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 design concepts in power distribution is described in the paper. The intention was to develop an open system that is easy to use and allows simple future expansions. Easy to use presumes that the software should be suitable for teaching purposes. This is achieved by introducing new libraries of signal sources and relay elements developed in the MATLAB/SIMULINK environment. Combined with the SIMULINK/SimPowerSystems, the mentioned libraries enable a variety of studies aimed at better understanding protective relay design approaches and procedures and related applications in power system.

I. 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 couple 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, an overview study has been conducted recently. Selection criteria in the study considered:

- Technical features of all three treatments concerning the earth-fault currents, overvoltages and network operation based on literature, measuring, computer analysis and operation experiences;
- Human safety requirements and rules (touch voltages), heath and voltage stresses and interferences with telecommunications lines;
- Network importance (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);
- Network reliability (SAIFI and SAIDI);
- 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 rules renovation regarding a new way of operation and protection relay requirements as well as harmonization with European norms. The need for implementation of new protection methods and primary measuring equipment (current and voltage transformers) coordination have also been considered and analysed. The analysis performed and the results achieved are described in this article.

In the scope of the study, measurements of pre-fault and earth-fault currents and voltages were conducted in 10 kV and 20 kV distribution networks supplied from two HV/MV substations. Earth-faults were done with different fault resistances and types as well as by using different neutral point grounding methods: isolated, low-ohmic resistive and resonant.

II. CHARACTERISTICS OF SELECTIVE EARTH-FAULT PROTECTION 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. A special property of the isolated and resonant earthed networks is the rise in magnitude of the measured earth-fault current due to the contribution from healthy feeders, while feeder with the failure has no impact on it. Measurements of available currents and voltages in the event of an earth-fault, unless these values are not post processed, indicate the use of directional earth-fault protection. Because of compensation in resonant earthed networks, with reference to earth-fault current reduction, it is obvious that protective equipment, including transformers, must meet very high requirements. Most methods work under adverse conditions of the phase shift between current and voltage (~90°). Contrary to the measuring conditions during short-circuits, current transformers (CT) are often not adapted to deal with a small earth-fault currents. Adjustment is to be achieved by using ring-type (toroidal) transformers. These requirements are even greater in meshed than in radial networks because of earth fault currents spreading through branches.

Most commonly used numerical relays for selective earth-fault detection are:

- Neutral overcurrent relay (50/51N)
- Directional and sensitive directional neutral overcurrent relay (67N(S))
- Wattmetric and warmetric neutral relays (32P/QN)
- Neutral overcurrent relay based on higher (5th) harmonic
  This relay operation is based on the fact that in the resonant networks 5th harmonic is not compensated by Petersen coil. 5th harmonic is usually intentionally added upon earth-fault occurrence.
- Relay for static or dynamic comparison of neutral currents
  This relays operation is based on comparison of neutral currents or their changes. Neutral currents of different feeders connected on the same busbar are compared.
- Admittance and conductance neutral relays
  This relays operation is based on comparison of neutral admittances/conductance’s changes.
- Transient relays
  This relays tracks and compares voltage and currents wave shapes at earth-fault occurrence.

### III. 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 things 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.

### IV. RELAY MODELLING IN MATLAB

Matlab has been selected as programming environment for protective relaying software modelling for the following reasons:

- Matlab is well recognized as one of standard tools for protective relay modelling in industry and in university environment [1, 2, 4].
- Matlab has powerful calculation and visualisation tools and enables fast and efficient software expansion without developing any extra programming tools.
- Matlab and its time domain solver Simulink create an open and user friendly system. They provide libraries, models and programs enabling integration of different model components. New models and libraries can be easily added.
- 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]. SimPowerSystems enable modelling of power system components. It provides computations and analyses similar to other electromagnetic transient programs permitting modelling of the power systems and its controls in the same environment and thus, facilitating closed-loop simulation.

The (earth-fault) 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. In this manner the application of relay models can effectively support the education of students and engineers.

Intention is to develop relay software modelling for relevant testing prior the building of a prototype relays. This is essential in the development process because, it allows testing of various relaying algorithms, the relay logic, and to make 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.

