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# Automation of cycles of protections' non-traditional tests using traditional injectors and electromagnetic transient programs via Python

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This article shows a method to perform cycles of non-traditional tests to electric power system protections, in an automated way, using traditional injectors and Electro-Magnetic Transient Software (EMTS) via Python. Non-traditional tests of protective relays, using non-sinusoidal current and voltage waveforms computed from an EMTS, have been performed since the invention of programmable injectors but different non-obvious steps are necessary for this purpose (the obtained files from the EMTS must be converted to a standardized format to be transferred to the injector, injected to the relay under test, and the relay contacts have to be monitored in order to record their operation or non-operation, and/or to record their operation time). In order to easily perform repetitive cycles of these non-traditional tests, with different conditions of simulation in the EMTS, these steps were automated using Python, which is simply applied to control the injector and the EMTS in a loop. This method is suitable for different practical cases, and it is useful to avoid some costs and disadvantages related to the use of real-time simulation (which probably is the most known alternative to perform these cycles of tests). Herein, the obtainment of tripping times of distance protections as a function of fault location and source impedance in case of a series-compensated line is shown as an example. The results were obtained for mho and quadrilateral characteristics of three commercial relays, using a very basic injector and a royalty-free EMTS in order to illustrate that the tests can be performed with very low resources. The proposed method is considerably less expensive than the use of real-time digital simulators, and considerably faster than the use of the same resources without the proposed automation, which currently are the main available methods for these tests.

Keywords: tests of protective relays, electric power system relaying, electric power system protection, distance protection, source impedance ratio diagrams, series-compensated line

## 1 Introduction

The electric power system protection is a specialized field of the electrical engineering, related to protective devices which are typically located at power system substations. This field of knowledge has different subtopics, such as: a) the selection of equipment during the design of substations; b) the calculation of settings for the protective devices to obtain the best combination of sensitivity, selectivity, speed and reliability of the protection system; c) the analysis of the behavior of protective devices during power system faults; d) the design of protective relays, by the corresponding manufacturers; e) the tests of protective relays. There are different types of tests for protective relays; for instance, some tests are specifically performed to: a) guarantee that the design of a protective device fulfills the user requirements; b) guarantee that protective relays have been properly installed and wired at the substation; c) guarantee that protective relays still are in good condition. The tests of protective relays are very important because these devices must be very reliable (they are usually installed, without tripping during years, and they should suddenly trip in a proper way when it is necessary). This article is related to tests to guarantee that the protective device design fulfills the user needs; these tests are usually performed in a power system protection lab, which has specialized injectors to feed the relays with the proper voltages and currents for the tests.

On the other hand, real-time power system simulators have been also applied to perform cycles of non-traditional tests for different applications related to electric power system protections, for instance: effect of inverter-based generation on distance protection [1-2], tests of high speed distance protection for the entire line length [3], tests of protections for multi-terminal high voltage DC transmission systems [4], tests for transformer differential protections [5], tests of protections based on time-domain transforms [6], tests of coordination of overcurrent protections in microgrids [7-8], detection of islanding operation of inverter-based generation [9], and tests of loss-of-field protections for synchronous generators [10]. Although the use of real-time simulators to test protective relays is becoming relatively common, often the corresponding real-time

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capability is not strictly necessary because the relay operation does not change relevant features of the power system model during the tests. Real-time simulators are relatively expensive tools because they need very efficient hardware and software in order to compute the power system simulation results in real-time. Furthermore, under some circumstances, real-time simulation can have some disadvantages, such as: a) the need of using the specific vendor simulation models, because they were coded to properly run in that real-time environment; b) the need of simplifying the power grid model to avoid the need of solving high-dimension problems with real-time computation tools. On the other hand, traditional Electro-Magnetic Transient Software (EMTS) and injectors are often used to simulate power systems and to test relays, respectively, in a reliable, flexible and relatively affordable way (e.g., ATP [11] is a royalty-free EMTS, widely used to do research related to transients in power systems). Traditional EMTS and injectors, as an alternative to real-time simulators, have been previously applied to perform simple tests (e.g. [12]), and their application to perform cycles of protections' tests was the challenge that motivated the work herein described, since there is no published precedent about this specific topic. These cycles of protections' tests are usually necessary to verify the suitability of a protection and do not necessarily need to be performed in real-time. The automation of these cycles of protections' tests, using traditional injectors and EMTS, implies a very important time saving regarding the non-automated way of performing these tests with the same resources, and this fact also motivates the work herein described.

The case herein selected as an example is the test of tripping times of distance protection as a function of fault location and source impedance. These tests are professionally known as the obtainment of *SIR diagrams* [13, 14] (SIR means Source Impedance Ratio, in this context), and they are featured by the need of performing many test repetitions with non-sinusoidal waveforms. The standardized method for these tests needs to be simplistic in order to be suitable to be easily applied with the typically available professional tools. Thus, the standardized test current is a basic asymmetrical current (i.e., a sine wave plus a decaying exponential), and the commercial injectors offer software tools to perform the standardized sequences of tests (e.g., [15]). On the other hand, the case herein selected as an example is the obtainment of SIR diagrams in a simple model for series-compensated lines; this non-traditional case is featured by more complex waveforms, in order to properly illustrate the scope of the developed testing method. Although the simulation of complex power systems using off-line EMTS is relatively easy, the selected example is very simple since the goal herein is the explanation of the developed testing method in an understandable way.

