HARDWARE IN THE LOOP MULTI-OBJECTIVE OPTIMIZATION OF MEDIUM-VOLTAGE SWITCHING DEVICES

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ABSTRACT

This paper deals with hardware in the loop multi-optimization for medium-voltage switching devices. Due to an increased complexity of medium-voltage grid topologies, the associated switching devices have to be adapted and optimized in order to further extend their lifetime and enable excellent switching and protection capabilities.

INTRODUCTION

Medium-voltage protection and control devices are now representing an important grid component that connects different grid sources, increases the network/grid reliability and makes 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 switching devices is therefore extremely important in order to enable excellent switching capabilities.

Figure 1. ABB 3-phase GridShield® Recloser [1]

The switching capabilities of medium-voltage devices can be influenced by various parameters such as actuation energy responsible for opening and closing the device. Therefore, to maximize the lifetime of the reclosers, it is essential to establish an optimized control of such actuation energy. This paper examines hardware in the loop multi-objective optimization of an electromagnetic actuation unit integrated in a medium-voltage recloser. The goal is to identify an optimal actuation energy control strategy for the device operation.

The ABB Reclosers are representing a well-established medium-voltage protection device in which single coil actuators are used as main components 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.

One pole of such a 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. 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 proprieties, electric and mechanical elements. The magnetic, electric and mechanical dynamics are actually mutually dependent. Therefore, in order to ensure a fast and efficient design, it is important to consider, at first, the Finite Element modelling and simulation that enables virtual prototyping of electromagnetic actuators. The next step in the recloser design process is the emulation of its behaviour in a multi-physics modelling approach including electronics, reduced order electromagnetic models and mechanical subsystems [2]. Depending on the switching device complexity, it might be extremely challenging to identify the optimal model parameters. Also, when it comes to extremely fine analysis of design parameters, a real prototype needs to be considered.

Another solution is to consider the Hardware in the Loop (HIL) simulation. This approach enables the coupling of two subsystems, namely hardware and software, in a controlled environment. This technique has been initially used in the aeronautics industry and nowadays it is a commonly used technique for studying the behaviour of mechatronic devices, relay systems, distributed generation systems, automotive applications or human-robot applications.

This paper focuses on Hardware in the Loop optimization of the electromagnetic actuators integrated in reclosers. At first, this paper will give an overview of the operating principle of a single phase recloser. The next session will focus on the set-up of the Hardware in the Loop test bench dedicated for the test and validation of different control strategies. The following section will illustrate the coupling of the HIL test bench with modeFrontier optimization software and will also present different validation and optimization case studies. The final part of this paper will present the contributions of this work and the perspectives.

TECHNOLOGY OVERVIEW

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.

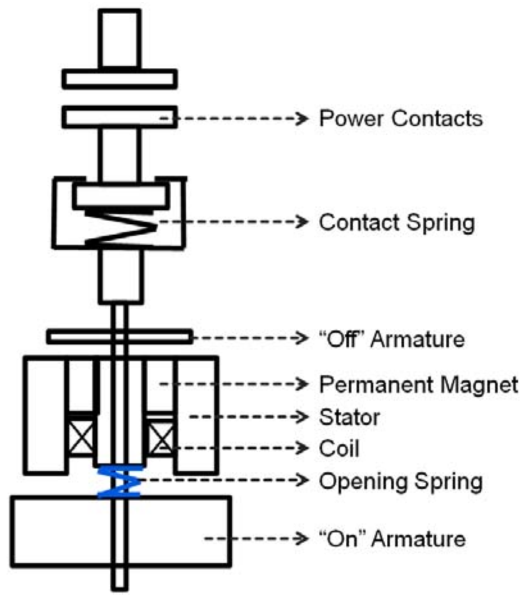

Figure 2. Structure of Single Pole Recloser

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.

HARDWARE IN THE LOOP TEST BENCH

The two main subsystems of the test bench are the hardware and software components. The hardware part consists of the device under test (medium-voltage recloser) and of a suitable power amplifier allowing the driving of actuators up to 50A, 300VDC. The software part is represented by the implementation of the control scheme on a suitable real time target that can drive the coil current in a closed loop bandwidth up to 10kHz.

As presented in Figure 3, the designed prototyping power amplifier 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.

