SIMULATING THE STEADY STATE AND TRANSIENT RESPONSE OF PROTECTIVE RELAYS

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ABSTRACT

This paper describes a generic approach to modelling the steady state and transient behaviour of protection devices. A protective relay (overcurrent, distance or any other type) is modelled using a multi-level approach, where a relay frame (which describes the topology), a relay type (which specifies the actual algorithms used), and a relay element (which specifies the actual settings used for a specific application) is defined. Using a simplified current transformer (CT) and voltage transformer (VT) model the steady state response of a relay in a network can be studied, using a normal short circuit simulation. The effect of CT saturation can be studied by performing a time based electromagnetic transient simulation with a detailed CT model. The transient behaviour of capacitor coupled VTs can be investigated using a detailed VT model. A graphic user interface displays any parameter on a flexible single line diagram or on a time based plot.

INTRODUCTION

Proper settings of protective relays are essential for the reliable operation of electrical power systems, during both fault and normal system operating conditions. The ideal relay operating characteristics can also be influenced by parasitic phenomena, such as CT saturation.

Computer simulations are useful for both the analysis of the ideal operation of protective relays (including the computer assisted coordination of relay settings) and the identification of incorrect relay operation.

Owing to the huge variety of protective relays from different manufacturers and technologies, the modelling approach must be flexible. The approach must cater for the old, electro-mechanical relays, static relays as well as the modern digital protective relays. One way of complying with this requirement is to identify basic building blocks that are common to the majority of protective relays. Using a combination of these basic building blocks, very complex relay operations can then be modelled.

The simulation of the relay operation must be carried out at different levels of precision. For a general verification of protection settings, a steady state short circuit simulation (e.g. IEC 909) is sufficient. However, in some cases, a detailed electromagnetic transient simulation might be necessary, especially if the influence of CT saturation needs to be considered correctly.

For simulating the performance of dynamic relay operations of, for example, out of step tripping or blocking relays, a transient stability analysis is the most efficient approach. The three types of simulation available are:

- Steady state (Load flow, IEC short circuit)
- Stability (steady state models for measurements, dynamic models for relay operation)
- Electromagnetic transients (EMT) (fully dynamic relay model)

GENERAL APPROACH

Defining new relay models from scratch is a difficult task, requiring a lot of simulation and modelling knowledge, as well as an in depth understanding of the protection devices to be modelled.

The data structure is therefore designed according to the following two user types:

- The **standard user**, who is testing and setting up relays in a network model using existing relay types from a library.
- The **advanced user**, who benefits from the complete modelling possibilities provided by the software.

The distinction between using just existing relay types, and defining new relay types is reflected in the object oriented data structure shown in figure 1. The model of a complete relay is comprised of three levels, namely the relay frame, the relay type and the relay element.

The **relay frame** specifies the general relay functionality using a block diagram. Blocks for timers, measurement and logic elements can be defined. It defines, how many stages the relay consists of and how these stages interact. The relay frame, however, has no intelligence, as it does not specify any algorithmic details. Each block is merely defined by the number of input and output signals. The signal lines define how these blocks are interconnected.

The **relay type**, referring to a specific relay frame, defines the contents of each block of the frame. At this level the mathematical function, or the type of characteristic, is specified, for example the type of filter used for processing the input signals, or the type of operating characteristic. Since many relays support more than one type of characteristic a set of characteristics or functions can be defined. In addition, the relay type specifies the ranges for the various relay settings, including whether the parameters are set continuously or in discrete steps.