The fundamentals about protection of series-compensated lines are often explained using phasor analysis [13, 16-18], but the simple solution of the differential equation related to the series connection of capacitances and inductances implies the occurrence of more complex transient phenomena (featured by electro-magnetic oscillations with natural frequencies, and possible resonance for some fault locations). Furthermore, metal-oxide varistors (MOV) and air gaps are connected in parallel with the capacitors for series-compensation [19] and these nonlinear elements have an influence on currents and voltages during short-circuits. The literature about protection of series-compensated lines is abundant (e.g., [19-34]) and deals with different interesting details, such as: a) proposal of new protective methods [20-24]; b) assessment of protective systems [25, 26] and procedures for simulation [27, 28]; c) sub-synchronous resonance [29, 30]; d) voltage or current inversion problems [31]; e) parameter estimation of series compensated lines [32]; e) fault location algorithms [33]. In practice, the protection schemes and devices for this application have been tested with non-standardized methods; for example, different relay options were extensively tested, using different cycles of protections' tests, in order to select the protections for a system with series-compensated lines [34]. Although the literature about this topic considers many interesting details, they are not herein covered since the objective of this article is mainly related to the proposal of a method to perform cycles of protections' tests using traditional EMTS and injectors.

The problem of controlling an injector software and an EMTS to iteratively change the details of power system simulations was herein solved with the help of Python [35]. Python is a programming language which can be easily applied to code sequence of steps to control software packages.

This article shows a novel method to automatically perform cycles of tests of protections using traditional injectors and EMTS via Python. There is no precedent in the literature about the development of this type of method. This method cannot be considered a real-time simulation tool, since it is not dependent on the capability of computers to calculate power system transients in real-time. Despite this fact, the proposed method is suitable for many possible practical cases, avoiding some costs and disadvantages related to real-time simulation. The method is herein applied to automatically perform cycles of tests of tripping times of distance functions in a series-compensated line, as an example to illustrate the possibility of testing relatively complex electromagnetic transients with very low resources. Although the case taken as an example is very specific, the scope of the developed method is considerably wide, and some alternative ways to apply this method are also herein briefly described.

## 2 Developed method

The algorithm of the developed method is very simple and it is shown in Fig. 1. Python [35] was herein applied to control one specific EMTS [11] and one specific injector [36], but this method is conceptually applicable to any combination of EMTS and injector. On the other hand, the following details are specific for the EMTS and the injector software herein applied. In case of the EMTS, the changes in power system models can be controlled via data files. In case of the injector software, the control was performed via the graphical user interface. In case of the EMTS, the output can be directly obtained as a COMTRADE file (COMTRADE means "Common Format for Transient Data Exchange", and it is a standardized file format that can be understood by the professional injectors to test power system relays); thus, it was not necessary to build computer routines to convert the data files. In case of the injector software, the successive tests' results can be automatically added to the same table of the report of results (thus, it was not necessary an external action to consolidate the results of all the test points).

The speed of the developed method can be easily improved by performing tasks in parallel. For example, the solving of case i+1 in the EMTS can be started simultaneously with the injection of case i. This refinement can be important in cases of high computational burden for the EMTS, but it was considered unnecessary for the simple examples herein shown.

The algorithm shown in Fig. 1 is only an example of a way to program these routines, and other options are obviously possible. For example, a loop can be firstly run to solve all the cases in the EMTS, in order to subsequently perform another loop to transfer the COMTRADE files to the injector and run the sequence of tests. This option is shown in Fig. 2, and it is currently being applied in an undergoing research project (at the Protection Systems Lab of the Universidad Carlos III de Madrid) since the advantage of having two independent loops was very important in that case. In fact, if the applied EMTS has efficient specific routines to perform the first loop of Fig. 2 (as it can occur in case of some options of EMTS), then only the second loop of Fig. 2 has to be programmed in Python to complete the automation of the cycles of tests. That is, there are different options to develop in detail the proposed method, depending on the specific available resources and the specific user needs.

