A New Hierarchical Approach for Modeling Protection Systems in EMT-type Software

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***Abstract*-- This paper presents a new hierarchical approach for modeling and simulation of protection systems in an EMT-type software. Various protective devices, such as relays and fuses are assembled using block diagrams through a hierarchical structure. The advantages of the chosen development method are demonstrated in this paper. It is shown that despite the complexity level of protective relays, acceptable computational performances can be achieved when simulating numerous protection devices in the EMT approach. Even better computational performances are achieved by simulating in a multi time-step environment. Simulating relays in time-domain provides various benefits: representation of nonlinearities such as transformer saturation; inclusion of harmonics; and accurate representation of power electronics-based devices.**

***Keywords*: Protections, relays, fuses, power swing, out-of-step, differential protection, multi-time-step, multi-core.**

I. Introduction

TRADITIONALY, protection system studies are performed in specialized software packages where the power systems are simulated in phasor-domain. This approach assumes that the power system is linear and at fundamental frequency only. Although acceptable for many power system studies by taking into accounting the given assumptions, this approach may encounter several limitations in the context of modern power systems. This is especially more important with the increasing integration of power electronics-based devices and with the growing accuracy needs in various system studies for protection applications.

The accuracy issues in phasor-domain simulation methods are highlighted in several publications. Important accuracy problems for short-circuit calculations for MOV-protected series-compensated lines are presented in [2]. The impact of current transformer (CT) saturation on protections systems is studied in [3] and [4]. Problems related to protection systems for renewables are discussed in [5], [6] and [7].

The applications of phasor-domain and time-domain methods for protection system studies are summarized in [8]. The circuit based time-domain approach used in the simulation of electromagnetic transients (EMTs) is very accurate for the simulation of complex systems with multiple nonlinearities, conventional and renewable generation sources, and power electronics-based systems with switching devices with all related control systems.

The implementation of relay models in EMT-type tools is challenging. The measured signals are similar to those captured in the field since the network model response includes actual signals with noise and harmonics. The relay model must include anti-aliasing filters, and phasor calculation algorithms must be represented since the inputs of the model are sinusoidal with harmonics. It is possible to account for various delays such as breaker opening at current zero-crossing. As a consequence, the EMT-type relay model algorithms can and must closely imitate those found in the actual device. This results in numerically heavy models.

Another important complexity in detailed relay models is the capability to investigate cases where the relay device does not operate as expected. In such cases, the model implementation must allow the user (or developer) to identify the actual relay functions/blocks that did not operate properly or had setting errors. The analysis of problems can be then brought to the levels of physical relay testing comparisons and discussions with manufacturers.

Relay models have already been developed in EMT-type software [9], [10], but the approach presented in this paper innovates in several aspects for addressing the aforementioned challenges. An open-architecture approach is presented using a hierarchical design with block-diagrams. The model contents are visible and allow to navigate and customize different functionalities. The hierarchical implementation is optimized to improve numerical performance and memory. This aspect is very important due to the very large number of blocks found in a typical relay model and for simulating large scale power systems with multiple relays. Computational speed is further enhanced through a multi time-step parallel programming environment.

The models presented in this paper are implemented in the EMTP software in [1].

II. General Architecture

A. Design approach

When designing protection device models in a time-domain software there are several design criterions. It is necessary to

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optimize numerical performance and memory usage. This is a challenging problem due to the involved complexity levels. The protection device behavior must allow to investigate its prescribed performance, debug and adjust its settings.

The protection device model must be reconfigurable and customizable. Reconfiguration allows to implement different algorithms for each function. For example, in a distance relay, the voltage polarization [11] calculation used for Mho characteristic depends on the type of polarization (self, crossed, memorized, etc.) and differs from one manufacturer to another. Thus, it is important to be able to reconfigure the voltage polarization function according to selections because this has a significant impact on the size of Mho zones. The model must be customizable by allowing the user to include or exclude different functionalities according to the type of study and available information.

One approach for optimizing performance is to implement the relay algorithms using actual codes through a dynamic link library (DLL) interfaced with the software package. This black-box approach does not allow the user to access the various relay functions and manipulate them using a graphical user interface (GUI). Debugging and adjusting settings becomes a complex process and it is almost impossible to understand how the model works. The black-box approach does not respect the design criterions specified above.

