DISTRIBUTION PROTECTION RELAY SOFTWARE MODELS IN INTERACTION WITH POWER SYSTEM SIMULATORS

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ABSTRACT

Modelling and simulation software developed for analysing protective relaying applications and relay (IED) design concepts in power distribution is described in the paper. Matlab has been selected as programming environment for protective relaying software modelling. Within Matalabs Simulink environment, SimPowerSystems is selected as a design tool for modelling and simulating a distribution power system. The system is modelled according to the two real radial distribution networks in which field (short-circuit) tests were conducted. Current and voltage measured records from tests are used for model verification and also as a signal source for testing the relay models.

INTRODUCTION

In the MV networks in Croatia there are three ways of substation (transformer) neutral point grounding treatment: isolated, low-ohmic grounded and, from a dozen of years ago, resonant grounded. Croatian MV distribution networks are mainly radially operated.
With an aim to define the criteria for appropriate neutral treatment selection depending on the substation and MV network type, a study has been conducted recently. Selection criteria in the study considered: (i) technical features of all three neutral treatments concerning the earth-fault currents, overvoltages and network operation, allbased on measurements, computer analysis and operation experiences; (ii) human safety requirements and rules (touch voltages), heath and voltage stresses and interferences with telecommunications lines; (iii) network ”significance” (number and type of connected customers), size (length of galvanic connected lines), type (cable to overhead lines ratio, type of poles and types of cable junctions and screens); (iv) quality of supply (SAIFI and SAIDI); (v) earth systems requirements concerning earthfault currents and soil resistivity. Every criterion has been economically evaluated regarding capital and operation expenditure and then cost-benefit analyses have been made. The results of those analyses are criteria for adequate neutral treatment selection concerning mentioned features, requirements and rules.
The study also emphasized the need for amendments of rules currently in force regarding operation and protection relay requirements as well as harmonization with European norms. The need for implementation of new protection methods and primary measuring equipment coordination (current and voltage transformers) have also been considered and analysed. The analysis performed and the results achieved are described in this paper.

RELAY MODELLING

Protective relays together with current and voltage transformers are a substantial part of the power system. Protective relays rapidly isolate faulted part of the system which allow system stability and undisturbed power supply for most customers. Incorrect operation of protective relays can have adverse consequences for continued power supply. Developing, using and teaching protective relay application and design concepts assumes multidisciplinary approach comprising among others power system physics, mathematical formulations and electronic devices. Majority of components that constitute a modern electrical power system have been successfully modelled for transient studies for more than forty years. The exception is protective relaying. Progress in modelling of power relays in transient analysis appeared in the last twenty years.
Electrical faults, switching actions and other power system disturbances, cause a redistribution of the electric and magnetic energy stored in capacitive and inductive elements and mechanic energy stored in rotational elements of the network. This redistribution of electric energy cannot occur instantaneously and the power system must undergo through a transient state before it reaches a new steady state. During the first few cycles following a power system fault, high-speed protective relays are expected to make a correct decision as to the presence and location of the fault in order to preserve system stability and to minimize the extent of equipment damage. The majority of protective relays make their decisions based on fundamental frequency (50 Hz or 60 Hz) voltage and current signals. However, it is precisely at this moment that the voltage and current signals are badly corrupted by fault-induced transients in the form of an exponentially decaying DC component, and with frequencies above and below the fundamental power system frequency. The dynamic performance of protective relays depends to a large extent on their design principle that addresses aspects such as selectivity, sensitivity, security, and dependability. In addition, the dynamic performance of high-speed protective relays depends to a large extent on the signals produced by instrument transformers, and these signals depend on the overall transient response of the instrument transformers, and the type of transients generated by the power system [1, 2, 3].
Relay software models are useful for relay manufacturers, utilities, customers and also for educational purposes. In

general, manufacturers use more sophisticated models to support development and presentation. Representatives of manufacturers can explain the behaviour of the relays to their clients with the help of relay models using input from network simulation programs or from power system transient recorders.

Depending on the purpose they serve it is possible to create more or less sophisticated relay models. Simple models use only mathematical equations to describe the pick-up and tripping characteristics of the relays. These models can be used to make general decisions for the selection of relay types, and together with network calculation programs they can be used to derive relay settings. More sophisticated relay models are much more comprehensive. They process voltage and current transient waveforms from EMTP simulations, actual fault waveforms captured by numerical relays, or digital fault recorders. This way user can observe their response to these transients and reaffirm the protection behaviour during network disturbances.

