Electromagnetic Actuators Modeling, Simulation and Optimization: Review of Methods and their Application for Switching Devices

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Abstract: Single coil actuators are representing one important component of ABB's medium voltage switching devices. Their optimal design is strongly required in order to ensure a robust design. Different problems are usually studied by employing different methods. Therefore, this paper focuses on a review of methods applied for electromagnetic actuators modeling, simulation and optimization.

Keywords: medium voltage reclosers, single coil actuator, 2D static simulation, reduced order modeling, 3D dynamic modeling, simulation, optimization, validation.

1. Introduction

Electromagnetic actuators are representing one important component of ABB's medium voltage reclosers [1], [2]. Their performance is strongly influenced by the considered material properties as well as by the electronic control units that will power the actuator.

Figure 1. ABB 3-Phase GridShield Recloser.

Depending on the studied phenomena, different modeling, simulation and optimization methodologies are being used for medium voltage reclosers analysis. One could note: reduced order modeling approach [3], 2D static simulations [4], 3D transient analysis [4] or coupling of the Finite Element model with other mechanical simulation software. Once the models are being validated, they are integrated into an optimization loop in order to identify a robust design for medium voltage reclosers.

Therefore, this paper focuses on a review of the different methods employed for reclosers optimization and presents the advantages and the limitations of the different methods. In the next section, this paper gives an overview regarding the operating principle of a single phase recloser as well as the motivation of the research work. The next section presents the different modeling and simulation methods considered – from reduced modeling approach to 3D dynamic simulation. The models validation is presented in the fourth section. Different optimization case studies are also considered and presented in the next section whereas the final part of this paper presents the contribution of this work as well as the considered next steps.

2. Operating Principle

The electromagnetic actuation unit used to drive the recloser is shown in Figure 2. The main subsystems of this unit are: the stator, the two armatures (corresponding to the "on" and "off" positions), the coil, the permanent magnet and the opening spring.

In the closed position, the magnetic flux generated by the permanent magnets attracts the "on" armature. The open position is reached when the repelling opening spring is discharged. The "off" armature will generate magnetic short circuits at the rear side of the stator. During the closing process a coil current will generate an attractive force that overcomes the holding force due to the short circuits on the rear side of the stator and subsequently the repelling spring force. At the end of the closing process, the "on" armature is attracted by the stator pole faces.

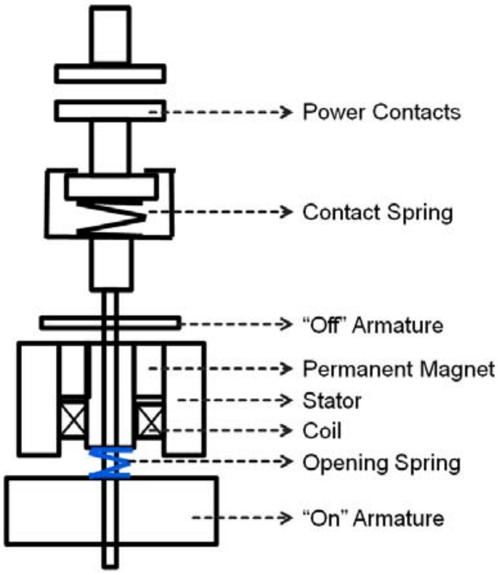

Figure 2. Single Pole Recloser Structure.

For the opening operation, a coil current in the inverse direction has to compensate the magnetic force of the "on" armature. Then the repelling spring force becomes greater than the attracting magnetic force and the actuator opening operation is initiated. Depending on the recloser's power rating, different stroke lengths are included in the actual products. At the same time, the driving current amplitude and control are adapted accordingly [1]. Therefore, depending on the application, different variants of electronic control units are used.

3. Modeling and Simulation Methodologies applied to Single Coil Actuators

The single coil actuator presented in the paper represents an important component of a complex multi-physics system. The mechanics, the electronics and the control systems are all crucial aspects of a recloser design. In order to obtain accurate and realistic simulations, it is important to develop simulation models with different levels of detail of the electromagnetic actuator. Different simulation methodologies can be applied using Comsol multi-physics: Static simulation (2D or 3D), Lumped Parameters Modeling or 3D Transient Simulations. The different models are described in the following sub-sections.

3.1. Static Simulations

This section presents the setup of a 2D Static simulation model of the electromagnetic actuation unit presented in Figure 2. The subsystems of this model are the stator, the two armatures, the coil and the permanent magnet.