In the approach developed here, the relay model is based on block diagrams organized in a hierarchical manner (see Fig. 1). A top level subcircuit is given a mask and contains several layers of subcircuits organized in a top-down structure with transfer of data and establishment of functions through a hierarchy. This approach also includes some DLLs for basic functions or functions that can be best implemented (for efficiency and facility) through a programming language, like a Discrete Fourier Transform, for example.

The proposed approach provides an open architecture (open-source). It offers several advantages, but creates a very large hierarchical system with interconnected block diagrams. A complete line protection relay, for example, can contain up to 10 000 devices. It is thus required to organize the hierarchy through an object-oriented approach. Once a relay is placed in a design, adding another one is merely creating a new instance of its object which minimizes memory increase.

It is not possible to use a single hierarchical object since the relay subcircuit (object) would then have to include the block diagrams for all possible relay configurations and options, and occupy unnecessarily large memory. Instead, the relays are built with several macro-objects (subcircuits in the hierarchy, see Fig. 1) which are automatically activated or deactivated according to top block selections. Therefore, two relays with different option selections can share macro-objects and save memory. For example, all relays with inputs having a Wye connected Voltage Transformer (VT) have the same voltage acquisition functions (Signal Acquisition block in Fig. 1). All the ones with inputs to delta-connected VT have another acquisition function. As another example, all line protection relays using Mho zones have a common object, but might have different polarization voltage (Memory Manager block in Fig. 1) according to the manufacturer selection.

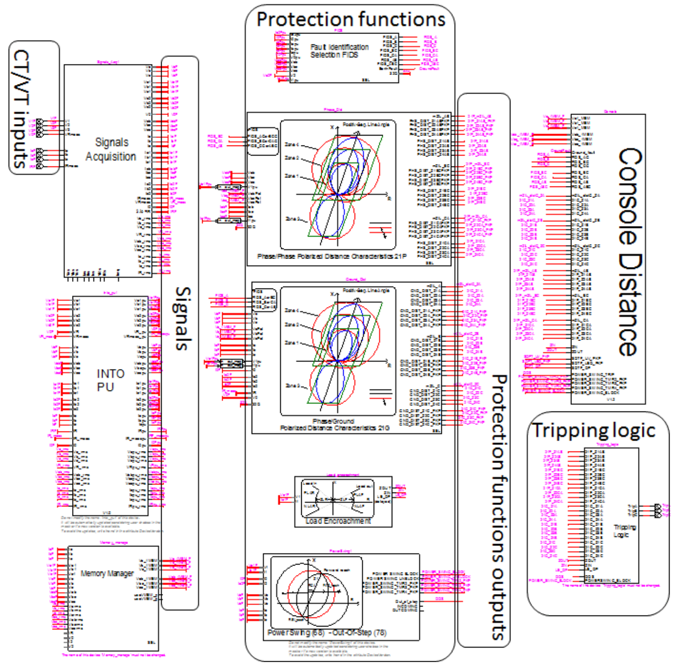

Fig. 1. Distance relay model internal architecture.

In order to quantify the computer memory gain in the above design approach, it is proposed to consider three benchmarks, namely, Benchmark 1, Benchmark 2, and Benchmark 3. Benchmark 1 is shown in Fig. 2. Benchmark 2 is the same as Benchmark 1 except that it has 3 more identical relays (two for the top line and one more for the bottom line). Benchmark 3 (see Fig. 3) has 4 different relay types.

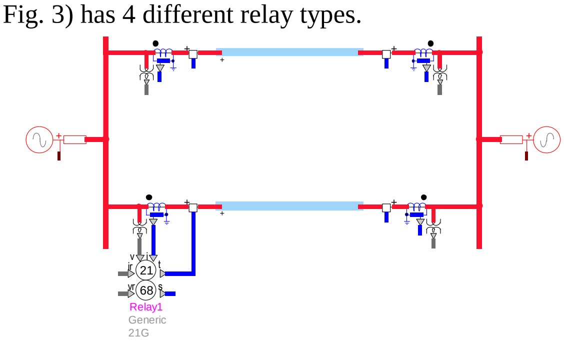

Fig. 2. Benchmark 1: parallel lines between two networks with one relay.