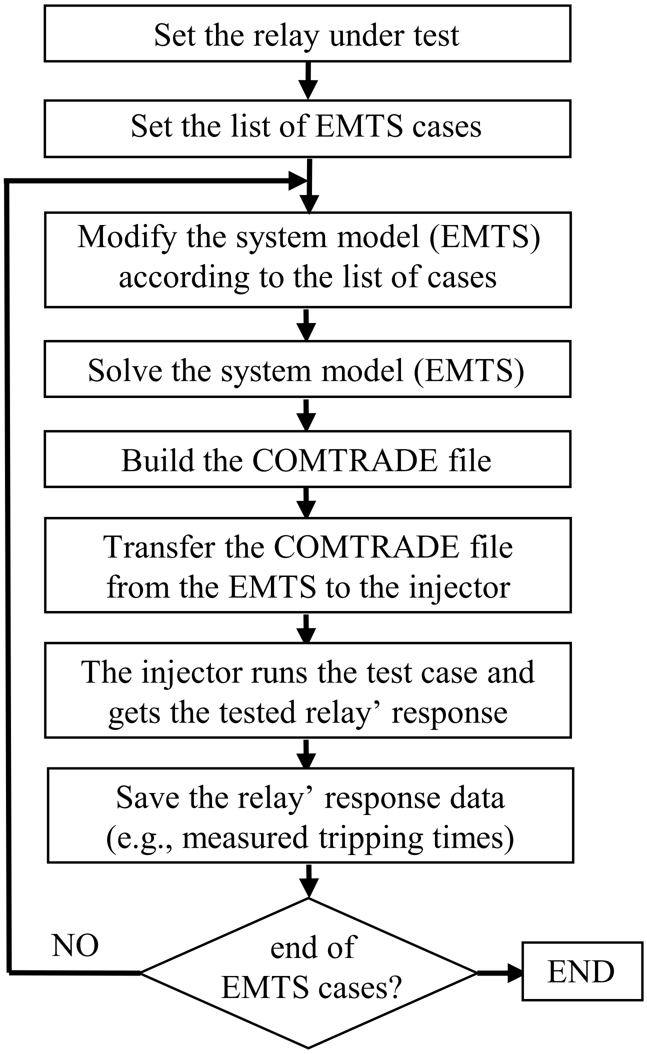


**Fig. 1.** Basic algorithm of the developed method

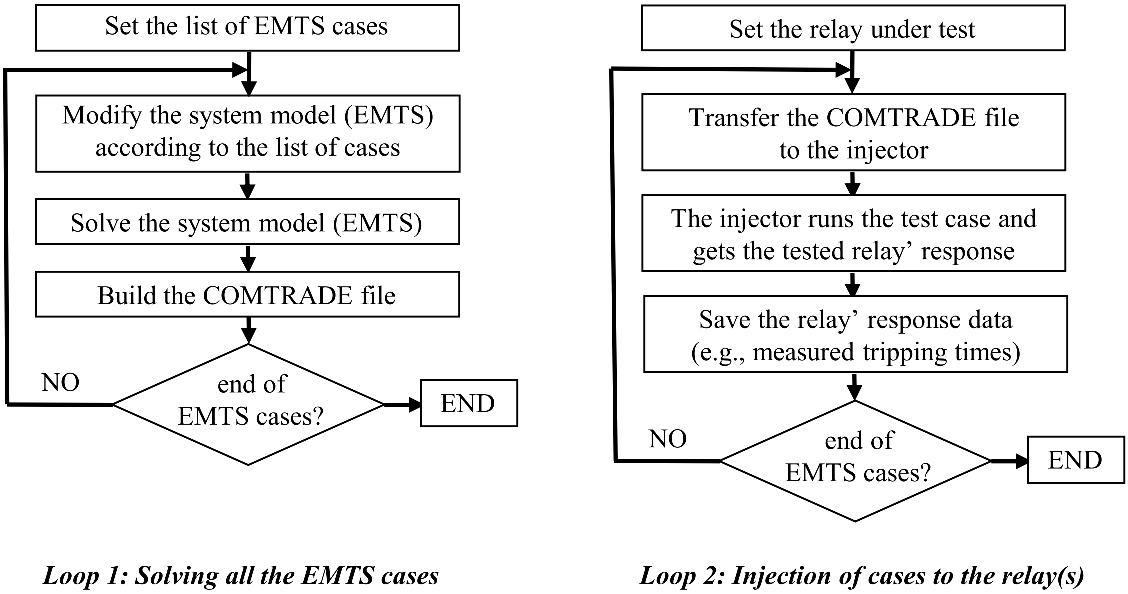


**Fig. 2.** Alternative algorithm of the developed method, using two sequential loops

## 3 Example of non-traditional test: effect of source impedance ratio on the tripping times of distance functions in the case of series-compensated lines

### *3.1 Fundamentals of the source impedance ratio*

The term source impedance ratio (SIR) is, to some extent, related to the modulus of the ratio of the system source impedance divided by the protected line impedance, but the exact definition depends on the standard and on fault type. The system source impedance ($Z_S$) is related to a simplistic Thévenin equivalent. The protected line impedance ($Z_L$) only considers the series impedance of the transmission line. Herein, positive-, negative- and zero-sequence values are identified with +, – and 0 subscripts, respectively. For example, for three-phase faults, the SIR is: a) $Z_{S+}$ divided by the 80% of the $Z_{L+}$ in IEC standard [13]; b) $Z_{S+}$ divided by $Z_{L+}$ in IEEE standard [14]. The definitions for asymmetrical faults have more details but follow the same general concept. In general, the tripping of distance functions tends to be slower for higher values of SIR [13,14].

### *3.2 Example of traditional tests (based on IEC Std 60255-121)*

The IEC Std 60255-121 [13] establishes one standardized way to test the effect of SIR on tripping times of distance functions. These tests are based on a simplistic power system, with the remote line-end opened, all the positive- and zero-sequence impedance angles are 85º, with zone-1 set at 80% of the line without considering load nor remote infeed, with 15 Ω and 10 Ω of primary fault resistance coverage for phase-to-ground and line-to-line faults at 0% of line length, respectively (if such coverages are settable), with $Z_{S+}=Z_{S-}$, $Z_{S0}=4Z_{S+}$ and $Z_{L0}=4Z_{L+}$. Solid faults with different SIR values, fault locations, fault inception angles and fault types should be simulated, with a repetition of 4 injections by case. This implies 1792 tests for each type of line (short line or long line), and the order to perform the tests is algorithmically described in [13]. Some important details, such as pre-fault stage duration or percentage settings of memory- and/or cross-polarization settings, are not specified in [13].

