Electromagnetic Actuators Modeling, Simulation and Optimization

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Abstract: Single coil actuators are representing one important component of ABB's medium voltage reclosers. Their performance is strongly influenced by the considered material properties as well as by the electronic control units' proprieties that will power the actuator. Therefore, this paper focuses on electromagnetic actuators modeling and simulation and optimization.

Keywords: medium voltage recloser, single coil actuator, modeling, simulation, optimization, validation.

1. Introduction

Medium voltage reclosers now represent an important grid protection device that connects different grid sources, increase the network/grid reliability and make possible implementation of self healing and auto reconfiguration schemes for overhead lines. With a high level of renewable energy penetration, medium voltage networks are becoming bidirectional. Therefore, the associated switching devices must ensure the protection of newer types of power systems as well as new types of loads. The optimal design of medium voltage reclosers is therefore important in order to enable the required switching capabilities.

Figure 1. ABB 3-Phase GridShield Recloser.

The ABB 3-phase GridShield® recloser is a well know medium voltage protection device in which single coil actuators are used main component driving the opening and closing the device. It has the ability to perform as a recloser, sectionalizer or automated load break switch. The proven design is rated for 10,000 full load operations [1].

One pole of such device can be considered as being composed of two main subsystems: power and actuation. The first is represented by the power connections and the key element that ensures the arc extinction - the vacuum interrupter [2]. The second subsystem can be either mechanical or an electromagnetic-based actuation unit. The electromagnetic solution presents several advantages compared to the mechanical approach, such as fewer components, higher reliability and less maintenance.

The dynamic characteristics of electromagnetic actuators are strongly influenced by their shape, material properties, electric and mechanical elements. The magnetic, electric and mechanical dynamics are actually mutually dependent, with each affecting the others. Therefore, in order to ensure a fast and efficient design it is important to consider the Finite Element modeling and simulation enabling electromagnetic actuators virtual prototyping [3].

This paper focuses on modeling, simulation and optimization of the electromagnetic actuators integrated in ABB's reclosers. In the next section, this paper gives an overview regarding the operating principle of a single phase recloser. The third part focuses on the set-up of a steady-state 2D finite element simulation including materials non-linearity. The fourth section illustrates the coupling of the 2D model with an optimization software, modeFrontier [4] as well as an optimization case study. The next section introduces the challenges related to the actuator's modeling and simulation in 3D Transient. The final part of this paper presents the contribution of this work as well as the perspectives.

2. Operating Principle

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

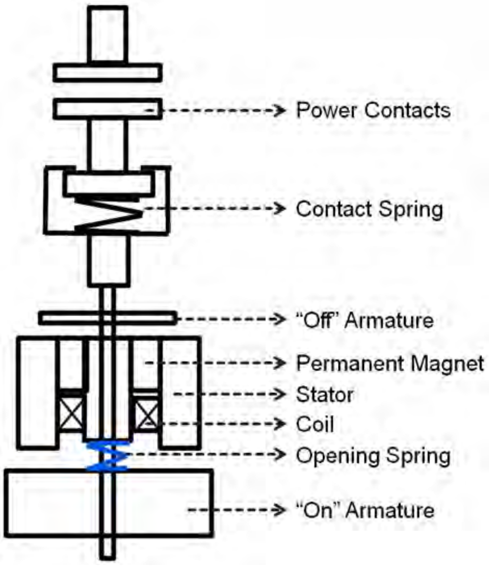

Figure 2. Single Pole Recloser Structure.

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 permanent magnets 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.

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.

Both for closing and opening processes, the maximum amplitude of the coil current must be high enough in order to cause movement over the whole stroke length.

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 is adapted accordingly [1]. Therefore, depending on the application, different variants of electronic control units are used.

3. 2D 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.

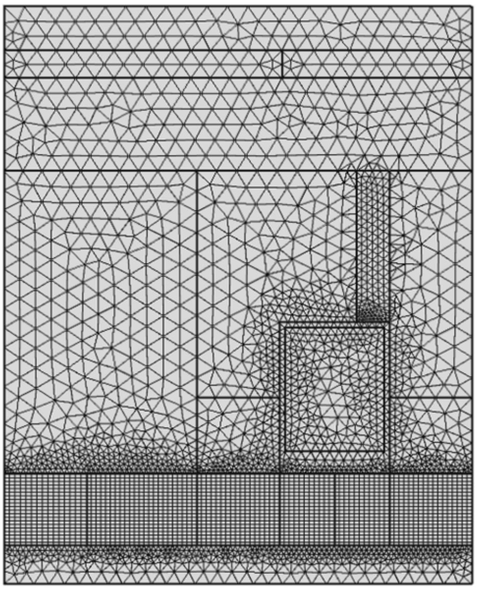

Figure 3. Simplified 2D Static Comsol Actuator Model.