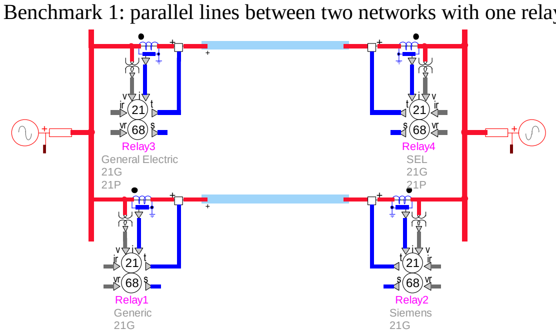

Fig. 3. Benchmark 3: parallel lines between two networks with 4 relays of different types.

Table 1 summarizes the total number of devices in each Benchmark and the number of instances which is an image of the memory usage. Benchmark 2 adds three relays to

Benchmark 1, so there are 4 times more devices. However, because macro-objects are shared, the number of instances only increases by 54. A total of 18 macro-objects are shared in these line protection relays. Between Benchmark 2 and Benchmark 3, the number of devices does not increase significantly, but the relays are of different types and contain different macro-objects. Therefore, the number of instances increases but remains far from being 4 times more than that of Benchmark 1.

TABLE 1: COMPARISON OF THE NUMBER OF DEVICES AND INSTANCES

Benchmark	Number of devices	Number of instances
Benchmark 1	9612	1694
Benchmark 2	35570	1748
Benchmark 3	37430	3421

B. *Implementation*

Several protection system models have been implemented in EMTP [1] following the above approach.

Phase and Ground distance protections (ANSI 21P, 21G) are based on 4 polarized zones which can be either forward, reverse, or non-directional and Mho, Lens or Quad-shaped. Calculation methods of memorized voltage polarization from different manufacturers are available. Each zone can be supervised by directional, overcurrent, load encroachment, fault identification and reactance elements. This level of details allows to study the protection coordination of power systems and to conduct detailed investigations studies, as shown below.

Phase, ground, neutral and negative-sequence overcurrent elements (ANSI 50-51P, 50-51G, 50-51N, 50_2-51_2, 46) are set using ANSI, IEC, manufacturer or user-defined time curves. Polarized directional elements are also available (67P, 67G, 67N, 67_2). Protection schemes and protection coordination can be accurately simulated and studied. This is particularly important with fast-dynamic systems where fault current magnitudes change before relays operate or when the level of renewable energy penetration in the system is high.

Expulsion and current-limiting fuses are modelled using melting curves, pre-arc energy and clearing energy. These models provide the unique capability to simulate the peak-let-through current of current-limiting fuses. Graphical tools allow to display fuse and relay time-current curves. Transformer and conductor damage curves are also included.

Phase and ground differential protections (ANSI 87, 87G) include different manufacturer algorithms with internal and external fault detections, harmonics restraint and harmonics blocking. They are based on phasor or instantaneous values of differential currents. Scenarios of faults inside or outside the protected zone can be simulated considering CT saturations. Transformer energization and overexcitation can also be studied as demonstrated below.

Power Swing and Out-Of-Step detection functions (ANSI 68, 78) are based on operating characteristics detection using 2 or 3 zones which can be Mho, Quad or Mho with blinders. Contingency studies are used to accurately determine the time settings of each characteristic (see Section IV.) and study the coordination with distance and loss-of-field (ANSI 40) protections, the latter being also included in the protection toolbox. Continuous impedance calculation-based detection is another algorithm available for Power Swing and Out-of-step functions.

Phase undervoltage (ANSI 27), phase, neutral, negative-sequence and compensated overvoltage (ANSI 59, 59N, 59_2), overfrequency, underfrequency and rate-of-change-of-frequency (ANSI 81O, 81U an 81R) are also available and used for studies such as transient stability, load-shedding, and islanding detection.