### *3.3 Simplified power system taken as an example*

Figure 3 shows a simplified one-line diagram of Venezuelan Central-Western system at 400kV (interconnections at 765 kV and 230 kV are not shown in Fig. 3, for the sake of simplicity). $X_C/X_{L+}$ is the quotient of the compensation capacitive reactance $X_C$ divided by the positive-sequence reactance of the line $X_{L+}$. The detailed simulation of systems with series-compensation (as the ones shown in Fig. 3 or in [34]) in off-line EMTS can be still an interesting challenge, due to the high number of busbars, even though there is a long tradition of engineers working in this area. On the other hand, an equivalent simulation of these systems with real-time tools is considerably much more difficult. The systems shown in Fig. 3 or in [34] are unnecessarily complex for the purpose of this article. A simplistic representation of only one Tablazo-Yaracuy series-compensated line (Fig. 3), fed by a simple Thévenin source (as in IEC Std 60255-121 [13]), was selected to illustrate the application of the proposed method.

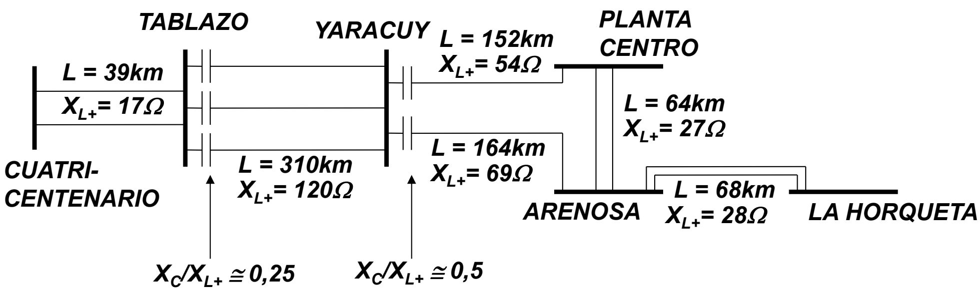


**Fig. 3.** One-line diagram of Venezuelan Central-Western 400 kV system; some protection details are shown in [37]

In practice, the capacitors of series-compensated lines have additional elements [19], such as metal-oxide varistors (MOV), auxiliary damping circuits (inductances and resistances), air gaps and by-pass switches. The voltage measurement for the distance function can be at the line or at the busbar side of the capacitor; only the case of voltage measurement at the line side of capacitor is herein considered for the sake of brevity. The simplified system shown in Fig. 4 was taken as an example to perform the cycles of protections' tests in order to obtain the effect of SIR on tripping times of distance functions in case of series-compensated lines.

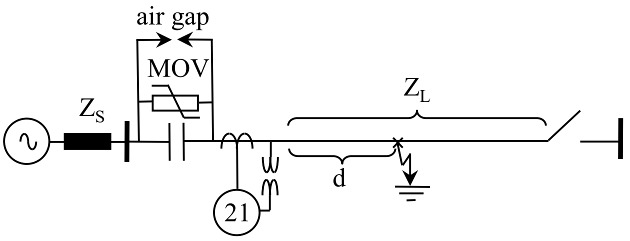


**Fig. 4.** Simplified system taken as an example for tests; *d* is the distance from the relay location up to the fault location

There are different line models in EMTS (e.g., with/without distributed parameters, frequency dependent or not). The line model selection can have an important influence on simulation results and relays' response [38]. A simple lumped parameter line model was herein applied, as well as ideal current transformers and potential transformers were herein considered, in concordance with standards' examples about the experimental obtaining of SIR diagrams [13, 14].

### *3.4 Non-traditional tests to apply the proposed method*

The following test conditions, based on IEC Std 60255-121 [13], were included: line capacitances are neglected; $Z_{S+}=Z_{S-}$, $Z_{S0}=4Z_{S+}$; the angles of $Z_{S+}$, $Z_{S0}$ and $Z_{L+}$ are 85°; the remote line-end is opened; the zone-1 reach is set at 80% of the line impedance; in quadrilateral characteristics, the adjustments for primary fault resistances are set to cover 15 Ω and 10 Ω for phase-to-ground and line-to-line faults at 0% of line length, respectively; sequence of tests according to the flowcharts shown in [13]. On the other hand, the following conditions were selected: $Z_{L+}=120\ \Omega \measuredangle 85°$ and $Z_{L0}=300\ \Omega \measuredangle 75°$; $X_C=30\ \Omega$; only solid faults for four fault locations (0%, 20%, 50%, 75% of line length), two fault inception angles (0°, 90°), three values of $Z_{S+}$ (12 Ω, 40 Ω, 200 Ω) and two fault types (3ϕ, 1ϕ) were considered; the injections were repeated 3 times in each case. The pre-fault and fault intervals were set in 2 and 0.6 seconds, respectively. The potential transformer and current transformer ratios are 400 kV/100 V and 2000 A/1 A, respectively. The system frequency is 60 Hz.

The main characteristics for the MOV and the air-gap were herein selected according to recommendations shown in [19]. The maximum continuous operating voltage of the MOV is 45 $kV_{RMS}$ to permit the maximum load current considering a safety margin. The voltage-current characteristic of a class 4 MOV was taken from [39], and an arrangement of 20 elements in parallel was considered (the voltage-current characteristic for the ATP model is shown in Fig. 5). The trigger for the air-gap is set to an energy of 16 MJ in the arrangement of 20 MOVs, to permit the maximum external fault current for 1 second, considering a safety margin. The air-gap was modelled as an ideal switch, in series with a damping resistance and a damping inductance ($R$=0.01 Ω; $L$=0.01 mH), which closes 0.5 ms after the triggering condition.