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.

The holding force in close and open position is being computed (based on the Maxwell Surface Stress Tensor) in order to identify the optimal actuator dimensions as well as the permanent magnet required proprieties. Different permanent magnet materials and different ambient temperatures are considered. Figure 4 presents the computed magnetic flux density distribution for one selected design.

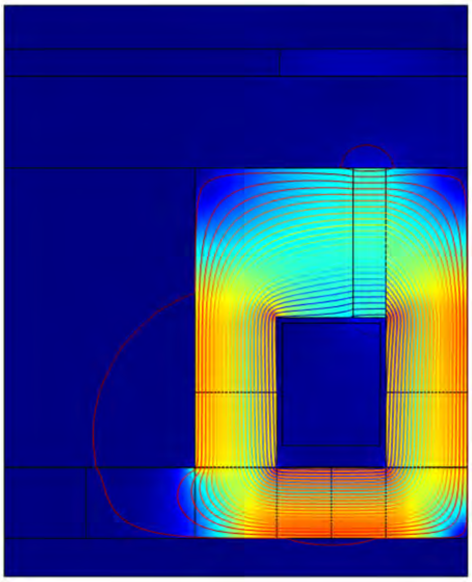

Figure 4. Magnetic Flux Density.

4. Actuators Optimization

This section introduces the coupling of the FE 2D Static simulation model with an optimization toolbox (modeFrontier). The goal of the 2D static optimization is to identify the optimal geometric parameters of the actuator with respect to the costs, available space and required holding force in end-open and end-closed position.

The coupling between the optimization toolbox and Comsol is realized via Live Link for Matlab. At first, modeFRONTIER initiates the Matlab process. The initial parameters (e.g. actuator geometry, permanent magnet type, coil excitation) are being set via Matlab LiveLink which will start the Cosmol process. Once the 2D Static calculation is finalized, the post-processing of results is started. Afterwards, the next iteration is ready to start. Depending on the actuator type and associated post-processing, the above described process will last approximately 100 seconds. Figure 5 presents one example of optimization case study. The input is represented by the computed magnetic force in closed position while the optimization outputs are 6 geometrical parameters corresponding to the permanent magnet and the on/off armatures.

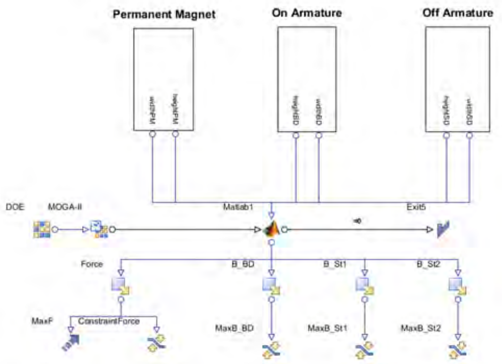

Figure 5. modeFrontier Optimization Workflow.

The algorithm used in order to solve this optimization problem is the MOGA-II [5]. The major advantage of this algorithm is the usage of multi-search elitism functionality. For a multi-objective optimization, a classic Genetic Algorithm can encounter difficulties in converging to the true Pareto frontier and can get stuck in a local Pareto front.

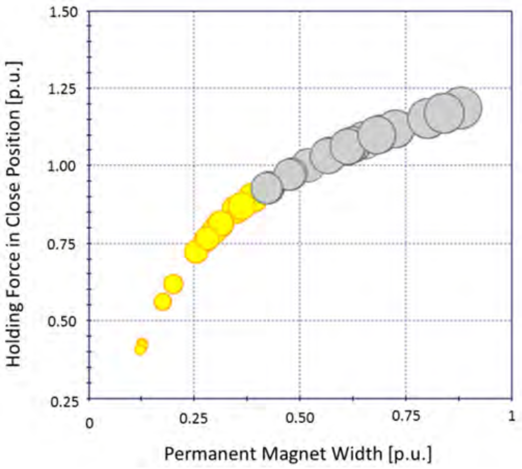

Figure 6. Holding Force as a function of the Permanent Magnet Width (Grey – Feasible Solution, Yellow – Unfeasible).

As illustrated above, the optimizer will output the holding force characteristic as a function of the output parameters (e.g. permanent magnet width). For this case study, the Pareto frontier is located at 0.9 p.u. holding force.

With the selected solution, a second optimization process is initiated. This time, several other parameters and objectives are being considered (e.g. ambient temperature, coil excitation). Among the identified optimal solutions presented in Figure 7, a set of parameters is selected in order an actuator with a robust design.

