ignore – or heavily simplify – the interaction between the electrical machine and the converter circuit. The separate study of the subsystems seriously limits the analysis of the interactions in the whole system. There are a few guidelines to decide, when such separate analysis is justified.

1. 2D FEM modeling of the electrical machine with the converter supply voltage wave is justified if the voltage waveform can be considered as pre-defined. Usually this is the case if:

   - The control does not change the switching pattern.
   - In the studied operation point the converter behaves linearly. (Voltage can be considered independent from the motor current.)
   - The control parameters do not change.

2. Circuit simulator modeling of the converter, connected with analytical machine model is justified if the machine parameters remain constant and well definable. This is the case if:

   - The machine runs in a well-known operation point.
   - The machine parameters can be calculated or measured with desired accuracy for the simulated operation point.

For the experts of modern drive systems it is obvious that these conditions cannot always be met. With increased frequency the very reason for drive simulation is to study what happens when the drive is running in an operation point where such restrictions do not apply.
It can be stated that accurate analysis of the drive system for such cases requires a coupled simulation of the components.

3. COMBINED SOLUTION OF THE MAGNETIC FIELD AND CIRCUIT EQUATIONS

The combined solution of the magnetic field equations in electrical machines and the circuit equations of the windings and the external components is more than a decade old research topic [1,2,3]. The first papers were dealing with the inclusion of the circuits of the electrical machine itself into the field equations, but the combination of power electronic components of inverters soon followed.

3.1 Strong - weak, direct - indirect coupling

The terminology of weak – strong, direct – indirect coupling is continuously developing and it is quite freely defined by individual authors.
Some regard strong and direct, weak and indirect as synonyms. This is a simplified but very sober approach, which helps to avoid misunderstandings about the properties of the coupling. It is however harder to define special coupling methods by this definition.
Others relate the strength of the coupling to the accuracy of the physical model used and the directness of the coupling is viewed in light of the numerical technique applied.
The explanation presented in this paper is adjusted for the better description of the specific problem of the coupling in drive systems, using FEM machine models and circuit simulator models of converters. Table 1. represents the different possibilities for the coupling methods by the terminology used in this paper:

	Strong coupling	Weak coupling
Direct coupling	Mutual interaction between the converter and the machine is modeled. Equations are solved together in one system. Eq.1.	NO mutual interaction between the converter and the machine is modeled. Equations are solved together in one system, but the coupling between components is missing. Eq.4
Indirect coupling	Mutual interaction between the converter and the machine is modeled. Equations are solved separately. Usually in the form of numerical decoupling, or iterative process. Eq.2,3	NO mutual interaction between the converter and the machine is modeled. Equations are solved separately. Eq.5

Table 1. Representation of coupling methods

3.1.1 **Strong, direct coupling**

The combination of the equations leads to the assembly of one unified system of equations, which has been solved together, thus leading to a strong coupling between the magnetic field and electrical circuit domains. Several high quality publications are available to describe the methods for strong coupling. Eq.1 shows the basic philosophy of the strong coupling in one possible formulation.

$$\begin{bmatrix} FEM & c1 & c2 \\ c3 & PE & c4 \\ c5 & c6 & CONT \end{bmatrix} \begin{bmatrix} A_{FEM} \\ A_{PE} \\ A_{CONT} \end{bmatrix} = \begin{bmatrix} rhs_1 \\ rhs_2 \\ rhs_3 \end{bmatrix} \quad (1)$$

The variables in Eq.1 stand for:

- FEM - stiffness matrix of the FEM equations
- PE - the matrix for the power electronics circuit
- CONT - Matrix for the control logic
- c1-c6 - coupling matrices
- A - variable vectors, e.g.: A_{FEM}=vector potential
- rhs - Right hand side vectors

3.1.2 **Strong, indirect coupling**

When using indirect strong coupling, the same equation system - as presented in Eq.1 - is solved in a subdivided manner. The subdivision can be implemented at several stages of the solution process, e.g.: subdivision in every nonlinear iteration step [1], subdivision at the solver level, subdivision at mixed levels [5], etc.. Eq.2 and Eq.3 show a possible separation of Eq.1 into two systems of equations. One part includes all nonlinear variables, which are needed to be iterated. This is created by the gauss elimination of the linear variables. The elimination can be easily repeated in consecutive time steps by storing the "eliminating matrices" [1,5]. The other system of equations contains the linear variables, which can be calculated in one step after the iterative solution of the other system has converged. Such formulation reduces the size of the system of equations for the duration of the nonlinear iteration process.

$$[NL][A_{NL}] = [rhs_{NL}] \quad (2)$$

$$[L][A_L] = [rhs_L] \quad (3)$$

NL is the non-linear system matrix including all sub-systems. A_{NL} stands for the non-linear variables and rhs_{NL} is the corresponding right hand side vector after the gauss elimination of the linear equations. Accordingly *L*, A_L, rhs_L stand for the linear system matrix, variable vector and right hand side vector respectively.