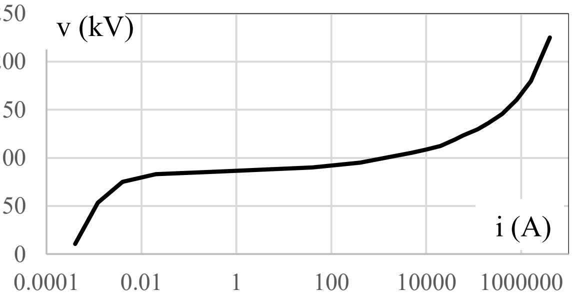


**Fig. 5.** Voltage-current characteristic of the arrangement of 20 MOVs

### *3.5. Relays and distance functions taken as examples for tests*

The selection of protective relays for series-compensated lines is a professional challenge, which is not within the scope of this paper. On contrary, the relays taken as examples for the tests were simply selected as the available ones in the Protection Systems Lab of Universidad Carlos III de Madrid at the moment of these tests, regardless if they could be recommended, or not, to be applied in protecting series-compensated lines. That is, the objective of this article is to show the developed method of testing (and it is not to assess the relays taken as examples for the tests).

The three relays under test are herein identified as A, B and C, without identifying the specific model of each one of them. The selected distance functions for the tests are mho and quadrilateral, in each relay. One of these relays [40] has: a) a *classic method* and a *reactance method* as options for these distance functions, and only the *classic method* was enabled; b) selectable levels for memory- and cross-polarization of mho functions, which were selected at the default values (0.15pu and 0.15pu, respectively). Other relay [41] has: a) an *adaptive resistive element* option for the quadrilateral ground-distance function, which was not enabled; b) a *self-polarizing quadrilateral elements* option, which was enabled, with the tilt of the reactance element at the default value (15º). The other relay [42] for these tests has: a) an optional *delta directionality* function, which was not enabled; b) a selectable index for the mixture of self- and memory-polarizing voltages, which was set at the default value (1 pu). Other details of relays' settings are not herein described for the sake of brevity. The characteristics of these relays in the R-X plane, with the proper settings for these tests, were previously tested using the traditional lab procedures for this purpose.

### *3.6 Particular description of the proposed method for the case of this specific example*

After describing the case taken as an example, in the previous subsections, the steps shown in Fig. 1 can be particularly described for this specific example. Each title of the following subsections corresponds to one step shown in Fig. 1.

#### *3.6.1 Set the relay under test*

The settings for the tests must be uploaded to each relay using the particular human-machine interface of each relay. In this case, due to the criterion of simplicity which was applied to design these tests, the relay settings only are: a) the shape of the characteristic (mho or quadrilateral), and the details selected according to the particularities of each manufacturer, described in Section 3.5; b) the reach of zone-1, at 80% of the line length, with $Z_{L+}$=120 Ω ∡85º and $Z_{L0}$=300 Ω ∡75º as primary values, and the potential transformer and current transformer ratios described in Section 3.4; c) in case of quadrilateral characteristics, the adjustments of resistive reach are set to cover 15 Ω and 10 Ω for phase-to-ground and line-to-line faults at 0% of line length, respectively, as described in Section 3.4; d) the output contacts to detect the operation in zone-1 of the selected characteristic of the distance function of the relay. Furthermore, it is also necessary to make the wiring between the injector and each relay, which consists in connecting the voltage and current outputs of the injector to the corresponding relay inputs, and the relay output contacts to the corresponding inputs for the detection of operation in the injector. This step is necessary to perform (and explain) these tests but it is not included in the developed automation (that is, this step is manual); the automation of this step would be very cumbersome and was not considered justifiable.

#### *3.6.2 Set the list of EMTS cases*

Due to the criterion of simplicity which was applied to design these tests, the main constant data of the power system shown in Fig. 4 are: a) the ideal voltage source (balanced, three-phase), whose peak value is 346.6 kV phase-to-neutral, which corresponds to 400 kVrms phase-to-phase; b) $Z_{L+}$=120 Ω ∡85º and $Z_{L0}$=300 Ω ∡75º; c) $X_C$=30 Ω; d) the MOV and air-gap features described in Section 3.4.

On the other hand, the remaining power system data are combinatory variations, according to four loops for these specific tests. These loops, ordered from the outermost loop to the innermost loop, are: a) variation of the source impedance, with $Z_{S+}$ equals to 12 Ω, 40 Ω or 200 Ω ($Z_{S+}$=$Z_{S-}$, $Z_{S0}$=4$Z_{S+}$); b) variation of the fault location, with d equals to 0%, 20%, 50% or 75% of the line length; c) variation of the fault type, with only two options (3ϕ, 1ϕ); d) variation of the inception angle, with only two values (0, 90º), which were executed by changing the phase angle of the ideal source voltage. Actually, there is another loop, to repeat the injection three times, but it is located in the step described in Section 3.6.7 because this loop does not require any change in the power system simulation performed by the EMTS. The end of these loops corresponds to the final step of the algorithm, labeled as "end of EMTS cases?" in Fig. 1.

#### *3.6.3 Modify the system model (EMTS) according to the list of cases*

The changes in the power system model, according to the four loops described in Section 3.6.2, are performed by updating the input data file for the EMTS. For the sake of simplicity, the name of the input data file was always the same in the specific developed program for this example; however, the use of different names for each variation of the input data file obviously is another option that could be choose by the programmer.

