

Application of a software package for transmission line digital overcurrent protection testing in the MATLAB-SIMULINK environment

Abstract. The article proves the possibility of implementing a software package for digital overcurrent protection testing in the Matlab-Simulink environment. A comparison of simulation results obtained with the use of the proposed software package with the results obtained with the use of the other software, as well as with the calculations of transient processes has been performed. The parameters calculation methods of the proposed software package are presented.

Streszczenie. Artykuł udowadnia możliwość implementacji pakietu oprogramowania przeznaczonego do badania cyfrowego zabezpieczenia nadprądowego w środowisku Matlab-Simulink. Przeprowadzono porównanie wyników uzyskanych za pomocą proponowanego pakietu oprogramowania i innego oprogramowania, jak również obliczeń stanów przejściowych. Zaprezentowano metody wyznaczania parametrów proponowanego pakietu oprogramowania. (Zastosowanie pakietu oprogramowania przeznaczonego do badania cyfrowego zabezpieczenia nadprądowego linii przesyłowej w środowisku MATLAB-SIMULINK).

Keywords: software package, Simulink, Matlab, SimPowerSystems, digital overcurrent protection, model, current transformer
Słowa kluczowe: pakiet oprogramowania, Simulink, Matlab, SimPowerSystems, cyfrowe zabezpieczenie nadprądowe,

Introduction

Digital protection testing at the stage of their development is being performed with the help of software packages (SP) that simulates the digital protection analogue inputs supplying with the currents and voltages that are similar in volume and waveform to the actual secondary signals of current and voltage under the conditions of real exploitation of the protected object.

A comprehensive mathematical model, that calculates the input signals of relay protection, is being prepared for the generalized electric power object (GEO).

Model of GEO can be realized either on the basis of mathematical descriptions of electric and magnetic circuits of the modeled elements, or in systems of dynamic modeling.

The present work substantiates the possibility of implementing a software testing system for digital overcurrent protection in the Matlab-Simulink system of dynamic modeling.

The main part

Models of GEO can be divided into rigid and flexible ones.

A rigid model is characterized by a constant set of elements that can change their parameters. In order to obtain reliable results, one must solve dozens of differential and algebraic equations. The disadvantages of rigid structures include the complexity of the creation and especially the change in any element of the model, since this requires substantial processing of the entire algorithm of the program.

For flexible models of GEO the set of elements is unlimited. It is implemented in the Matlab-Simulink system of dynamic modeling, that includes the SimPowerSystems expansion package (SPS), focused on the simulation of electrical devices. All the models included in this package, had been tested in the laboratories of the Canadian manufacturer of electric power i.e. Hydro-Québec, where the adequacy of their implementation and mathematical description had been confirmed [1].

However, standard SPS libraries do not contain all the required models of electrical equipment. For instance, there is no model of the current transformer (CT), and as far as for the model of the power transformer the method of calculation of its parameters is not specified.

The ease of complex models creation, which is especially important for engineering objectives when it is required to model a fragment of the power system independently, without delving into the details of mathematical modeling of the elements themselves, should be considered as the undoubted advantages of Matlab-Simulink using. At the same time, the carefully chosen demos of the SimPowerSystems package create a sense of simplicity of the use of library blocks, although the deviation of the parameters from the ones specified by default often leads to incorrect functioning of the model.

Therefore, the simulation results obtained from the SP, made up of library blocks of Simulink-SimPowerSystems are necessary to be compared with the results obtained from other SPs, adopted as a reference, and with the field tests and calculations of transients according to standard procedures. If a high convergence of results from different sources is achieved, this suggests that models created in Simulink – SimPowerSystems adequately operate and can be used to create other systems, the structure of which significantly differ from the reference.

The software package to study the performance of power line digital overcurrent protection with a rigid structure of GEO

GEO contains a mathematical description of the protected line, of its sources of power and measuring transformers, as well as of the associated elements that has a significant quantitative and qualitative impact on the nature of the course of the emergency and post-accident conditions.

