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Hardware-in-the-loop simulation applied to protection devices testing

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ABSTRACT

Circuit breakers are ubiquitous elements used for ensuring safe operation of low-voltage power systems. Nowadays the loads supplied by the power systems migrate towards exhibiting significant strong non-linear behavior accompanied by inrush currents or high-order harmonics that can cause a false tripping of circuit breakers. It is thus necessary to study the interaction between these new loads and the protection devices in order to fully assess their compatibility. Following this context, this paper deals with a new test rig dedicated to protection switching devices, which is based on the hardware-in-the-loop real-time simulation concept. The proposed approach is focused on replicating the tripping conditions of a real circuit breaker coupled to a power system emulated by means of a real-time simulator. The software part of this simulator adds flexibility to the test rig as the circuit configurations and the operating scenarios may conveniently be adapted at lowest cost. The control of the interface between the software simulator and the hardware under test, as well as the closed-loop stability issues, has been thoroughly approached. Experiments carried out on this test rig show the effectiveness of this new test prototyping concept in characterizing real circuit breakers behavior when they protect lighting circuits.

1. Introduction

Electrical loads can nowadays be reported as undertaking significant technological evolution focused on improving their efficiency (e.g., recent evolution of electrical lamps [1,2]). This evolution has however determined deep changes of their dynamic behavior. Thus, they have become highly non-linear devices due to embedded power electronics, which introduce in the low-voltage power systems new perturbations such as high-amplitude high-frequency inrush currents (in the powering phase) or strong harmonic pollution (in the steady-state regime). In this context, these loads influence negatively the operation and reliability of the electrical protection and control devices (i.e., circuit breakers or contactors). New problems have thus emerged in the low-voltage switching devices, like false tripping or contacts welding. Therefore, the compatibility between these elements must be revisited in order to establish new end-user recommendations for the protection and control devices [3]. This is usually done on dedicated hardware test rigs in laboratory conditions or even on real-world power systems for typical predefined scenarios. This approach is precise, but lacks flexibility and involves significant costs as the entire circuit must be reconfigured to accommodate new scenarios. Also, when the protection devices are tested directly for specific electrical loads, these latter become unreliable after a certain number of operations (e.g., lighting loads), making difficult to achieve endurance tests. Moreover, these approaches will not enable a flexible testing environment as the number of scenarios and the power grids to be tested will be limited.

These limitations can be overcome by building simulators of power circuits that interact with the protection devices. Protection relay test benches based on power circuit simulators have already been reported in the literature [4–6]. These tools avoid the use of electrical analog protection devices models as it is known that such modeling is not an obvious task, and sufficiently accurate simulations are rarely done [7]. The concept of hardware-in-the-loop (HIL) simulation [8] can also be used for studying the real behavior of protection switching devices (for certain power grid ranges and architectures), allowing repetitive and fully flexible prototyping tests. The HIL-based test rigs suppose the exchange of real physical variables; in such setups the hardware under test (HUT) is as it is in the real application, while the other part of the plant interacting with it is entirely emulated. When the two mentioned subsystems

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(hardware–software) are interfaced a challenge is to ensure the HIL simulator stability. Depending on the employed power interface (as presented also in [9]) there are several unavoidable problems to be solved when a HIL testing infrastructure is set up, such as time delay or limited bandwidth.

The HIL concept is widely used for testing industrial equipments in controlled environment, especially when their natural environment induces erratic perturbations that make impossible repetitive tests [8]. The HIL simulator applications have been successfully reported in the automotive industry [10,11] (e.g., vehicle drive trains), in wind power [12] (e.g., turbine rotors) or other renewable energy conversion technologies [13,14], in power systems or power delivery [15,16] (e.g., multiple generators and loads connected to a real grid node), in applications related to power quality [17], etc.

This work proposes a HIL simulator that allows the study of low-voltage real protection devices in their habitual environment. The focus is here put on replicating the tripping condition of the switching device by considering the complete grid-load interaction. This allows to assess compatibility with a certain load, all by emulating the real-world conditions. The protection device behavior during the circuit breaking is not detailed in this paper.

To conclude, a real protection device – in this case a low-voltage analog circuit breaker – is used within the test rig while the electrical power grid is entirely emulated. This structure allows fast change (with minimal costs) of the electrical grid structure that interacts with the protection device; infinite number of scenarios and fully controllable test conditions are theoretically possible. The power grid simulator is based on RT-LAB HIL Box [18] that is MATLAB®/Simulink®-driven and allows multi-CPU computing. Thus, electrical and electronic drives, control systems or large electrical power systems simulations at a time step of 10 μs are possible (1 μs in case of the FPGA programming) [19]. This paper is based on the preliminary work reported in [20], which has been enriched with more illustrative real-time results and aspects that discuss closed-loop stability in presence of a pure time lag.