#### *3.6.4 Solve the system model (EMTS)*

Once the input data file has been updated, this step simply executes the EMTS. The output data file of ATP is in a particular format (extension: ".pl4").

#### *3.6.5 Build the COMTRADE file*

The output data file of ATP (extension: ".pl4") is converted to COMTRADE format by the simple use of an executable program (*pl42com.exe*). This format converter is traditionally applied to the ATP output data files in order to obtain suitable files to perform simple tests using injectors for electric power system relays.

#### *3.6.6 Transfer the COMTRADE file from the EMTS to the injector*

Once the input data file is in COMTRADE format, it must be uploaded to the injector. In this particular case, this step must be performed using the graphical user interface of the injector, because this injector was not designed to be externally controlled by an independent software. In order to do that, three instructions from *pyautogui* (a Python library) were necessary: a) *pyautogui.click* is the instruction to make a click in a specific screen location; b) *pyautogui.write* is the instruction to write text, and it is applied to enter the name of the COMTRADE file to be uploaded by the injector; c) *pyautogui.press* is an instruction that was useful to emulate the manual action of pressing "return", to continue the execution of the injector's human-machine interface. Another important Python instruction is *time.sleep*, since the uploading of the COMTRADE file and the answer of the injector require some waiting times.

#### *3.6.7 The injector runs the test case and gets the tested relay's response*

As in the previous step, this step is also performed using the graphical user interface of the injector. In this step, the number of required repetitions is simply controlled by a loop (using a counter from 1 to 3, as described in Section 3.4).

#### *3.6.8 Save the relay's response data*

As in the two previous steps, this step is also performed using the graphical user interface of the injector. Fortunately, this injector simply appends the new results in the open output data file. This feature was very convenient for this application since all the final results were automatically stored in a single file.

## 4 Results

### *4.1 Examples of obtained waveforms*

Figure 6 shows an example of waveforms computed by the EMTS in order to illustrate the effect of MOV and air-gap on results. The results "without MOV, without air-gap" are the natural response of the series RLC circuit near to resonance. The results "with MOV, without air-gap" show that the MOV limits the voltage across the protected capacitance, and the results "with MOV, with air-gap" show the effect of bypassing the MOV (because the energy in it reaches the triggering value). Obviously, the tests were performed "with MOV, with air-gap", and Fig. 7 shows the corresponding example of computed and measured results during a test. For this example, the measurements of relay tripping time were: a) 35 ms, from the relay COMTRADE file; b) 39 ms, from the oscilloscope, c) 42 ms, from the injector. The SIR diagrams of the next Subsection were obtained from the relay tripping times reported by the injector.