Of course, all previously mentioned cannot completely replace tests with the actual protection devices in a real environment. Whatever degree of detail is used in a model, the engineer must be aware of the limitations of the model. Failure to bear this in mind is a well-known weakness in all design studies based on models [3].

V. DISTRIBUTION POWER SYSTEM MODEL

Within Matalab Simulink environment, SimPowerSystems are 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 real-time simulations are possible by using variable step integrator and zero crossing detection capabilities.

The system is modelled according to the two real radial distribution networks in which earth-fault tests were conducted. Current and voltage measured records from tests are used for model calibration and also as a signal source for testing the relay models.

Earth-fault and resonant curve field tests have been conducted in the substations 110/20 kV Botinec and 110/10 kV Velika Gorica. Tests consisted of earth-faults over different fixed resistances (1÷5 Ω, 1, 4 and 10 kΩ) and in different conditions (phase wire fell on dry and wet ground, phase wire fell on trees, transient faults simulated with variable spark gap) at few places in the networks with ungrounded, low-ohmic grounded and resonant grounded neutral points. Earth-faults with resonant grounded neutral points have been done with different tuning of Petersen coils with and without shunt resistor (connected on secondary winding). Resonant curves were also measured and recorded.

MV networks supplied from these substations are mostly wide spread semi urban radially operated, with only a few meshed branches. This kind of network was considered as most interesting for resonant grounding method implementation. It is because these networks have 8 to 12 feeders on one bus-bar system, with total sum of 100 to 300 A capacitive currents, large numbers of short and long supply interruptions and a lot of households and small industries connected and with ~21 MVA of average peak load.

Modelled distribution network with wattmetric relay (red box) on feeder 1 is shown in Figure 1. Earth-fault is simulated on phase A of feeder 1.

VI. RELAY MODELS

Earth-fault relays are modelled as generic numerical relays. In Matlab/Simulink environment, relays are modelled in the function blocks as it is shown in Figure 2.
Power system model

Power system is modelled in Simulink environment by use of SimPowerSystem and other Simulink library elements.

SimPowerSystem is a design tool for modelling and simulating electrical power systems within the Simulink, allowing a power system model to be built in an easy manner. It is a powerful solution for modelling the electrical power system, especially when designing associated control and protection systems. The library contains blocks that represent common components and devices found in electrical power networks. The blocks are based on well-known electro-magnetic and electro-mechanical equations. The libraries contain models of typical power equipment.

Distribution system is mostly modelled by common library elements with minor modifications where necessary, as for example with arc model. Even though Matlab is inherent slower power system simulation (compared with EMTP (ATP) [1]), this drawback is negligible since the distribution model does not present large system.

Measuring (instrument) transformer models

Power system high voltages and currents cannot be directly applied to the relays. Therefore, voltage (VT) and current (CT) transformers reduce power system voltages and currents. In Croatia distribution system voltages are typically reduced to the nominal value of 100 V and currents are reduced to the nominal value of 5 A or 1 A.

Special attention has been paid to the CT modelling regarding the CTs DC saturation effect (noticed and recorded during the earth-fault tests with resonant grounding and small fault resistances, Figure 3) has a great impact on earth-fault protection. With increase of the fault resistance the time constant decreases and the saturation DC component is not so effective so the problem becomes less noticeable. Therefore, it has been recommended [8] that with resonant grounding ring type current transformers should be used in all bays for earth-fault protection. It is expected that the ring type CTs will not have the saturation problem as significant as phase CTs. In addition, a resistance can be added in a series with Petersen coil by adding a suitable resistor or by increasing the copper loses of the coil. With the series resistance the defined higher limit of time constant can be ensured.

Both types of CTs (phase and ring) have been modelled in appropriate detail.

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.

But, it is fair to mention that some authors recommend that saturation modelling of auxiliary CTs, including saturation due to low frequency signals, should be made in the relay models.

![Figure 3: Neutral point voltage (blue), “faulted” line zero current (brown) and current trough Petersen coil (red) during earth-fault over 1 ohm](image)

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 of 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 \( s^q(n) \). The difference between the elements of the sequence \( s^q(n) \) 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 CTs 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 this project, 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 the only fundamental frequency (50 Hz) is extracted from waveform through filtering process, this would result in a lower magnitude with heavily distorted waveforms than it is case when the total magnitude (true RMS) from entire signal spectrum is extracted.