3.1.3 **Weak, direct coupling**

In this case the physical interaction between the electrical machine and the converter is not modeled, or only a semi empirical model is used. In the weak coupled formulation the coupling matrices in Eq.1 are not present or all are "zero matrices". Eq.4 presents the weak - direct coupling formulation:

$$\begin{bmatrix} FEM & 0 & 0 \\ 0 & PE & 0 \\ 0 & 0 & CONT \end{bmatrix} \begin{bmatrix} A_{FEM} \\ A_{PE} \\ A_{CONT} \end{bmatrix} = \begin{bmatrix} rhs_1 \\ rhs_2 \\ rhs_3 \end{bmatrix} \quad (4)$$

3.1.3 **Weak, indirect coupling**

As the coupling terms are all zeros in Eq.4 it can be cut into 3 independent equations, row by row. Eq.5 presents the separated equations:

$$\begin{aligned} [FEM]\,[A_{FEM}] &= [rhs_1] \\ [PE]\,[A_{PE}] &= [rhs_2] \\ [CONT][A_{CONT}] &= [rhs_3] \end{aligned} \quad (5)$$

4. SELECTION OF THE COUPLING METHOD

Utilizing Eq.1, Fig.1 and the general knowledge on drive systems, certain guidelines for the selection of the coupling method can be defined. The following variables will be used to choose the coupling method:

- T_{EM} = Time constants of the electrical machine. (depending on machine properties, including all inductances, e.g.: end windings, etc.)
- T_{CC} = Time constants of the converter and the cabling.
- T_C = Time constant, (describing the speed) of the control algorithm.

The following variables describe the outcome of the coupling method selection. These will be defined as the functions of the variables above:

- t_{MAX} = Maximum time steps size allowed for the analysis. It will be defined as a function of the dominant variables above.
- From the coupling matrices c1-c6, those which can be set to zero - meaning weak coupling between corresponding sub-domains - will be named.

The following simple guidelines can be used to define the type of the physical coupling model:

- The smallest time constant is the dominant and the one, which defines the maximum allowable time step size: $t_{MAX.}$
- Large difference between time constants, indicates that the modeling of the interaction can be ignored between those sub systems and the coupling can be defined as weak coupling.
- If the control is slow the effect of it to the whole system should be considered one (or more) time steps later than the effect of the interaction between the converter electronics and the electrical machine.

Some examples for the coupling selection are presented in Table 2. The relationship of the variables are presented as the conditions on the left-hand side and the proposed coupling model is given by introducing the proposed "zeroed" coupling coefficients. Eq.1 is used to define the coupling matrices, which can be set to zero. They indicate, that only a weak coupling is required for those related subsystems.

Condition	**Proposed "zeroed" coupling coefficients**
Small machine at the end of long cabling, with slow control. $T_{EM} << T_{CC}$ and $T_{EM} << T_C$	c1, c2, c3, c5 $t_{MAX} = f(T_{EM})$
Speed of the control, is significantly slower than the speed of the electrical transients. $T_{EM} \sim= T_{CC}$ and $(T_{EM}, T_{CC}) << T_C$	c2, c4, c5, c6 (The control effects the system, but only in a later time step.)

Table2. Example cases for coupling method selection.

4. NUMERICAL ISSUES

When coupling the 2D FEM models of electrical machines for magnetic field calculation with the circuit equation models of converters the following numerical problems have to be addressed:

5.1 Time step size

Transient time stepping simulation requires the choice of time steps both in the magnetic domain and in the circuit simulator domain. The time steps size can be significantly different in these domains - depending on the time constants - but the co-simulation requires adjusting the different time steps sizes. The simplest solution is to choose the smaller time step for both domains, although this could lead to unacceptably long calculations. Another option is to use variable time step size but the choice of such variable time stepping method requires also careful strategy. If eddy currents are present at the magnetic system, the variable time step size must be defined considering the correct modeling of those time dependent embedded sources of the magnetic field.

5.2 3D effects modeled in 2D FEM

The exact end winding reactance values for a 2D FEM machine model are inputs from the FEM calculation point of view. These inaccuracies due to the missing 3D effects in the 2D model can have an important effect because the end winding reactances act as smoothing filters.

5.3 **Realization of strong coupling**

When the magnetic field model is solved with a FEM solver and the power electronic circuits and the control logic is modeled in a circuit simulator the realization of the strong coupling represents a great challenge. It has been discussed in section 3.1.2 that strong indirect coupling is possible, but it requires special formulations (e.g.: unification in each iteration step [1]) Using commercial products those special solver techniques must be supported commercially. This requires very close cooperation between the calculation tool developers.

6. CONCLUSIONS

The paper highlighted some of the major issues with co-simulation of the magnetic field in electrical machines and the circuit simulation of the power electronic circuits and the control logic for the modeling of drive systems.
It is obvious, that while thorough knowledge of both domains - electrical machines and converters - is a must, expertise in these areas alone might not be anymore sufficient in all cases of modern drive system analysis. It is likely that the development of a new "science of coupling" will be required to build efficient calculation tools for drive system modeling in the future.

The emerging fields of applications for the coupled modelling could include:

- Controlled drive working separately (e.g.: double fed wind generators)
- Controlled drive working in a network
- Other multi-physics phenomena – involving electro-magnetic field calculation and converter circuit simulation - in sub-domains.

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