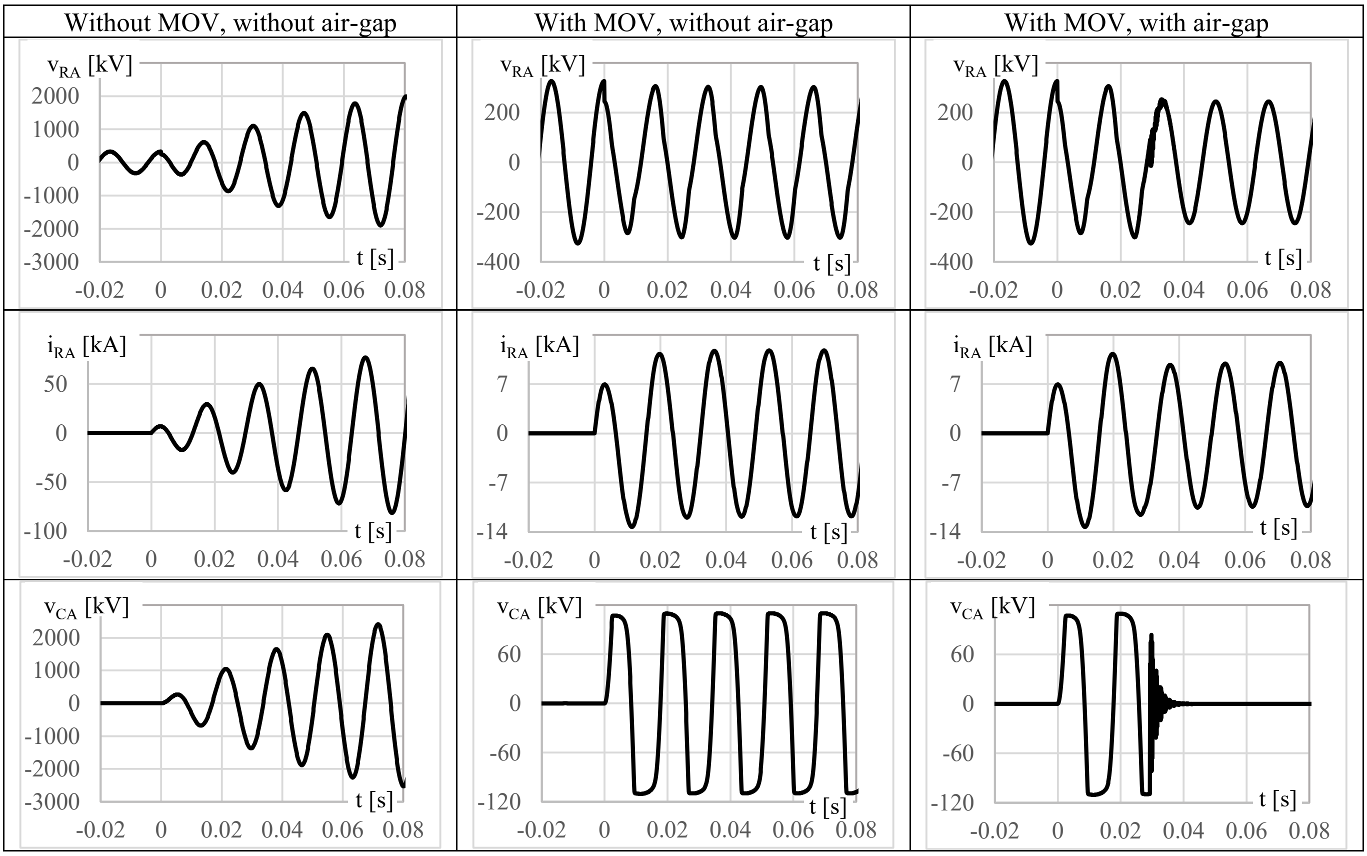


**Fig. 6.** Example of voltage and current at relay location, and voltage across the capacitance (in phase-A: $v_{RA}$, $i_{RA}$ and $v_{CA}$, respectively), computed by the EMTS. $Z_{S+}$=8 Ω; fault: 3ϕ at 20% of line length; inception angle: 90º

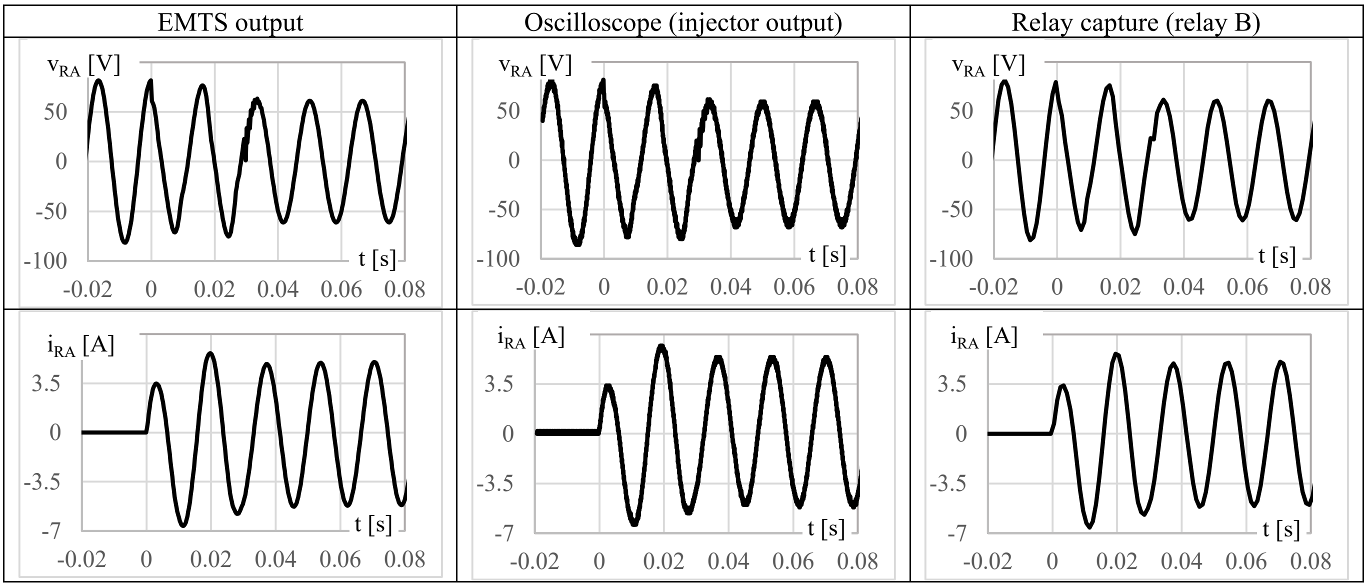


**Fig. 7.** Voltage and current at relay location for case with MOV and with air-gap of Fig. 6; computed (EMTS output) and measured (oscilloscope and relay B)

### *4.2 Examples of obtained SIR diagrams*

Figure 8 shows examples of obtained SIR diagrams. Two interesting points are herein highlighted: a) some distance functions did not operate in some cases, as shown in Tab. 1; such cases were not included to compute the statistics for the corresponding SIR diagrams; b) the vertical scale for the SIR diagrams is typically in the range between 10ms and 50ms; the only exception is the case of the quadrilateral characteristic of relay A, whose SIR diagram has points notoriously slower. That is, as the traditional expected response of distance functions for these faults (that should be within the zone-1 reach) is the operation for all the cases, with operation times between 10 ms and 50 ms, the existence of this type of results is useful to illustrate the need of performing this type of tests to assess the behavior of protective schemes for series-compensated transmission lines.