The supply system is represented as a system of ultimate power with a constant EMF and frequency. The power transformer is a three legs two-winding transformer with the Y0/Δ-11 winding connection scheme. On the lines of protection that are the subject of the test CTs controlling the phase currents and a core balance CT are set.

The mathematical description of the stationary elements of the settlement scheme contains, in general case, two groups of equations i.e.:

- differential equations that are the equilibrium equations of the EMF and the equations of balance of currents in the nodes of a design scheme with capacities;

- algebraic equations that are equations of balance of currents in nodes without capacities as well as balance equations of MMF in the magnetic core circuits and characteristics of magnetization.

The SP has been developed in object-oriented Delphi software system. The main results of the SP functioning are the instantaneous values of the secondary currents of the CT in the circuit protected line, i.e. the input signals of the protection system being tested. For this purpose the shell software based on a modified FORTAN module was developed (Fig.1). With the aid of the interactive graphical interface the shell software makes it possible to activate the input window and edit the source data of the individual elements of the design scheme, to select the line, place and type of circuit, to change the settings for the design mode.

At the BNTU "Power Stations" Department the work on the mathematical modeling of electric power facilities and the development of computer programs to study the behavior of relay protection method for a computing is being done for over 40 years.

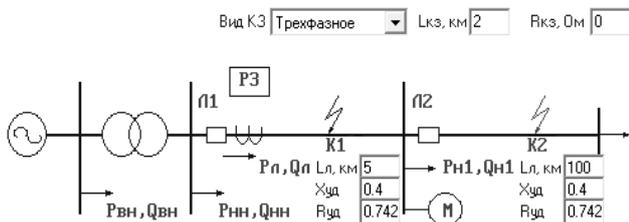


Fig.1. Interactive graphical SP interface

The long experience of usage of such software products for scientific research as well as of comparison of simulation results with field tests (the error does not exceed 10%) [2], suggests that the results of mathematical modeling reproduce processes in real energy objects with a high degree of precision and accuracy. Therefore, the considered SP with the rigid structure of GEO is a benchmark to compare the simulation results of the same power objects implemented in other simulation systems (e.g. in Matlab-Simulink) with.

The software package to study the performance of power line digital overcurrent protection with a flexible structure of GEO

In accordance with Fig.1 the model of GEO and the model of a 3-stage overcurrent protection Line1 (L1) is being made out of the blocks of the Simulink-SimPowerSystems (Fig. 2).

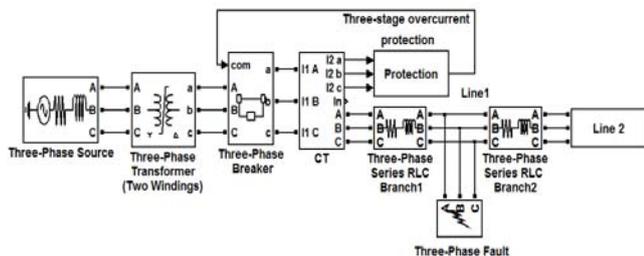


Fig.2. SP in the Simulink-SimPowerSystems system

Mathematical model of most electric power objects are represented by library units of the SPS package. The determining of such parameters for these units as voltage, frequency, active and reactive power, etc., usually does not cause difficulties. However, at almost every library unit there are several key parameters that require additional calculations for the correct functioning of the model.

The following are the basic blocks which make up the model of a distribution network with the indication of specific features of calculation of their parameters.

1. The power system is simulated by the Three-Phase Source (three-phase voltage source) unit from the SPS library. The main parameters that require additional calculation are: the source resistance R_s , Ω and source inductance L_s , H.

