3D Dynamic Linear Electromagnetic Actuator Modeling and Simulation

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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' properties that will power the actuator. Therefore, this paper focuses on electromagnetic actuators modeling and simulation.

Keywords: medium voltage recloser, single coil actuator, 3D dynamic modeling, simulation, 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.

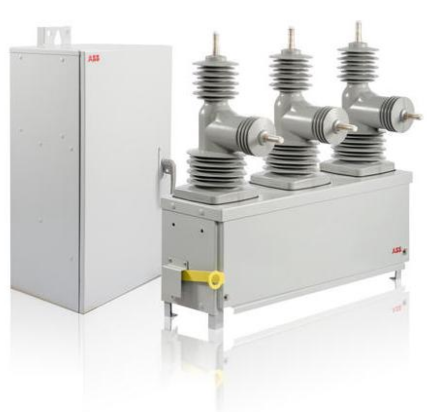

Figure 1. ABB 3-Phase GridShield Recloser.

The ABB 3-phase GridShield® recloser is a well know medium voltage protection device in which single coil actuators are used as main component driving the opening and closing of 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 and simulation 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 section focuses on the set-up of a steady-state 3D finite element simulation including non-linear material properties. The fourth 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: the stator, the two armatures (corresponding to the "on" and "off" positions), the coil, the permanent magnet and the opening spring.

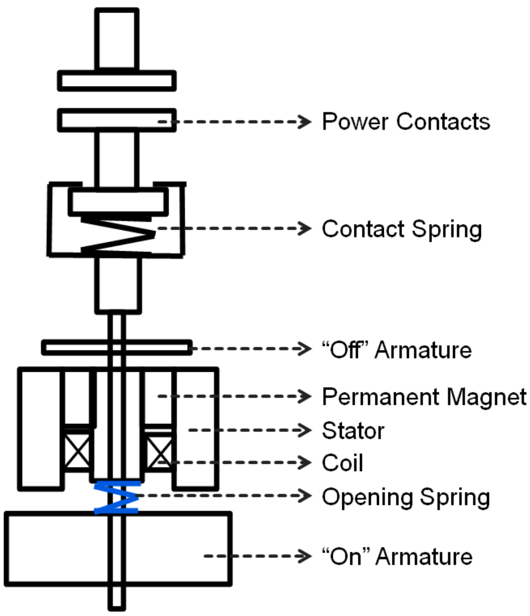

Figure 2. Single Pole Recloser Structure.

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 "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.

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.

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3. 3D Static Simulations

This section presents the setup of a 3D Static simulation model of the electromagnetic actuation unit presented in Figure 2. The subsystems of this model are the stator, the two armatures (only the "On" presented in this figure), the coil and the permanent magnet.

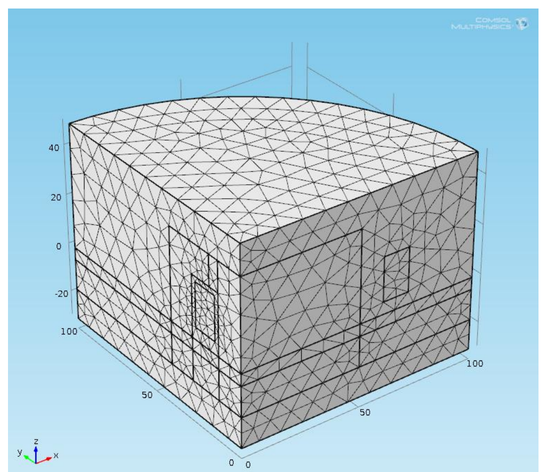

Figure 3. Mesh for the Simplified 3D Comsol Actuator Model (4-fold symmetry).

The 3D Static Actuator modeling involves the usage of the Magnetic Fields (mf) Interface of the AC/DC Module. The multi-turn coil domain feature (introduced in v4.3a) is being used for the actuator's coil modeling.

The holding force in close position is being computed using the Force Calculation feature (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.

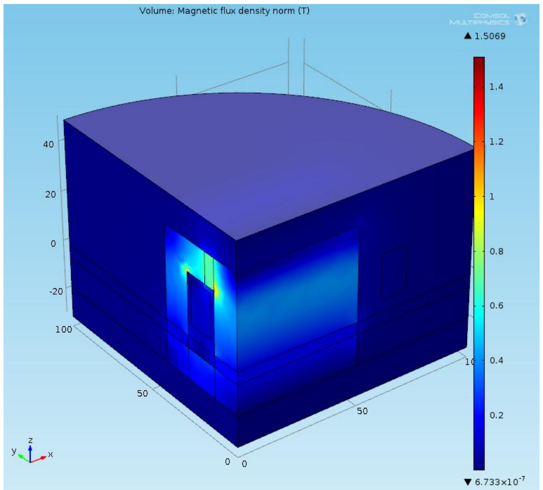

Figure 4. 3D Magnetic Flux Density (4-fold symmetry).