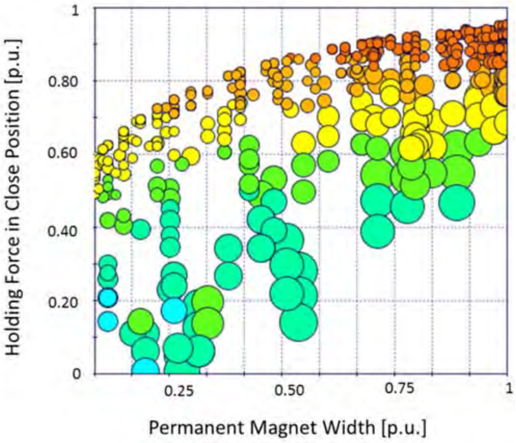

Figure 7. Holding Force as a function of the Permanent Magnet Width, Coil Current Excitation (bubble size) and the Magnetic Induction (colour).

The next step in the development process is represented by the 3D Dynamic modeling and simulation.

5. 3D Dynamic Simulations

This section will introduce the challenges of setting up 3D Dynamic Simulation including eddy currents, materials non-linearity, driving electronics and simplified mechanical system.

The actuators dynamic modeling 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. The model involves a 3D geometry (presented in Figure 8) and a time-dependent study step.

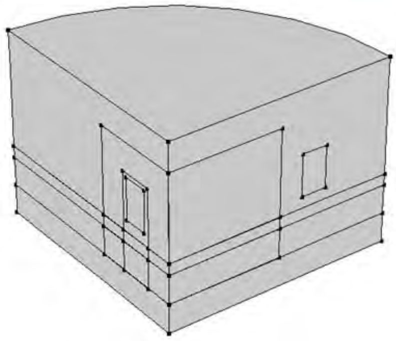

Figure 8. 3D Dynamic Comsol Actuator Model.

A typical electronic control unit for electromagnetic actuators is presented in Figure 9. It consists of a capacitor bank that will supply the actuator via an H-bridge convertor. The capacitor bank is controlled by a suitable charging circuit. For the initial modeling approach, the circuit will be represented by the capacitor bank that will power the coil with either positive or negative voltage (involving the Electrical Circuit Interface - cir). The resistance and inductance of the actuator coil are to be taken into account.

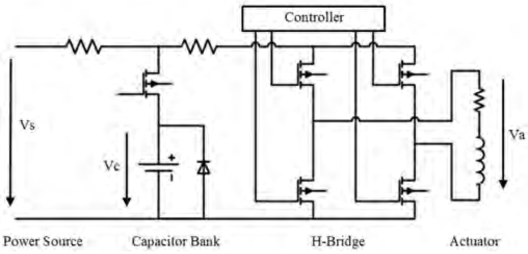

Figure 9. Power Amplifier for Electromagnetic Actuators.

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 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.

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.

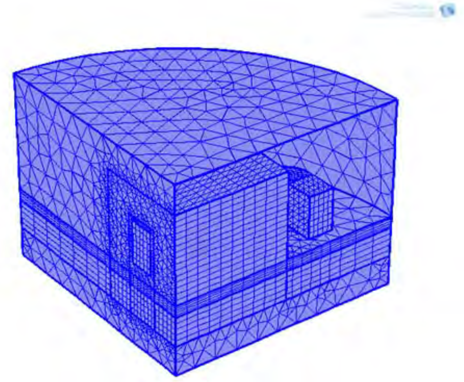

Figure 10. Mesh for the 3D Dynamic Comsol Actuator Model.

In the V4.2a version of the model, the transient current density of the multi-turn coil is defined in the (mf) interface with External Current Density subdomain settings. The current density distribution is assumed to be uniform over the total coil cross-section (A_coil).

As part of the External Current Density, an initial constant current density is defined in order to obtain a value for the coil's single-turn self-inductance (L) for $t = 0$. This self-inductance value ($L \times N^2$), taking into account the number of turns of the coil (N), is coupled with the RLC-circuit of the (cir) interface. Also the coil's single-turn resistance (R), assumed to be a constant parameter, is used in the (cir) interface as $R \times N^2$.

The model development in V4.2a has so far investigated two methods for calculating the coil's single-turn self-inductance (L). In the absence of boundary conditions which would allow the automatic inductance calculation the first, standard method is that of the volume integration of the magnetic energy (E) over the complete volume of the geometry. This allows the calculation of the self-inductance according to $E = 0.5 \times L \times I^2$.