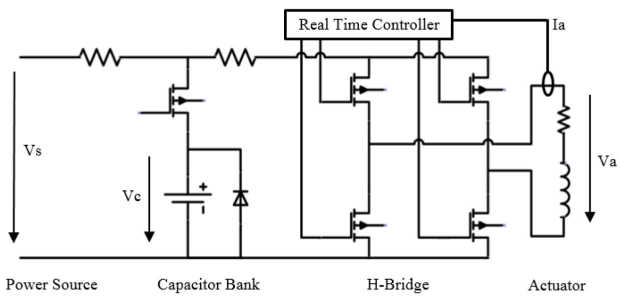

Figure 3. Power Amplifier Designed for Electromagnetic Actuators HIL Optimization

The real time industrial control unit employed in this application is the CompactRio-9073 from National Instruments [3]. This consists of an embedded controller for communication and processing, an industrial 266MHz real-time processor, a reconfigurable chassis housing, the programmable Spartan3-2M FPGA, I/O modules, and

LabVIEW software for rapid real-time and FPGA programming.

The PWM actuator current control loop is implemented on the FPGA. The corresponding Virtual Instrument is translated afterwards into VHDL code by using a Xilinx compiler.

Once the FPGA code is ready for execution, this is synchronized with the internal real-time embedded clock source. Therefore, the real-time platform is used for the purpose of setting up the parameters for the coil current controller, for synchronizing the different phases for the control scheme, for starting the switching operation and for shutting down the FPGA once the corresponding switching operation is finalized.

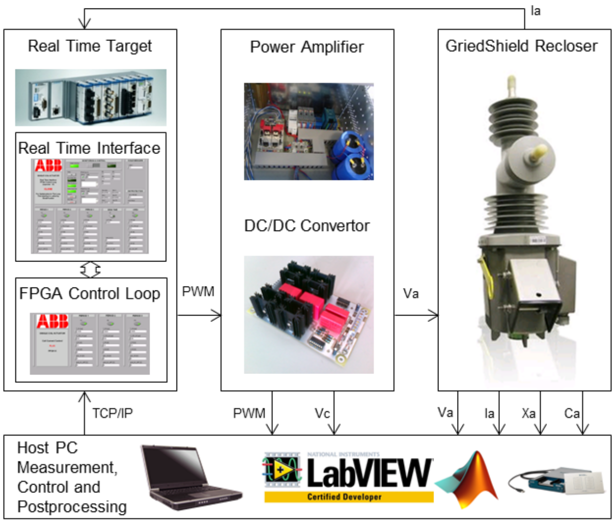

Figure 4. Structure of the Hardware in the Loop Testing and Analysis Approach

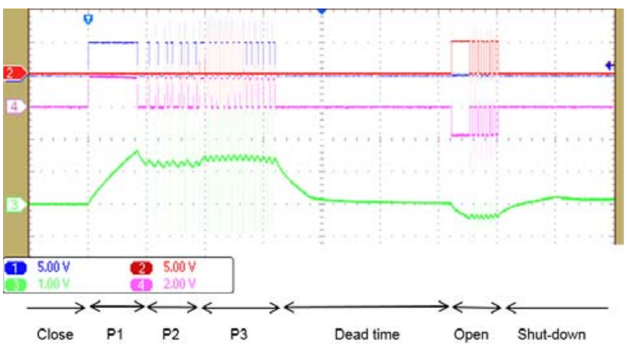

Figure 5. Single Closing Opening Operation for Single Phase Medium-Voltage Recloser

In the above example (please refer to Figure 5), a closing - opening cycle has been considered. At first, once the controller is switched on, the closing cycle is initiated (the controller is configured for three time periods, namely P1, P2 and P3). Then, the voltage is switched off and the actuator energy is released (dead time). Once the dead time has elapsed, the opening operation will be initiated (only one control period). The final stage consists of the shut-down procedure of the FPGA.

HARDWARE IN THE LOOP OPTIMIZATION

The implemented HIL testing and control test bench coupled with optimization software will be described in this section. The goal is to optimize the controller parameters in order to achieve a low overtravel and backtravel, all by having the considered boundary conditions fulfilled (e.g., contact breaking, opening speed). In this example, the multi-objective optimization is realized for the opening operation.

The main part of this setup is represented by the HIL test bench presented in the previous section. In order to perform the optimization directly on the prototype, the HIL test bench was coupled and controlled by the optimization software package (modeFRONTIER) that controls the complete testing sequence.

The coupling is performed via the real-time interface. Thus, all parameters that are normally set on the real-time interface are included as outputs from the optimization workflow.