Relay modelling in Matlab

Matlab with its time domain solver Simulink has powerful calculation and visualisation tools and is one of standard tools for protective relay modelling in industry and in university environment [1, 2, 4]. Therefore it has been selected as programming environment for protective relaying software modelling in this paper. Simulink and SimPowerSystems allow fast development and closed-loop testing of protection and control systems used in power systems and drives. This is important since actual power systems and their protection systems operate in a closed-loop manner [2, 5].

The relays are modelled so that the general working principles of protection systems can be demonstrated. The interaction between network calculation program and software protection system models is achieved. Closed-loop simulations of relay software models with an electromagnetic transient simulation enables evaluation of the transient behaviour of the protective relaying algorithms due to changes and switching in the network. Different protection settings and their consequences on the protection behaviour are possible as well as protection coordination analysis. The study presented in this paper aimed at development of relay software modelling for relevant testing prior to the building of a prototype relays. This is essential for the development process because, it allows testing of various relaying algorithms, the relay logic, and making necessary changes without the need to make changes in hardware or software modules of the actual device. Relay algorithm development enables use of relay software models to test different digital signal processing techniques, protection algorithms, the transient response of digital filters, phasor estimating methods, directional or distance element unit performance and evaluation of new measuring techniques.

DISTRIBUTION POWER SYSTEM MODEL

Within Matlab/Simulink environment, SimPowerSystems is selected as a design tool for modelling and simulating a distribution power system. In Simulink environment it is possible to model and simulate the total system by combining SimPowerSystem with control system tools. This allows optimisation of control parts of the model. Accurate and fast simulations are possible by using variable step integrator and zero crossing detection capabilities.

The system is modelled based on two real radial distribution networks in which short-circuit and earth-fault tests were done. Current and voltage measurements have been used for the model calibration and verification and also as a signal sources for testing the relay models.

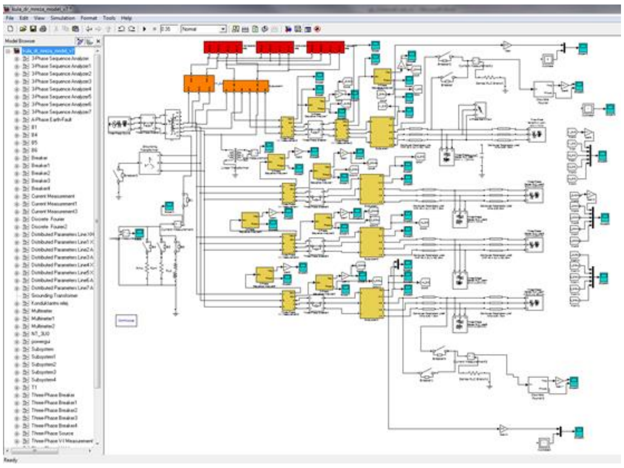

***Figure 1** Radial distribution network modelled in Matlab*

Modelled distribution network with 4 feeders is shown in Figure 1. On feeder 1 VT and CT (orange boxes) and distribution relays embedded with different earth-fault protection functions (red boxes) are displayed. Earth-faults with various resistances are simulated on phase A of feeders 1 and 4.

DISTRIBUTION RELAY MODELS

In Matlab/Simulink environment, relays are modelled in the function blocks as shown in Figure 2.

Power system model

Distribution system is mostly modelled by common library elements with minor modifications where necessary, as for example with arc model.

Measuring (instrument) transformer models

Special attention has been paid to the CT modelling regarding the CTs measuring errors and DC saturation effect (noticed and recorded during the earth-fault tests with resonant grounding and small fault resistances).

The accuracy and reliability of the relay protection is therefore directly related to the behaviour of these devices during stable and transient conditions at disturbances and faults in the network. Protective relays often need to react in a time shorter than is duration of fault transient phenomena in the protected network. Larger errors of instrument transformers during transient conditions may delay or prevent proper relay reaction.

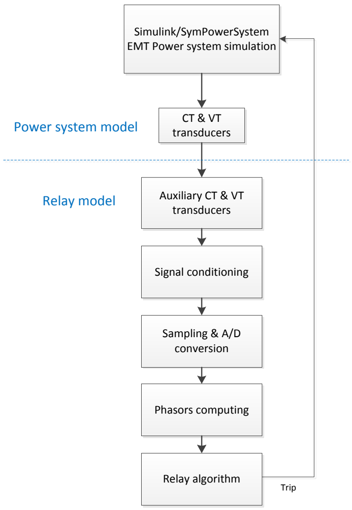

Figure 2 *Power system and relay device model presented in the function blocks*

On the other hand, instrument transformers may affect the operation of relay protection functions with time delays much larger than transient phenomena where protection sensitivity and selectivity are more important than fast reaction. In particular, it relates to ground faults with a high resistance when the voltages and especially fault currents have low values. Then the amount and angle errors can affect the selectivity and proper operation of protection. The accuracy of current transformers for protection is specified by IEC-60044 and IEEE C57.13 standards. In our study special attention has been paid to CT modelling (Figure 3) and its verification by the standards and measurement test results (Figure 4).