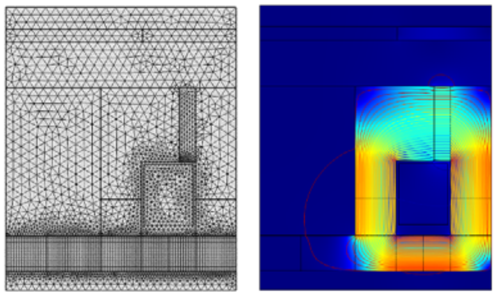

Figure 3. Simplified 2D Static Comsol Actuator Model (Mesh and Magnetic Flux Density).

The 2D Static Actuator modeling involves the usage of the magnetic fields interface. The multi-turn coil domain feature is being used for the actuator's coil modeling. Figure 3 presents the computed magnetic flux density distribution for one selected design.

This model represents the easiest and computationally less expensive FE model that can be implemented. It can be used for initial analysis and design neglecting all the dynamic effects, such as eddy current distribution in the conductive materials. The model can be easily parameterized and therefore used for parametric analyses and optimization studies (please refer to Section 4).

A 3D static FE model can also be implemented in Comsol using the magnetic field interface. If the model is not axial-symmetric the 3D static model is a more accurate but computationally more expensive simulation. Most of the geometrical details can be represented whereas the eddy currents and the dynamic effects are still neglected.

The 2D or 3D Static Models can also be used to generate the look-up tables required for the Lumped Parameters Modeling – described in the next sub-section.

3.2. Lumped Parameters Modeling

This section presents a mid-complexity simulation model based on lumped parameter modeling approach. Such model includes an electromagnetic actuator model, a mechanical system, the supply and regulation converter and the control system. For the sake of brevity, the mechanical model as well as the control system will not be addressed in detail in this paper focusing only on the electromagnetic actuator model.

The lumped model has been developed using Matlab/Simulink and using the results of 3-D Comsol electrostatic analysis. This approach is based on the direct evaluation of the force and linked flux available in Comsol post processing. The main lumped parameters which need to be evaluated are: coil resistance R, differential inductance L_D and motional coefficient M.

Once the above lumped parameters are determined a model of the actuator can be implemented under the hypotheses of negligible eddy currents distribution in the electromagnetic conducting parts as explained in [3] and according to the following equations:

$$U(t) = U_R(t) + U_E = R \cdot i(t) + \frac{d\psi}{dt}$$

$$U(t) = R \cdot i(t) + M \cdot \mathrm{v}(t) + L_D \cdot \frac{di}{dt} \qquad (1)$$

where *U(t)* is the coil voltage, *R* is the value of coil resistance, *i(t)* the coil current and $\psi(i, x)$ the flux as a function of current and position.

One of the main advantages of this approach is the possibility to have a system level multi-physics simulation model featuring a relatively low computational time compared to 3D and 2D FE simulations.

3.3. 3D Dynamic Simulations

This section will introduce the challenges of setting up 3D Dynamic Simulation. Such a simulation model is the most accurate approach currently available for electromagnetic analysis. It allows representing the nonlinearities of ferromagnetic materials, the eddy currents distribution as well as the effect of the leakage fluxes. A 3D transient model can be used for detailed electromagnetic analyses and design. It can also be used for simple multi-physics simulation of the mechanical and electronic system. Nevertheless, even when all the existing symmetries are exploited to reduce the problem complexity, the computational burden related to such a FE simulation results very expensive.

The actuators dynamic modeling in Comsol requires the coupling of the Magnetic Fields (mf) Interface and the Electric Circuit (cir) Interface of the AC/DC Module together with the Moving Mesh (ale) Interface and the Global ODEs and DAEs (ge) Interface of the Mathematics Interfaces for Equation-Based Modeling provided by the COMSOL Multiphysics core package. As coupling between the (cir) and the (mf) Interfaces an External I.Vs.U node is used, taking into account the resistance and the inductance of the actuator coil.

The Magnetic Fields (mf) Interface involves the electromagnetic part of the simulation, taking into account the motion of the "on"-armature relative to the coil and the stator. The actuator coil is represented by a Multi-Turn Coil Domain, allowing a straightforward coupling with the (cir) Interface by means of a "Circuit (current)" coil excitation. The Coil Type "Numeric" is used for the Multi-Turn Coil Domain in order to take into account the rectangular shape of the coil. This set-up requires the introduction of an Automatic Current Calculation node in the Multi-Turn Coil Calculation definition as well as a Coil Current Calculation study step in the solver settings. In addition, Gauge Fixing for the coil domains is used for the benefit of the solution process.