This paper is organized as follows. Section 2 deals with the protection devices test bench requirements and specifications. Section 3 concerns the test bench hardware (power interface) and software (control system) implementation aspects. Section 4 presents aspects related to the real-time modeling of the studied power system and to the design of specific control laws which ensure a stable HIL simulation. Validation of the developed HIL test bench for different case studies is presented in Section 5. Section 6 ends this paper with conclusions and future work.

2. Test rig for circuit breakers

2.1. Components of the lighting circuit

The case study approached here is a low-voltage single-phase lighting installation protected by an analog single-pole circuit breaker (CB in Fig. 1a). Fig. 1a presents a typical circuit diagram for powering light sources in parallel configuration. The design of the lighting circuit also involves the choice of the circuit breaker characteristics [21], which, at its turn, must be optimized to provide absolute protection while ensuring continuity of service [22]. Among these features, the most important to be chosen are: operating voltage, breaking capacity, rating and tripping characteristic (time interval for a certain tripping current).

Concerning the breaking capacity, it must be larger than or equal to the prospective short-circuit current upstream of the circuit breaker. In general, the CB rating must be larger than the rated current of the circuits (especially for electrical systems employing electronic-based loads).

Concerning the tripping diagram, several types of curves are specific to low-voltage circuit breakers (see Fig. 1b) and are chosen depending on the circuit's behavior during transients. For example, as lighting circuits are expected to exhibit high power-up inrush currents, false tripping may be avoided by choosing a less sensitive curve (e.g., to pass from B to C – Fig. 1b).

The transient current profile of a lamp circuit generally comprises a powering-up phase, a preheating phase and the steady-state regime. All these phases may vary – in both magnitude and duration – over the lamp lifetime, making even more complex its modeling [20].

The powering up of a low-voltage installation comprising electric lamps may produce a high inrush current reaching up to 100 times the rated current for a short time interval. This transient phenomenon depends on the power system characteristics (short-circuit impedance and electrical network configuration), as well as on the lamp types used in the circuit. Fig. 1c shows different inrush current shapes depending on various particular phenomena: very low resistance of the cold lamp filament (first curve in Fig. 1c), magnetic saturation effect (second curve in Fig. 1c) or electronic-based loads switching (third curve in Fig. 1c). Also, discharge lamps require a phase of gas ionization before ignition, which can result in a variable current consumption comprised between 0.2 and 2 times the rated current. Their preheating currents have waveforms similar to those in the steady-state regime but with larger magnitudes. Note that in three-phase power systems the presence of the third-order harmonic may cause the neutral cable overloading, further requiring a specific design [21].

2.2. Test rig specifications

As already stated, the interaction between a lighting load and the power grid via a circuit breaker by means of real-time simulation is aimed at. To this end, the physical simulator must contain a physical current controller source coupled with the circuit breaker in a closed circuit. The current source must accurately provide the current resulted from the load-grid interaction in a specific operating scenario.

As previously detailed, the transient phenomena in the lighting applications suppose strong peak currents (e.g., around 1.5 kA) with large bandwidth (e.g., up to few kHz). Therefore, the real-time simulator should be able to reproduce this kind of currents in a variety of electrical network configurations and operating scenarios. Beside these transient tests, the simulator must ensure the possibility of repetitive tests (e.g., endurance tests) both in steady-state, as well as in dynamic conditions. The integration time step should be of order of tens of microseconds for handling fast transients involved in the emulated power system [15]. Also, the software part must be able to accommodate complex power system models, possibly including power electronic devices.

2.3. Test rig structure

The HIL concept supposes to split the analyzed plant into two parts: the investigated subsystem (hardware under test – HUT) and the simulated subsystem representing the remainder of the plant [23]. The entire system – viewed as an interaction between the three subsystems depicted in Fig. 1a – is simulated in the software environment (see Fig. 2a). Further, the investigated subsystem is "pushed out" from the software environment (simulator) and becomes a physical part, namely the HUT [23] (see Fig. 2b). This structure allows the use of a real circuit breaker (thus eliminating the need of modeling it) in a flexible working environment, easily changeable in software.

The test rig structure follows the general HIL concept. One can note in Fig. 2b the coupling between the real-time simulator