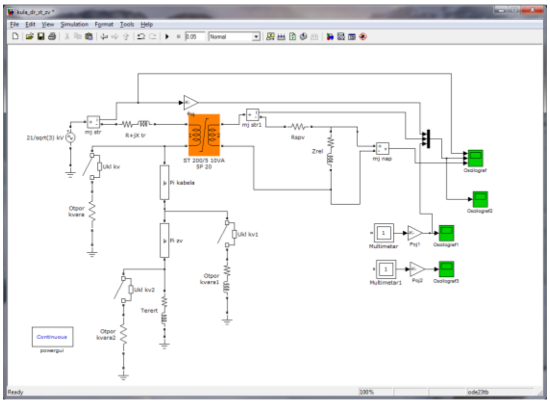

Figure 3 *CT model in the test circuit*

Auxiliary transformer models

Numerical relays cannot process 100 V of nominal voltage during normal operation and currents of few tens of Amps during faults. The voltages are usually reduced to within 5 V to 10 V range so that the electronic components are not damaged. The voltage reduction is achieved by using either auxiliary VTs or resistance dividers. Since these devices operate in their linear range, proportionality factors are used in the relay models.

Auxiliary CTs are used to reduce the levels of currents applied to the relay. The outputs of the auxiliary CTs are passed through precision resistors. Voltage drops across the resistors are used to represent currents. If no saturation is expected, modelling the CT and its burden is an easy process. In general, the relay input auxiliary CTs may saturate adding to the complexity of modelling and analysis. But, saturation of relay input auxiliary CTs may be neglected because the secondary current is substantially reduced under severe saturation of main CTs. Moreover, saturation of the main CT makes the secondary current symmetrical eliminating the danger of exposing the relay input auxiliary CT to decaying DC components. The secondary current has a form of short lasting spikes and this limits the flux in the cores of auxiliary CTs. Therefore, auxiliary CTs are not modelled as saturable ones.

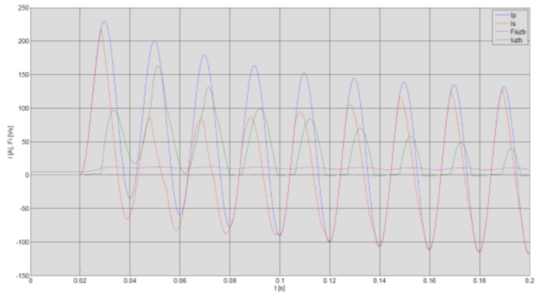

Figure 4 *Primary (blue), secondary (red) and excitation (green) current and magnetic flux oscillograms for 200/5 A C40 CT with 50% remanent flux and symmetrical short-circuit current of 20xIn and X/R=20,13*

Signal conditioning

Currents and voltages applied to numerical relays during faults contain components of high frequencies. Most algorithms of numerical relays are adversely affected by signal components of high frequencies. Some high frequency components are also likely to seem to be of the fundamental frequency because of aliasing. Therefore, low pass filters are used in numerical relays. These filters are analog devices. Typically, a second order filter is used with a cut-off frequency about three times less than of the sampling rate. For modelling standard analog low-pass filter, Simulink low-pass filter block is used with parameters: method, order and edge frequency.

Sampling and A/D conversion

Numerical relays convert the analog information to numerical form using sampler and analog to digital (A/D) converters. A/D conversion process can be considered as a two-stage process consisting of a sampler and a quantizer. At the first stage sampler creates the sequence s(n) by sampling the analog signal s(t) at regular intervals of ΔT seconds. This part of the process is usually considered accurate and without any addition of errors.

The second stage expresses each sample of the sequence s(n) by a finite number of bits giving the sequence sq(n). The difference between the elements of the sequence sq(n) and s(n) is the quantizing noise (it is also called A/D conversion noise). The quantizing process either could truncate the signal as it converts the analog information to numerical form or could round it.