Using the outputs of these protection functions, users can write their own tripping logic functions. These outputs and other quantities calculated by relays are also accessible outside the model in order to create protection scheme using communication between devices.

III. SIMULATION EXAMPLES AND PERFORMANCE

As explained in the introduction, an important advantage of an EMT-type solver over phasor-domain methods is the much higher accuracy level. In EMTP [1], a fully iterative solution is available for attaining very accurate results with nonlinear models, such as the magnetization branch model used in transformers and measuring devices.

A simple 500MVA, 315/120 kV transformer energization study is presented in Fig. 4 (Benchmark 4). Transformer energizations cause inrush currents due to the saturation of the transformer core. The current magnitudes depend on the switching instant of each pole of the circuit breaker and the residual fluxes of the power transformer prior to the event. This inrush current coupled with CT saturations during the energization can create a differential current with a magnitude reaching few per-units, enough to cause misoperation of percentage differential relays [12]. To prevent unexpected trips, the harmonics content of the differential current, especially the second harmonic, is monitored. When the ratio of the second harmonic component in the differential currents over the fundamental exceeds a pre-specified threshold, the relay detects the energization and blocks the trip. The blocking can be done individually for each phase or in common, in which case the blocking of one phase blocks the others. The challenge is to find a threshold which is sufficiently low to cover all energization scenarios and sufficiently high not to block in-zone faults which can saturate CTs and produce harmonics in the differential current.

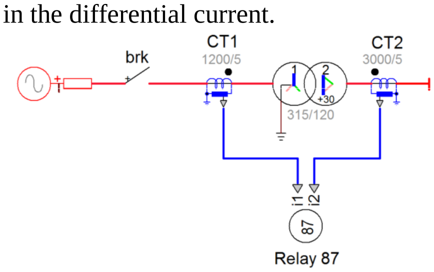

Fig. 4. Benchmark 4: Transformer energization

Fig. 5 shows the fluxes inside the transformer of Fig. 4

following an energization. After approximately 8 cycles, CT1 saturates (Fig. 6) so the harmonics in the differential currents calculated by Relay 87 (Fig. 7) are caused by the saturations of both transformers. The ratio of the second harmonic in phase-B differential current over the fundamental, while the differential current over the restraint current is higher than the slope setting (SLP) of the percentage differential, is shown in Fig. 8.

To determine the threshold setting of the 2nd harmonic blocking function, batch simulations are performed where the switching time of each pole of the circuit breaker is varied as well as the initial fluxes in the transformers.

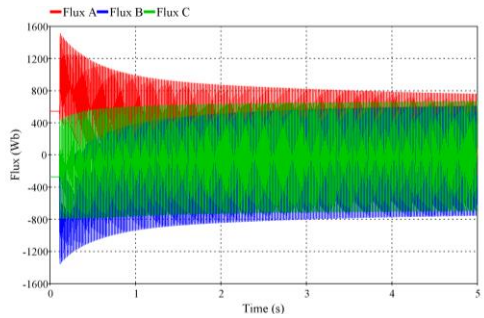

Fig. 5. Transformer fluxes (see Fig. 4).

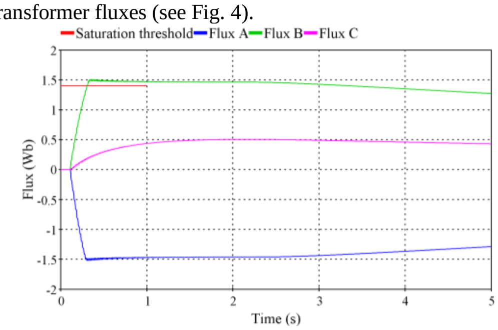

Fig. 6. Fluxes of CT1 in Fig. 4.

Two scenarios are demonstrated: a) 50 energizations without residual flux; b) 50 energizations with residual fluxes of 0.8 pu on phase-A, and -0.4pu on phases B and C. The second harmonic content when the differential current over the restraint is higher than SLP is analyzed. For individual blocking, the setting has to be set so that the current ratio (differential second harmonic component over the fundamental) of each phase remains above the setting. For common blocking, the condition is applied on the maximum of each phase ratio. These ratios, with and without residual fluxes, are displayed in Fig. 9 and Fig. 10, respectively. A value of 100 means the differential current over the restraint never reached SLP. According to these simulation results, the blocking setting to avoid misoperation must be lower than 15.1% for individual blocking and 23.2% for common blocking. The 4th and 5th harmonic blockings can be studied the same way.