The inductance of the supply system can be determined for a given short circuit current $I_{sc}^{(3)}$ on the buses of the load node with voltage U_n :

$$(1) \quad L_s = \frac{U_n}{\sqrt{3} I_{sc}^{(3)} \omega_0},$$

where ω_0 is the nominal angular frequency.

If the power of the system S_s , its relative resistance X_* and voltage U_s are set, the inductance of the system is:

$$(2) \quad L_s = X_* \cdot \frac{U_s^2}{S_s \cdot \omega_0}.$$

Source resistance can be determined from the average value of the time constant of the aperiodic component of the fault current ($T_s=0.05$): $R_s \cong 20L_s$.

2. Power transformer. The standard model of the three phase two-winding transformer called "Three-phase Transformer (Two Windings)" from the SPS library is based on three single-phase transformers [1].

The method of calculation is discussed in detail [3]. Table 1 demonstrates the expression to calculate in per-units (pu) the model parameters of the power transformer with winding connection scheme Y/ Δ -11 that uses only the nameplate data of the power transformer: S_n – rated transformer power (VA); P_{sc} – short circuit losses (W); U_{sc} – short circuit voltage (%); P_0 – no-load losses (W); I_0 – no-load current (%).

Table 1. Formula for calculation the power transformer model parameters

Parameter	Value, pu
The active resistance of the primary and secondary windings of the transformer	$R_{1(pu)} = R_{2(pu)} = \frac{1}{2} \cdot \frac{P_{sc}}{S_n}$
The inductance of the primary and secondary winding of the transformer	$L_{1(pu)} = L_{2(pu)} = \frac{1}{2} \cdot \frac{U_{sc}}{100}$
The active resistance of the magnetization branch	$R_{m(pu)} = \frac{S_n}{P_0}$
The inductance of the magnetizing branch	$L_{m(pu)} \approx \frac{100}{I_0}$

3. Power line (the 3-Phase Series RLC Branch block or three-phase serial RLC-circuit). The protected line is characterized by the length l , active r_{res} and reactive x_{res} specific resistances:

$$(3) \quad R = r_{res} l; \quad L = x_{res} l / \omega_0.$$

4. Load (the 3-Phase Series RLC Load block). Stationary loads are set by active (Three-Phase active power) and reactive (Three-Phase inductive reactive power) capacities.

5. Breaker (3-Phase Breaker), the control of which can be implemented by means of external input signal (1/0 – enable/disable).

6. The unit of the short-circuit (3-Phase Fault). It simulates a three phase device that closes phases with each other and to the ground.

7. WYE-connected CTs (CT). Since the library block of the CT in the system of SPS is missing, the model of the CT that specifies the average magnetizing characteristics of the steel magnetic circuit and the parameters of the CT are calculated according to its nameplate data [4], has been created of the standard Simulink blocks, having been based on the same equations as for rigid models. The model was tested as well.

For comparison of the modeling results in SP of a rigid and a flexible structures of GEO, model parameters of Fig.1 and Fig.2 were considered as identical. The calculations revealed a close match (discrepancy of the simulation results is not more than 1-3%), that confirms the possibility of using Matlab-Simulink to generate the input effects on the tested security model.

Digital modeling of a three-stage overcurrent protection of transmission lines

A three-stage overcurrent protection contains a instantaneous high current (IHC), definite time high current (DTHC) and definite time overcurrent protection (DTOC). In Fig.2a three-stage overcurrent protection is presented in the form of a "Protection" composite block. All the stages of protection are based on the current measuring element (CME), the implementation of one of the phases of the latter by library Simulink blocks is demonstrated in Fig. 3.