The Global ODEs and DAEs (ge) Interface sets up the global equations for the motion of the "on"-armature in terms of acceleration, velocity and displacement, as governed by Newton's laws of classical mechanics. So far, the recloser's opening spring is modeled by means of its lumped characteristics.

The Moving Mesh (ale) Interface involves the change of the model's geometry in terms of the motion of the "on"-armature relative to the coil and the stator.

Solver settings for the multiple interface couplings in the recloser model include in general the use of a Direct solver. As part of the model development, a Fully Coupled as well as a Segregated set-up of the solver settings have been investigated. In the case of the segregated set-up this has included 3 separate segregated steps: one for the Moving Mesh (ale) variables, one for the Global ODEs and DAEs (ge) variables and one for the Magnetic Fields (mf) and Electric Circuit (cir) variables.

4. Models Validation

In this section the simulation results are presented and commented. In order to prove the validity of the different models the simulation results have been compared to each other and validated against measurements. In Figure 4 the main simulation results obtained using the analytical lumped model, have been compared with the 3D transient simulation results. For comparative purposes in both the models the eddy currents effects have been neglected. The agreement between the two models is extremely good confirming the validity of the mathematical model implemented. In Figure 5 the measured (black) and the 3D transient FE simulations (blue) positions are reported in the same graph highlighting also a relatively good agreement. The slight discrepancy between the two curves is due to the simplified mechanical model and neglected eddy currents influence.

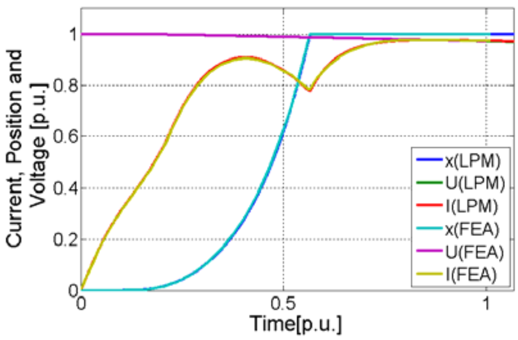

Figure 4. Models Validation: 3D Transient vs. lumped model simulation (coil current, position and voltage).

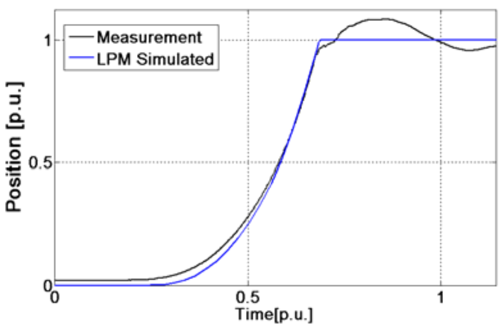

Figure 5. Models Validation: Lumped model vs. measurements (position).

5. Single Coil Actuators Optimization Approach

This section presents the coupling of the FE simulation model with an optimization toolbox (modeFrontier). The goal of the optimization is to identify – for example – the optimal geometric parameters of the actuator with respect to the costs, available space and required holding force in fully-open or fully-closed position. The coupling between the optimization toolbox and Comsol is realized via Live Link for Matlab (as presented in [4]). The same publication [4] presents also different optimization case studies.

6. Conclusions

In this paper the analysis of an electromagnetic actuation unit suitable for MV reclosers has been presented referring to different simulation approaches. Comsol Multi-physics simulation environment has been used to implement simulation models with different levels of detail. The agreement between the different simulation results as well as the validation against measurements confirms the validity of the different simulation methods. The different models can be used depending on the application for analysis, design, optimization or detailed system level simulations.

7. References

1. ABB Inc, GridShield 15/27/38 kV three-phase vacuum recloser, ABB Catalogue, 2012
2. ABB AG Calor Emag Medium Voltage Products, Vacuum interrupters and Embedded Poles - Medium voltage, ABB Catalogue, 2012
3. O. Craciun, V. Biagini, G. Mechler, C. Reuber: Multi-domain simulation and analysis of electromagnetically actuated reclosers, IECON2013, pp. 4222-4227, Wien, 2013.
4. O. Craciun, V. Biagini, G. Mechler, G. Stengel, C. Reuber, A. Linden, Electromagnetic Actuators Modeling, Simulation and Optimization, Comsol Conference, Milan 2012.
5. O. Craciun, V. Biagini, G. Mechler, G. Stengel, C. Reuber, A. van der Linden, 3D Dynamic Linear Electromagnetic Actuator Modeling and Simulation, Comsol Conference, Rotterdam 2013.