Other simulations, like in-zone faults with CT saturations or energizations with faulty phases can be used to validate the final settings [12].

IV. Relay Settings and Protection Scheme

The previous example demonstrated how a time-domain software provides a suitable environment for the simulation of saturations and their impact on differential protections. Another important capability with EMT-type software is the accurate simulation of renewable energy integration with protection systems. Inverter-based devices, such as wind or solar parks, behave differently from conventional generation during faults. Some protection packages model them the same way as synchronous (generators) machines (SM), but this approach can lead to significant errors in the reach of distance relays.

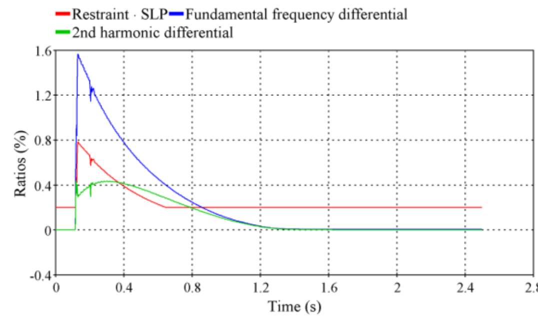

Fig. 7. Restraint current multiplied by SLP, 2nd harmonic and fundamental of the differential current, phase-B, calculated by Relay 87.

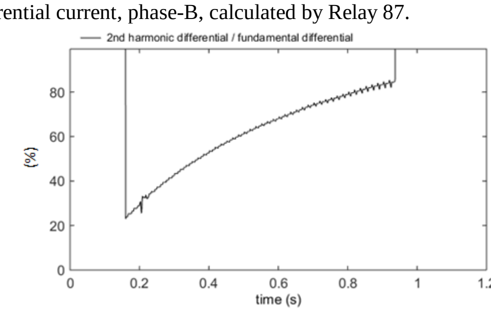

Fig. 8. Ratio of the 2nd harmonic over the fundamental component differential currents of phase-B, calculated by Relay 87 when the differential current over the restraint is higher than SLP.

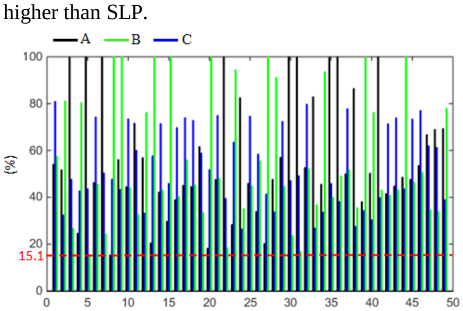

Fig. 9. Minimum ratios, differential 2nd harmonic over fundamental in each phase, energization of transformer without residual fluxes.

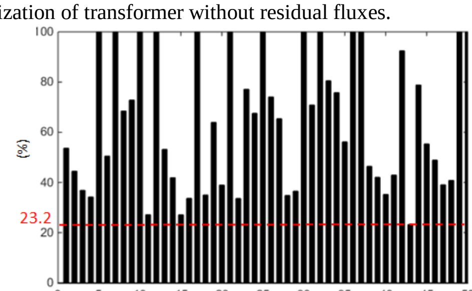

Fig. 10. Minimum of the largest phase ratio, differential 2nd harmonic over fundamental in each phase, energization of transformer with residual fluxes.

Benchmark 5 (Fig. 11) is a 3-bus system representing a 400 km transmission line between two 345 kV networks

(Network 1 and Network 2) with an infeed at BUS2 from a 150 MVA wind park. To illustrate the impact of wind park model on the result of protection studies, the wind park has been modelled either as an equivalent SM-type (SMEQ in Fig. 11) generator or an actual detailed WP. The SMEQ model is connected to an exciter (IEEE ST1). Typical values are assumed for all parameters. The WP model is based on aggregation of full-converter wind generators and includes all appropriate detailed control systems. The Q-control mode is used. It also uses the average value modeling technique for the electronic converters. Complete data for all test cases presented in this paper is available for download upon request.