The second method is based on the magnetic flux (ψ) linked to the full length of the coil wire. Refering to the components of the magnetic vector potential A and the current density J this can be calculated by the volume integration of the expression $(A_x \times J_x + A_y \times J_y + A_z \times J_z)$ over the coil volume. This allows the calculation of the self-inductance according to $\psi = L \times I$.

The circuit simulation in the (cir) interface provides a multi-turn current for the device's coil as part of the capacitor discharge circuit. This transient current ($cir.L1\_i$) is coupled back with the External Current Density settings in the (mf) interface, taking into account the single-turn aspects of the coil's External Current Density definition ($N \times cir.L1\_i/A\_coil$).

As part of the (mf) interface a Force Calculation, based on the Maxwell Surface Stress Tensor, is defined for the "on"-armature. This transient force is coupled with the global equations in the (ge) interface, specifically with the global equation for the acceleration (a) of the on armature. In addition, the equation for the acceleration includes the gravity force for the "on"-armature as well as lumped-element spring forces for further advanced motion control.

The global equations for the velocity (v) and displacement (s) of the closing plate are also being computed.

The set of global equations will provide the transient displacement of the closing plate. The displacement from the (ge) interface is coupled with the (ale) interface in order to simulate the motion of the closing plate in the 3D geometry with moving mesh.

In a more detailed description, the (ale) interface is defined in vertical stages. The coil and the stator together with their surrounding air regions are defined with the default Fixed Mesh subdomain setting. The closing plate and the air region at the same vertical height are defined with a Prescribed Mesh Displacement for a vertical displacement (s). With a further Prescribed Mesh Displacement the air regions below and above the closing plate, but below the coil and the stator, are allowed to get stretched and squeezed respectively.

A further model coupling is that the motion of the closing plate gives rise to a Lorentz term. This has been taken into account by means of a modification of the equation system of the (mf) interface for the induced current density. In this way, the velocity from the (ge) interface is coupled with the (mf) interface as part of a mutual coupling between these interfaces.

With the motion of the closing plate in mind, the geometry and the meshing are matched as much as possible. The geometry includes projections of the cross-section of the stator such that "Swept Mesh" features are applied easily. User-controlled meshing, such as swept meshing in combination with mesh conversion (from quad to triangle), is applied as much as possible in order to minimize the number of mesh elements.

Solver settings have resulted in the use of Segregated Solver settings for each interface, in combination with the use of "Direct" solvers. In particular, a single-iteration termination technique is used for the independent variables of the (ale), (cir) and (ale) interfaces. A tolerance termination technique is only used for the (mf) interface.

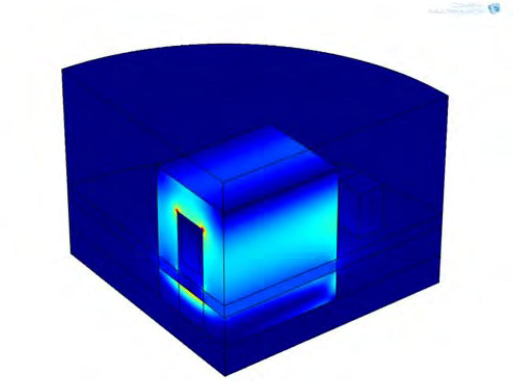

Figure 11. Transient Magnetic Flux Density.

In V4.2a substantial progress has been made in implementing and improving the coupling of the different interfaces. In addition, the strategy of combining the geometry and meshing stages of the modeling has led to increased robustness of the 3D model. Open issues in the V4.2a model development have been specifically:

b. the calculation method for the self-inductance

a. the exact method for taking into account the induced voltage in the actuator coil caused by the motion of the "on"-armature relative to the coil and the stator, as well as coupling this induced voltage with the Electric Circuit (cir) Interface.

V4.3 is offering additional functionality for the 3D model development and simulation of the actuator dynamics. In particular, the arrival of the 3D Multi-Turn Coil Domain feature in the Magnetic Fields (mf) Interface of the AC/DC Module has the potential to replace the External Current Density definition for the coil excitation. This will allow the automatic calculation of the coil's self-inductance as well as the resistive and induced voltages in the coil. For the 3D model, this will provide a more direct coupling of the Magnetic Fields (mf) and Electric Circuit (cir) Interfaces.

6. Conclusions

This paper presents the set-up of a FE simulation and optimization study platform for medium voltage reclosers. The accuracy of the developed methods has been proved by validation against measurements. Based on the described methodology, the influence of different design parameters is analyzed in order to enable the robust design of switching devices. Further work will focus on the 3D dynamic modeling by using of the new V4.3 functionalities.

7. References

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