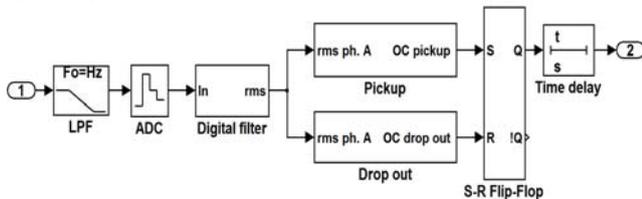


Fig.3. A-phase overcurrent protection model structure

A low-pass filter of the 2nd order (LPF) is represented by the 2nd-Order Filter block. The purpose of this analog filter is to suppress the spectral components whose frequency exceeds half of the sampling frequency. As parameters, the cutoff frequency of the filter and the damping parameter (0.707) are specified.

Analog-to-digital converter (ADC) (block Zero-Order Hold) carries out the conversion of samples of the output signal of the LFF unit into a digital code. The number of samples of the signal during the period of industrial frequency (50 Hz) in this work was accepted as 24, i.e. the sampling frequency of the signal is 1200 Hz.

The Digital Filter composite unit of the 1st harmonic contains a digital filter, designed to determine the RMS value of the fundamental harmonic of the signal containing the aperiodic component and the higher harmonics. Implementation of the digital filter based on the use of the discrete Fourier transform and can be represented by:

- the Discrete Fourier library block (fundamental frequency, number of selected harmonics and the sampling period signal being the specified parameters);
- on the basis of the Digital Filter library block, pre-calculated coefficients for the sine and cosine orthogonal components of the signal fundamental frequency being its parameters [5].

For reliable CME operation it is required that the condition of its pickup (drop out) were completed within the time equal to 3-5 samples of the monitored signal. These conditions are examined in the "Pickup" and "Drop out" blocks implemented using the Simulink blocks. If the conditions of pickup (drop out) is executed / not executed, at the output of the corresponding block the logical 1/0 signals are formed. The output signal from the "Pickup"

block is received at the S-input ("set"), and the output signal of the "Drop out" block is received at the R-input ("reset") of the S-R Flip-flop (the S-R Flip-Flop library block).

The direct trigger output Q is connected to the delay time unit (the Discrete On/Off Delay library block) which starts to count the time delay, if the logic 1 is present at the input. This condition occurs when the monitored signal exceeds the pickup setting. If this condition lasts during the specified time delay, the output of the block "time delay" will set the logic 1, which is a characteristic of the overcurrent protection trip in the controlled phase. If the signal will be less than the pickup setting during the time delay counting, the CME will drop out to its original state, the logic 0 will be set at the trigger output and the protection operation will not occur.

Comparison of simulation results of the SP with calculations of transients in the GEO

Another form of assessing the correctness of functioning of the SP is the comparison of the simulation results with the calculations of transients in the GEO, as well as with the calculated parameters of operation of the overcurrent protection and with the reaction of the latter on disturbances. As such an integrated parameter, that makes it possible to consider the totality of these factors, one can use the value of the second stage (DTHC) protection zone, which depends both on parameters of the external system, and on the ratio of the lengths of the protected and adjacent lines.

The parameters of the elements of the rigid (Fig.1) and the flexible (Fig.2) models were adopted as the same: power system: $S_s=240$ MVA, $X_s=0.4$; power transformer: $U_{sc}=10.5$ %, $S_n=16$ MVA, $U_{hv}=115$ kV, $U_{lv}=10.5$ kV; lines $l_1=5$ km, $l_2=2$ km, the resistivity of the lines: $x_{res}=0.4$ Ω /km.

The calculation of the resistances of the power system and transformer:

$$(4) \quad X_s = X_* \cdot \frac{U_{lv}^2}{S_s} = 0,4 \cdot \frac{(10,5)^2 \cdot 10^6}{240 \cdot 10^6} = 0,18 \quad \Omega$$

$$(5) \quad X_t = \frac{U_{sc}}{100} \cdot \frac{U_{lv}^2}{S_n} = \frac{10,5}{100} \cdot \frac{(10,5)^2 \cdot 10^6}{16 \cdot 10^6} = 0,72 \quad \Omega$$

External, in relation to the protected line, resistance:

$$(6) \quad X_{ext} = X_s + X_t = 0,18 + 0,72 = 0,9 \quad \Omega$$

The pickup current of the DTHC line 1 is tuned away from the IHC pickup current I_{ihcl2} on line 2:

$$(7) \quad I_{dthc} = k_s \cdot I_{ihcl2} = k_s^2 \cdot I_{l2}^{(3)},$$

where $I_{l2}^{(3)}$ is the three-phase short-circuit current at the end of line 2, k_s is the safe factor.