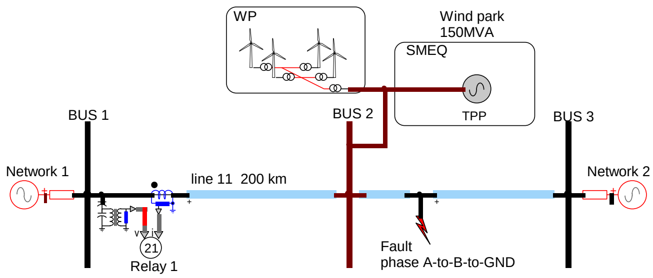

Fig. 11. Benchmark 5: impact of wind park integration on distance relay reach.

First, the SMEQ model is included and the WP is excluded. Fig. 12 shows the zones 1 and 2 of the distance relay (Relay 1) in an R-X diagram and the impedance trajectory seen by the relay for a fault located at 120% of the protected line impedance.

When the SMEQ model is used, the inductance seen by the relay few cycles after the fault is higher than that with the WP model. This is observed in Fig. 12 where the orange line shows the trajectory with the SMEQ model and the red line shows the trajectory with the WP model. The impedance locus keeps moving due to the SM oscillations whereas the locus of the WP model reaches a new steady-state within a few cycles. With EMTP, it is possible to perform contingency studies and, in this case, to vary the fault location using bisection technics to precisely determine the reach of the relay zones. The reach of zone 2 using the WP model is 121% whereas the one with the SMEQ mode is 112.8%. This is the reach considering only a few cycles after the fault, since the locus in that case is constantly moving. Without any infeed, the reach is 121.8%. This benchmark demonstrates the importance of accurate models for such system protection analysis and settings.

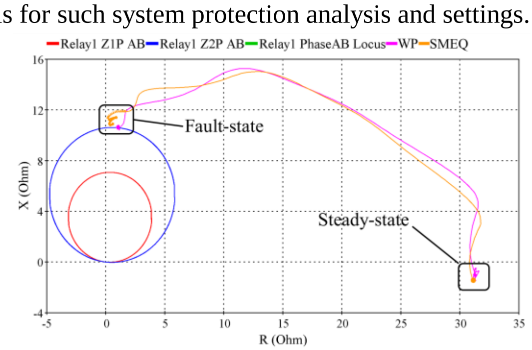

Fig. 12. Zones 1 and 2, line distance protection Relay1 impedance trajectory locus, comparison of SMEQ and WP models.

Benchmark 6 (see Fig. 13) focuses on the differences in the dynamic behavior between the two modeling approaches (WP and SMEQ).

Four 250 MVA generator units are connected to a 230 kV network through two parallel 500 kV transmission lines of 500 km. Substation A is connected to the generation units and Substation B is located at 280 km from Substation A. A 250 MVA Type-III WP is connected to BUS2 (model options SMEQ and WP). As in Benchmark 5, the aggregated WP model includes all typical controls and uses the average value model approach for converters. Figure 14 shows the distance and power swing protection relays of this benchmark.

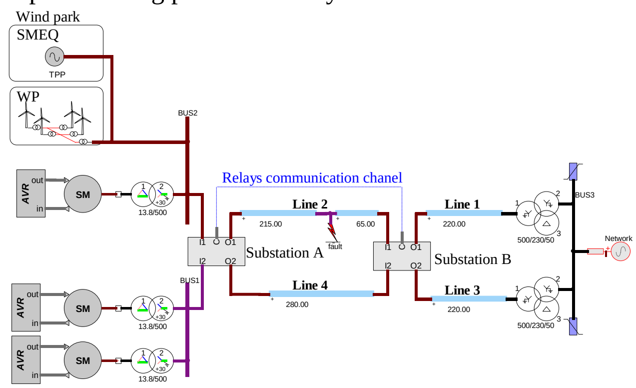

Fig. 13. Benchmark 6: impact of WP integration on power swing.