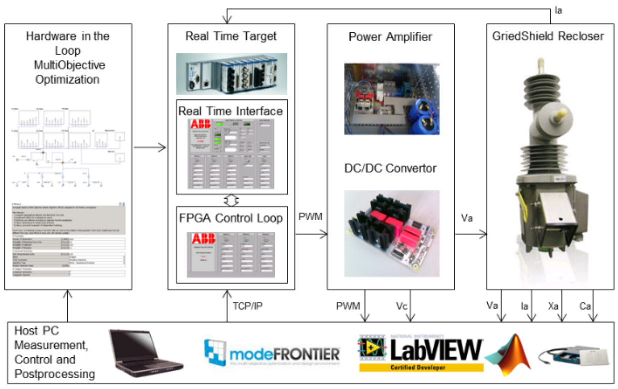

Figure 6. Hardware in the Loop Optimization Approach Applied to Medium-Voltage Switching Devices

The process presented in Figure 6 runs as follows: at first, modeFRONTIER starts the real-time process in LabView. Secondly, all parameter sets are transferred on the real-time interface and the deployment on the real-time target is performed (the FPGA control loop is precompiled). The third part consists of the actuator closing operation followed by the closing-opening dead time. During this time, the capacitor is charged to its nominal level. Afterwards, the opening operation is performed. In the sixth part, the shut-down mode is initiated for the FPGA and finally the LabView processes are on hold for the next iteration. After this stage, modeFRONTIER starts the online post-processing with Matlab, consisting of computing all the variables to be considered in the multi-objective optimization. Once this final process is completed, the next iteration is ready to start. Depending on the actuator type and associated electronic control unit, as well as the control scheme and control parameters, the process described will last between 10 and 20 seconds.

Figure 7 presents the modeFRONTIER optimization workflow. It should be noted that the outputs of this workflow are: parameters for control sequence corresponding to the closing and opening operations (P1_Open, P1_Close, …), for the dead time between closing and opening (DT), scaling factors for measurement and software fuse used as software protection for the HIL optimization process.

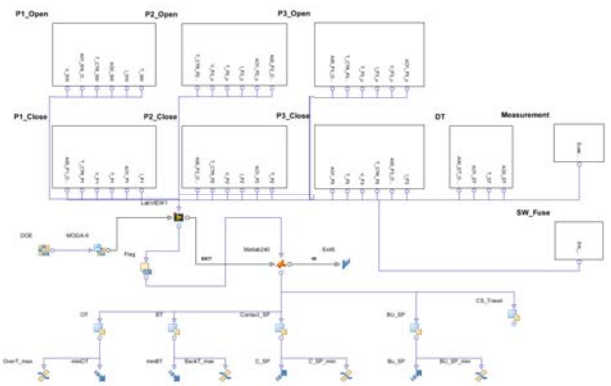

Figure 7. modeFrontier HIL Optimization Workflow

Input parameters are the calculated values after each iteration - namely overtravel, backtravel, contact breaking and opening speed. The objectives are to minimize overtravel and backtravel, and to maximize the opening and the contact breaking speeds. For each of the optimization objectives, particular constraints are also added.

The optimization algorithm used in order to solve this multi-objective problem is the MOGA-II [4]. 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 8 presents an example of optimization output for one selected control algorithm. By optimally controlling the electromagnetic actuator, the overtravel and backtravel can be significantly reduced. For this study, around 1200 closing-opening operations have been realized.

The 3D plot represents overtravel, backtravel and opening speed (represented by the size of the bubble). The solution is considered feasible (grey) if the opening speed is higher that the imposed limit. Otherwise, the solution will be considered as not feasible (yellow). As shown below, the Pareto frontier is located at the level of around 0.5 p.u.

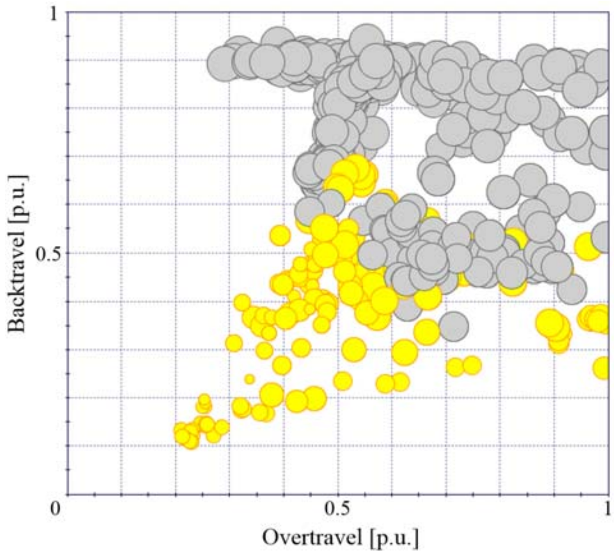

Figure 8. Hardware in the Loop Optimization of Medium-Voltage Reclosers Opening Operation

CONCLUSIONS

This paper presents the setup of a software and hardware study platform for medium-voltage reclosers Hardware in the Loop (HIL) optimization. Based on the described methodology, the efficient reduction of overtravel and backtravel is proved. Increased product lifetime or excellent switching proprieties are some of the advantages of the method. This fully flexible testing and optimization infrastructure represents a valuable hardware-software interaction.

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