The quantizer stage of a relay model may be skipped for some cases. Depending on the accuracy requirements of the relay model, the values obtained from the sampler may be directly used for phasor calculations and for modelling relay algorithm and relay dynamics.

A/D converters have a double impact. Any converter has a limited conversion range where signals above a certain level are cut off. The conversion range of the numerical relays is typically in the range of 10 to 50 times. For example, some relays cut off the inputs at 200 A secondary peaks while the rated current is 5 A.

The second aspect related to the A/D conversion is a limited sampling rate. Modern relays sample at rates up to 128 samples per cycle. As heavily saturated CT produces signal pulses of short duration, location of A/D samples on the waveform plays an important role.

Phasors computing

Electromagnetic transient analysis programs calculate voltage and current waveforms as functions of time. So, it may be necessary to convert the sequences of the values of voltages and currents to their equivalent phasors as functions of time.

For example, if a transmission line model is used by a numerical relay for detecting line faults, it would not be necessary to convert the sequences to phasors. On the other hand, numerical distance relays that compute apparent impedance have to compute phasors. The same is with the majority of the distribution earth-fault relays.

Phasors computing can be done by using one of the several signal-processing techniques. Two commonly used techniques are Discrete Fourier Transform (DFT) algorithm and Least squares algorithm. In our study, phasors are computed by Simulink standard DFT element. For example, overcurrent function calculates current magnitude from unpolished signal samples. Process of estimation prior Fourier RMS estimation can include digital filtering for DC offset removal. If only the fundamental frequency (50 Hz) is extracted from waveform through filtering process, this would result in a lower magnitude with heavily distorted waveforms than in case when the total magnitude (true RMS) from entire signal spectrum is extracted.

Protection algorithm

In many cases, modelling of numerical distribution relay protection algorithm is not complex. For example, a trip command of an overcurrent relay has to be issued when current is greater than the relay setting. In this case, the modelling consists of comparison of the calculated value and the set value, and issuing the trip command if calculated value is greater than the setting. In addition, algorithm security can be modelled requiring several consecutive checks for trip confirmation.

In some relays appropriate time delay has to be incorporated. For the definite time delays modelling is an easy process. The procedure commonly consists of the following steps:

1. Start a timer when a trip command is indicated.
2. Check the trip criteria after the next iteration is performed by the analysis program.
3. Increment the timer if the trip criterion is satisfied.
4. If the trip criteria are not satisfied, either decrement the timer or reset it. The decision should be based on what the relay being modelled is designed to do.
5. Check if the desired time delay has elapsed or not.
6. If time delay elapsed, model the tripping of the appropriate circuit breakers. Otherwise, revert to step 2.

The modelling of inverse-time delays, such as in inverse-time overcurrent relays is somewhat more complicated.

In Figure 5 a signal processing diagram of numerical relay with instantaneous overcurrent protection function (50) is shown. Model consists of input circuit comprising auxiliary CT and analog filter, A/D converter, Discrete Fourier transformation module and Comparator.

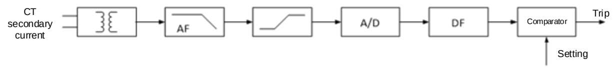

***Figure 5** Signal processing diagram of numerical relay with instantaneous overcurrent protection function*

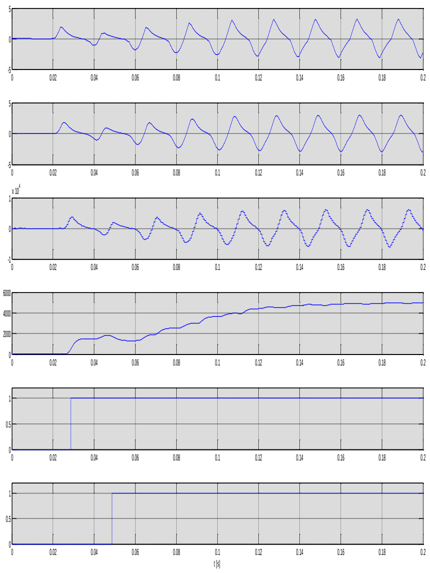

***Figure 6** Output by components of an numerical instantaneous overcurrent relay*

In Figure 6 output by components of the relay from Figure 5 for a distorted output of a saturated CT is shown.