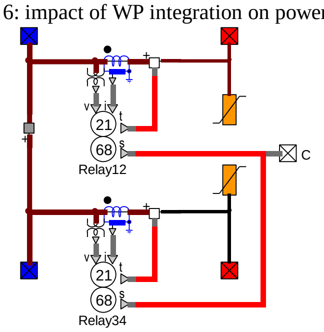

Fig. 14. Benchmark 6: protection relays in Substation A and Substation B.

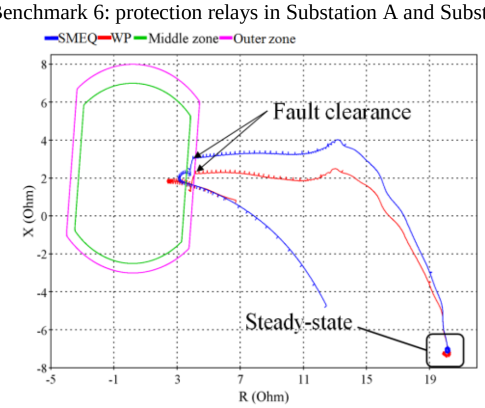

Fig. 15. R-X diagram: comparison of worst stable swings, with WP and SMEQ models.

A phase-A to phase-B fault is applied at 215 km from Substation A. When the fault occurs, distance protections in both substations detect the fault and use Permissive Over Reach strategy to clear it. The critical clearing time of the fault is found for the WP and SMEQ cases using batch processing (several simulations) in EMTP. The critical clearing time is the maximum time during which a fault can be applied without the system losing stability. In this case, the network loses stability 2.5 cycles earlier with the WP than with SMEQ. With both models, the worst stable (limit) swing seen by the relay in Substation A is displayed in Fig. 15 on the same graph as the Power Swing detection zones. The differences in the impedances observed by the relay for both modeling approaches are noticeable as soon as the fault is initiated. Once cleared, the first swing does not go as deep inside the detection zones for both cases, which is important to consider when setting up line protections [13] and studying the limit of detection between stable and unstable swings.

V. Multi-time-step implementation

In Benchmark 6, both Substation A and B have 2 relays for a total of 4 relays. In the case where the wind park is represented by a synchronous machine (to isolate the performance timings for relays from the computational burden of WP controls), the simulation with relay models takes 78% of the CPU time. However, relays have a sampling frequency and their internal algorithms only need to be solved after a preset sampling period.

The multi-time-step and multi-core computation options available in EMTP can be used to significantly improve computational performance. In this example, each relay has a sampling frequency of 20 samples per cycle, so a sampling period of 833 µs. Sufficiently good accuracy can be achieved when interfacing with relay models using a time-step of 400 µs while the rest of the circuit is simulated at 50 µs. With the multi-time-step approach, the relays can be simulated on different computer cores without loss of accuracy. The gains in CPU usage are substantial (3.2 times) (see Table 2). The simulations have been performed on a i7 computer with 4 cores.

Table 2: Computational performances, Benchmark 6, simulations using a single-time-step and 1 core or multiple time-steps on several cores. The simulation period is 2 s.

Simulation	CPU time (s)
Single-time-step and single-core	129
Multi-time-step and multi-core	40

VI. Conclusions

This paper presented a new approach for advanced and accurate modeling of protection systems in an EMT-type simulation environment.

A hierarchical and block-diagram based approach has been used. It delivers open-architecture models that can be easily analyzed and modified by users using a high-level graphical interface. Due to the complexity of resulting models (more than 10 000 devices in the hierarchy of some models), it was necessary to apply an object-oriented approach. The defined objects are instantiated according to relay types and protection options selected by users. This approach minimizes memory requirements and results in an overall optimized design. It becomes also suitable for simulating large cases with numerous relay models.

The implementation of advanced protection system models in an EMT-type package allows to achieve very accurate simulations and becomes essential especially for studying the integration of power electronics-based devices, such as wind generators.

This paper also demonstrated that significant computational gains can be achieved by simulating the relay models using multi-time-step and multi-core computations. It has been shown that the relay models can use much larger numerical integration time-steps than the protected power system, without compromising accuracy.

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