Relay algorithm

In many cases, the modelling of numerical distribution relay algorithm is not a complicated procedure. For example, a trip command of an overcurrent relay has to be issued when the current is greater than the relay setting. In this case, the modelling is consisted of comparison of the calculated impedance with the set value and issues the trip command if the calculated value is greater than the setting.

In addition, algorithm security can be realised requiring several consecutive checks for trip confirmation.

In some relays, an appropriate time delay has to be incorporated. For the definite time delays the 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 it has, 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 4 an earth-fault overcurrent definite time (51N) relay model is shown. Model consists of:
- Input circuit comprising auxiliary CT and analog filter
- A/D converter with digital filter
- Discrete Fourier transformation module and
- Comparator with time delay component.

In Figure 5 output of this relay by components is shown. The picture shows from up to bottom respectively: three phase current waveforms, 3I0 earth-fault waveform, earth-fault waveform after filtering, earth-fault current RMS of base harmonic (50 Hz) and relay module pick-up and trip signals.
VII. RELAY LIBRARIES

As shown in Figure 6, several models of earth-fault relays are modelled and stored in relay library.

Modelled earth-fault relays are: overcurrent (51N), directional voltage or current polarised directional (67N, 32U or 32I), directional sensitive or wattmetric/warmetric (67Ns, 32W) and admittance earth-fault relay.

Figure 6: Earth-fault relay models library

Definite time earth-fault overcurrent relay is non-directional relay which compares measured or from phase currents derived earth-fault current with set constant value.

Inputs for traditional directional current polarised relay are . Where is polarising current obtained from neutral point ground conductor [6]. So, this relay is only suitable for solidly or low impedance grounded distribution networks. It calculates torque (term derived from electro-mechanical relaying) based on magnitudes and relative angle of analog input quantities, Equation 1. Relay compares the result of calculated torque against set thresholds. If torque is positive and above the positive threshold, then relay determines a forward earth-fault. If torque is negative and below the negative threshold, then relay determines a reverse earth-fault.

\[ T = |I_{pol}| |3I_0| \cos (\phi_{pol} - \phi_{310}) \]  

(1)

where:  
- \( I_{pol} \): Polarising current  
- \( 3I_0 \): Directional voltage polarised relay makes directional decision according to Equation 2. The relay compares calculated \( Z_0 \) against \( Z_{0F} \) and \( Z_{0R} \) thresholds to determine the direction of the ground fault.

\[ Z_0 = \frac{Re [3V_0 (1e^{j\Theta_{0L}} - 3I_0)]}{|3I_0|^2} \]  

(2)

where \((\cdot)^* -\text{complex conjugate})

\[ 3V_0 \] \( V_0 \) \( I_0 \) \( 0 \) \[ \text{Line zero-sequence impedance angle} \]

Directional wattmetric relay makes directional decision according to Equation 3. The relay compares calculated \( W \) against -\( w \) and +\( w \) thresholds to determine the direction of the ground fault. \( W < -w \) indicates a forward fault and \( W > +w \) indicates a reverse fault.

\[ W = Re \left[ \frac{V_0^* - I_0^*}{V_{pol} \cos \phi_0} \right] \]  

(3)

Earth-fault admittance relay algorithm is centralised and it simultaneously uses zero currents from all galvanic connected feeders (on the same busbar) and common zero voltage. It calculates zero asymmetry admittance for each feeder. Asymmetries occur as a consequence of asymmetries of feeder capacities to the earth or of an earth-fault. Advantage is that it also calculates asymmetry admittance change \( dY \). This algorithm has two thresholds, an absolute \( Y_{as \_ max} \) and the sensitive one \( dY_{as \_ max} \).

VIII. CONCLUSION

In this paper methodology for power system and relay modelling is described in accordance to the relevant literature. A distribution system and several earth-fault relay models are developed using user friendly open system environment Matlab and Simulink.

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.

In the future intention is to develop relay software modelling for relevant testing prior the building of a prototype relays. This is essential in the development process because, it allows testing of various relaying algorithms, the relay logic and to make necessary changes without the need to make changes in hardware or software modules of the actual device.

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