4. 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 3) in which 4-fold symmetry is applied and a time-dependent study step.

A typical electronic control unit for electromagnetic actuators is presented in Figure 5. 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. Involving the Electric Circuit (cir) Interface the initial modeling approach is to represent the recloser circuit by the capacitor bank that will power the coil with either positive or negative voltage. 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. Because of the 4-fold symmetry in the geometry the External I Vs. U node is used 4 times to make up a realistic capacitor discharge circuit.

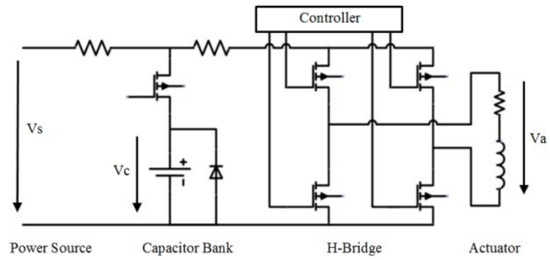

Figure 5. Power Amplifier for Electromagnetic Actuators.

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 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.

Special attention is required for the modeling of the permanent magnet in the time-dependent simulation. In order to avoid that the permanent magnet’s magnetization is switched on at t=0, the modeling approach is either: a) to ramp the magnetization from 0 to full strength in the early stages of the capacitor discharge, or b) to use a specific sequence of stationary and time-dependent study steps in the solver settings. Also, a combination of the two above points can be considered.

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. The set-up of the (ale) Interface is sensitive to: a) the complete definition of subdomain and boundary conditions describing the movement of the "on" armature, b) the solver settings (Fully Coupled or Segregated), c) the choice of meshing between fully Free Tetrahedral and a user-defined structured mesh and d) the order of the Interfaces in the modeling tree. Non-convergence and memory overload occur when the (ale) Interface is listed above the (mf), (cir) and (ge) Interfaces.

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.

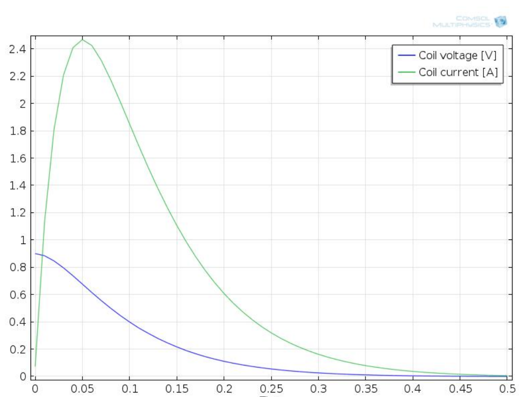

Figure 6. 3D Transient Simulation – Coil current and voltage (corresponding to an intermediate test model).

In summary, some of the lessons learned from this 3D multiphysics model development are:
- 4-fold symmetry in geometry;
- detailed coupling between physics, global circuit equations and moving mesh interface;
- capacitor discharge modeling in electric circuit;
- multiple use of External I Vs. U electric circuit node in 4-fold symmetry model;
- Multi-Turn Coil Domain modeling with type "Numeric" node Automatic Coil Current, coil excitation Circuit (current), Gauge fixing and study step Coil Current Calculation;
- detailed permanent magnet modeling in time-dependent study step;
- non-convergence and memory overload with (ale) Interface up in the model tree;
- detailed moving mesh modeling and solver settings optimization;

5. Conclusions

This paper presents the set-up of a 3D FE simulation study platform for medium voltage reclosers. Making use of the latest standards provided by V4.3b, important steps have been made in completing the 3D model development. The status of the 3D dynamical modeling is promising. The accuracy of the developed methods will be 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.

6. 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. G. Stengel, O. Craciun, G. Mechler, V. Biagini, J. Derkx, C. Reuber: Medium voltage circuit breaker multidomain modeling and analysis. Actuator Conference, Bremen, 2012.
4. O. Craciun, V. Biagini, G. Mechler, G. Stengel, C. Reuber, A. van der Linden, Electromagnetic Actuators Modeling, Simulation and Optimization, Comsol Conference, Milan 2012.