Protection zone of DTHC for the line L1 is:

$$(8) \quad L_{dthc} = \frac{100}{X_{l1}} \left(\frac{X_{ext} + X_{l1} + X_{l2}}{k_s^2} - X_{ext} \right), \%$$

With the regard of $x_{res}=0.4$ Ω /km and $k_s=1.2-1.25$ the approximate expression is being obtained:

$$(9) \quad L_{dthc} \approx \frac{65 \cdot (l_1 + l_2) - 85 \cdot X_{ext}}{l_1}, \%$$

Thus, for the accepted source data, DTHC protects 75% of the length of line L1, i.e. 3.75 km.

Fig.4 presents the results of the SP as applied to phase A at three phase short circuit at a distance of 3.5 km from the place of installation the DTHC, i.e. near the end of protection zone.

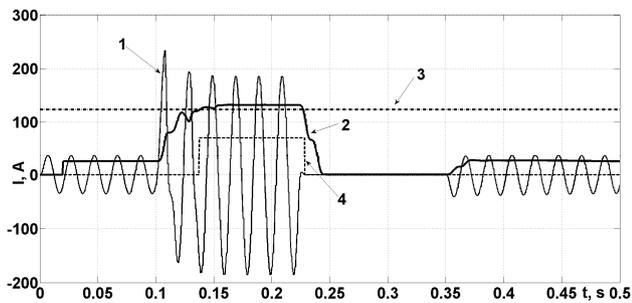


Fig.4. 1 – is secondary current of the CT phase A, 2 – is the RMS value of the secondary current, determined by a digital filter, 3 – is the pickup setting determined by calculations, 4 – is the output signal of the CME.

At time $t=0.1$ s. 3-phase short circuit occurs, at $t=0.13$ s. the CME of the DTHC operates (curve 2 exceeds pickup setting 3) and triggers the time delay unit ($\Delta t=0.1$ s.), after activation of which ($t=0.23$ s.) the breaker is being opened (square wave pulse 4 is set to 0). At time $t=0.35$ s. the successful automatic reclosing occurs, which again closes the breaker.

Attempts of modeling three-phase short circuit at a distance of $l_{sc}>3.8$ km from the start of L1 does not lead to DTHC action, i.e. the end of the line L1, approximately 25% of its length, is not protected by fast-acting protection (IHC does not work, by definition, and the DTOC is tripped, but with a long time delay). Thus, coincidence of results of calculations by formula (9) and the simulation results is confirmed, once again confirming the correctness of functioning of the SP based on Simulink – SimPowerSystems.

Thus, the obtained simulation results gave us the ground to conclude that the MATLAB-Simulink dynamic modeling system makes it possible to test the lines digital overcurrent protection in transient behavior taking into account all factors affecting their reliable performance during minimal time. Application of the MATLAB-Simulink compares favorably with the traditional approach with the use of programming languages that requires a long time to construct, debug and visualize a mathematical model of the power system and of the object of study, leading to the same result.

Conclusion

1. The possibility of using the MATLAB-Simulink system of dynamic simulation for the implementation of SPs for testing of current digital protection of transmission lines with arbitrary structure of GEO.
2. It is established that in case of the correct choice of block parameters of which models of electrical equipment are being constructed, the results of the simulation by the software package based on MATLAB-Simulink differ by no more than 3% from the results obtained from the reference programs, which, in their turn, is not more than 10% different from the results of the full scale experiment.

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