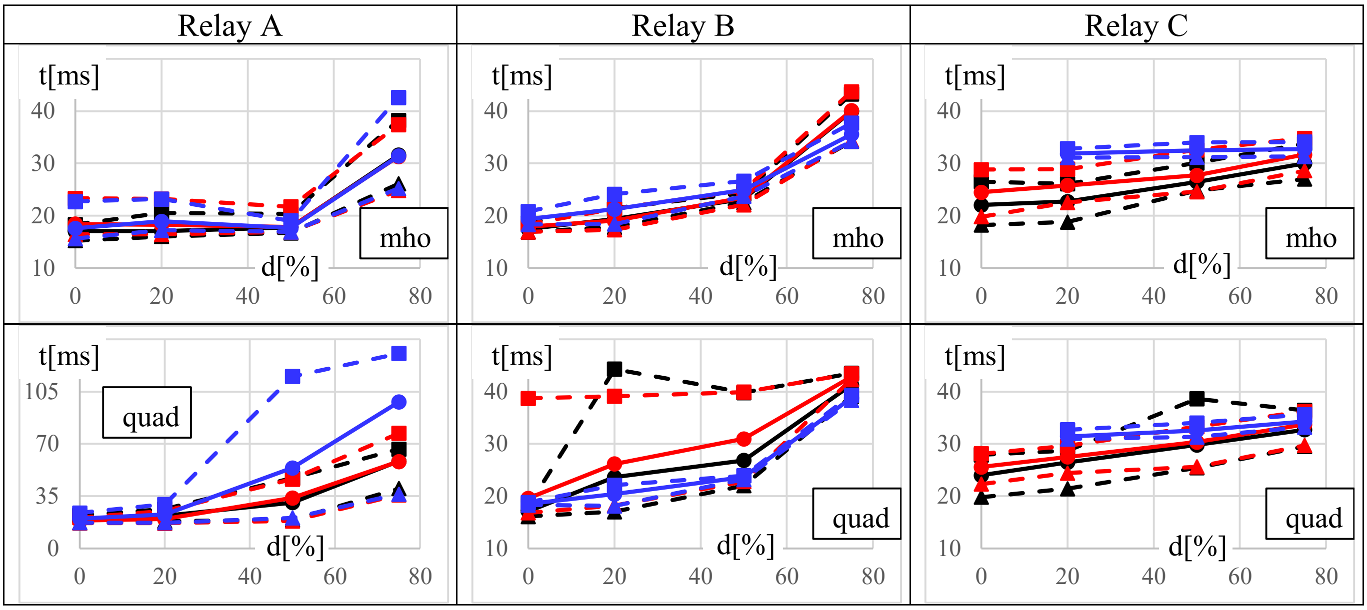


**Fig. 8.** Examples of SIR diagrams for $Z_{S+}$= 12 Ω (black), 40 Ω (red) and 200 Ω (blue). Solid line: average time; dashed lines: minimum and maximum times.

**Table 1.** Cases of no operation of distance functions during the tests

| Relay | Function | Cases of no operation |
|---|---|---|
| A | Mho | None (i.e., operation for all the tested cases) |
| | Quadrilateral | None (i.e., operation for all the tested cases) |
| B | Mho | None (i.e., operation for all the tested cases) |
| | Quadrilateral | a) 1ϕ faults with $Z_{S+}$=200 Ω, any value of d<br>b) 1ϕ faults with $Z_{S+}$=40 Ω and d=75% |
| C | Mho & Quadrilateral | a) 1ϕ faults with $Z_{S+}$=200 Ω, any d<br>b) 3ϕ faults with $Z_{S+}$=200 Ω and d=0% |

### *4.3 Examples of estimated benefits of using the proposed method*

The benefits related to the application of the proposed method can be illustrated using two independent comparisons. The first comparison is with the application of real-time digital simulators, which have similar performance regarding the time to perform the cycles of tests, and the main difference is on the cost of the required tools. The cost of a real-time digital simulator, with the proper voltage and current amplifiers for the injections, is in the order of 200×10$^3$ €, whereas the cost of a traditional injector for protective relays is in the order of 10 times less expensive. Furthermore, the traditional injectors for protective relays are usually available at the power system protection labs; therefore, typically there is no need of investments in new equipment to perform the tests with the proposed method. The second comparison is with the application of the same traditional injector but without the automation of the cycles of tests, since the main difference in this case is on the required time for the tests. An average estimated time to perform these tests by a well-trained person, with good skills using these hardware and software tools, is in the order of 40 minutes by test, which is in the order of 20 times slower than the required time when the tests are automatically performed with the proposed method.

## 5 Conclusion

A novel method to perform cycles of protections' non-traditional tests using traditional injectors and Electro-Magnetic Transient Software (EMTS), via Python, was proposed and successfully applied. Python is applied as a powerful tool to control the injector and the EMTS in a loop, in order to perform the cycles of tests. The obtaining of SIR diagrams (tripping times of distance protections, as a function of source impedances), in the non-conventional case of a series-compensated line, is shown as an application example of the proposed method. A basic injector and a royalty-free EMTS were applied for this example, to illustrate that relatively complex tests can be performed with very low resources. The proposed method was herein applied to obtain the SIR diagrams for the mho and quadrilateral characteristics of three commercial relays.

The main advantages of the proposed method, in comparison with the currently available alternatives, are: a) the proposed method is considerably less expensive than the use of real-time digital simulators, in general, and considering that it is based on equipment which are commonly available in the power system protection labs, usually there is no need of buying new equipment and this advantage becomes really huge; b) the developed method is considerably faster than the use of the same resources without the proposed automation. A weakness of the proposed method is that it has not been developed to perform real-time simulation; however, as the need of real-time simulations to modify the power system models according to the protective relays' response is not common at all, this drawback can be considered insignificant in comparison with the described advantages. On the other hand, considering the continuous improving in general-use computers' performance, a future development about this topic could be led to explore the possibility of performing some real-time simulations based on the proposed method, and the main challenges in this sense probably are: a) the obtainment of fast enough file transfer and playback in commercial injectors; b) the obtainment of fast enough solution of electromagnetic transients in general-purpose computers.

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