CHARACTERISTICS OF SELECTIVE EARTH-FAULT PROTECTION FUNCTIONS IN DISTRIBUTION NETWORKS

Methods for selective detection of earth faults are based on measurements either of permanent or transient currents and voltages upon earth-faults occurrence. Unless these values are not post processed, presence of currents and voltages in the event of an earth-fault, induces acting of directional earth-fault protection function. Because of compensation in resonant earthed networks, causing earth-fault current decrease, protective equipment, including instrument transformers, must meet very high requirements. Especially when they work under adverse conditions of the phase shift between current and voltage (~90°). Current transformers are often not adapted to deal with a small earth-fault currents. Adjustments are accomplished using ring-type (toroidal) CTs. Requirements are more demanding in meshed than in radial networks because of earth fault currents spreading through branches.

In the study several protection functions in numerical relays for selective earth-fault detection were analysed: neutral overcurrent (50/51N), directional and sensitive directional neutral overcurrent (67N(S)) [7], Wattmetric and warmetric neutral (32P/QN) [6], static and/or dynamic comparison of neutral currents [9], admittance and conductance neutral [6, 10], transient [11]. Earth-fault protection functions are modelled and implemented in numerical relay models as protection algorithm modules. Their response on various earth-faults with different neutral point treatments were tested and the results analysed. For all network neutral point treatments, majority of protection functions with proper settings succeeded in selective fault detection when fault resistances are small (of few Ohms). However, at higher fault resistances (of few kOhms) lack of sensitivity occurred, primarily due to small earth-fault currents in resonant grounded and isolated networks. Better sensitivity at high fault resistances achieve protection methods which comprise: (i) elimination of measuring errors and network natural asymmetries by usage of incremental voltage and current values (dI, dU) prior to and after fault occurrence, and/or (ii) centralised or distributed comparison algorithm for decision making based on relay responses on feeders connected to the same busbar.

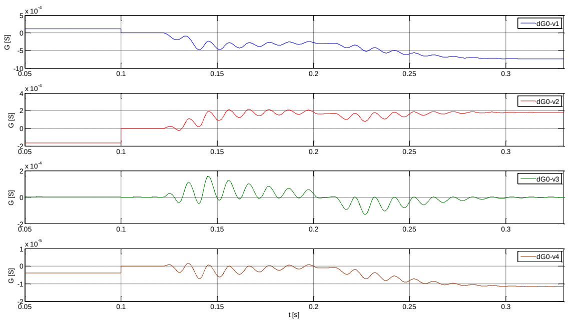

Figure 7 *Conductance diagrams for a 10 kΩ earth-fault on feeder 1*

For an earth-fault of 10 kΩ on feeder 1 in resonant earthed network, Figures 7 and 8 present conductance and qu elements (qu diagrams represents q_0 charges on feeders). Upon shunt resistor switching (Figure 7) conductance measured on feeder 1 has stabilised at -740·µS while conductances on feeders 2 and 3 are positive or near zero value. Conductance of feeder 4 is negative but has much smaller value (-11,5 µS) and is above negative threshold for forward fault decision. Feeder 4 is modelled as an overhead feeder, feeders 1 and 2 as mixed type and feeder 3 as purely cable type. From Figure 8 it can be observed that qu diagram of feeder 1 is an ellipsoid while those of feeders 2 and 3 are almost straight lines. The qu diagram of feeder 4 is tiny ellipsoid but lower by two orders of magnitude. This indicates that a special attention should be given to pattern recognition algorithms.

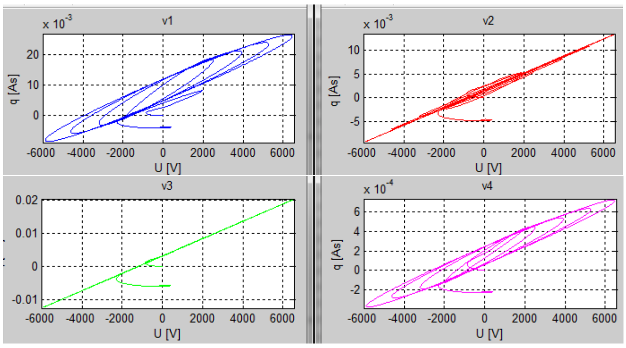

Figure 8 *qu diagrams for a 10 kΩ earth-fault on feeder 1*

CONCLUSION

In this paper methodology for power system and relay modelling is described. A distribution system, instrument transformers and relay models with different protection algorithms are developed using Matlab/Simulink environment. Developed comprehensive relay models process voltage and current transient waveforms obtained from electromagnetic transients simulations, actual fault waveforms captured by numerical relays, or from digital fault recorders. This way user can observe their response to these transients and reaffirm the protection behaviour during network disturbances.

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