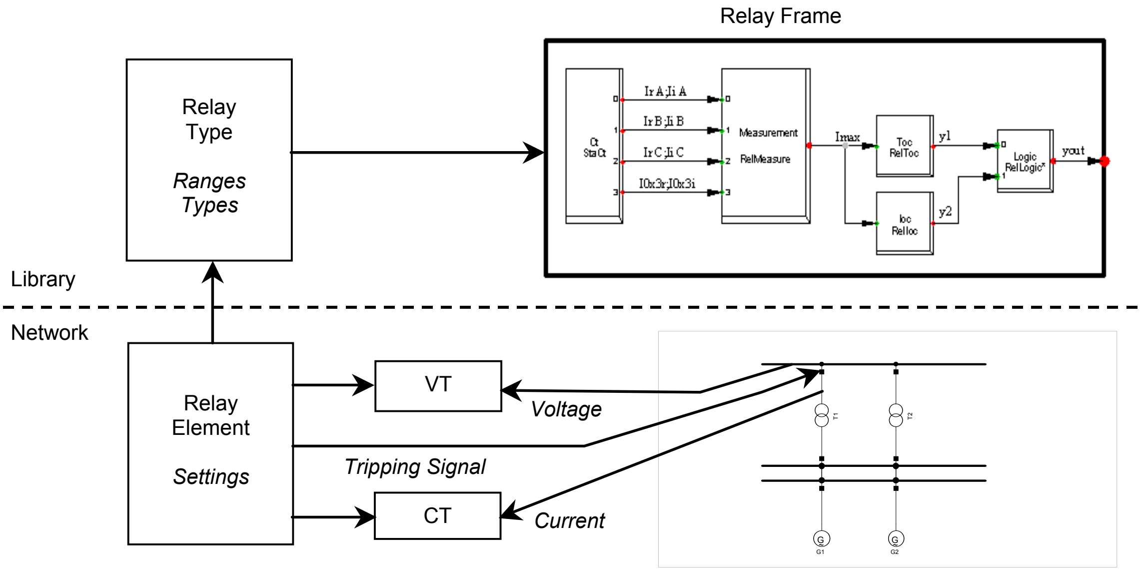

Figure 1: General Data Structure

The relay type defines the library information for a specific manufacturer's relay, which does not yet have any settings applied to it. The complete information described in the data sheet and manual is contained in the relay type. An advantage of this split concept is the possibility of re-using a relay frame for more than one relay type.

The **relay element** models the actual relay in a power system. It refers to a relay type in the library, which provides the complete relay structure including the setting ranges for all parameters. The actual settings of the relay, e.g. reach or the pick-up settings, form part of the relay element settings, considering the range limitations defined by the relay type.

CT and VT models form the input link between a relay element and the electrical network. For the relay output a tripping signal is sent directly from the relay element to a breaker in the modelled system. To simulate busbar protection, or any tele-protection schemes, a relay element can operate more than one breaker.

CURRENT TRANSFORMER MODELS

An ideal, as well as a detailed CT model, is available. For a general verification, the highly simplified, ideal CT model is sufficient. It consists of an ideal current controlled source. Only the nominal primary and secondary ratings need to be entered.

If a more detailed analysis of the CT performance, particularly relating to CT saturation, is required, the detailed CT model should be used. The parameters of the equivalent model (winding resistance, burden impedance and the non-linear magnetizing inductance) need to be entered. The non-linear saturation function can be described by either a piecewise linear or polynomial approximation function. The accuracy class parameters (to either ANSI or the European practice) also have to be entered.

For a steady state simulation the influence of CT saturation on the measured secondary currents can only be estimated. The ratio of excitation voltage over saturation voltage gives a good indication, whether the CT is operating in its linear region and what reserves are available.

To simulate the real influence of saturation on the overall tripping time of a relay, a dynamic CT model in combination with an EMT simulation of the electrical network, must be used.

VOLTAGE TRANSFORMER MODELS

Again an ideal, as well as a detailed VT model, is available. The ideal model consists of a voltage controlled source, which is defined by the nominal primary and secondary ratings.

Transient effects of VTs can be modelled with the R-L-C elements of the detailed model. The major transient effects of both purely inductive and capacitor coupled VTs can be modelled with sufficient accuracy.

OVERCURRENT TIME PROTECTION

The typical block diagram of a general overcurrent protective relay is shown in figure 2. It consists of the following basic building blocks:

- CT
- Measurement unit
- Time Overcurrent Characteristic (TOC)
- Instantaneous Overcurrent Characteristic (IOC)
- Logical unit

The CT, which derives its inputs signals from the electrical network model has been explained earlier.

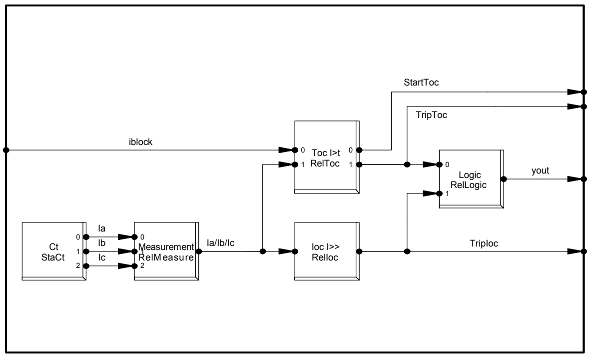

Figure 2: Basic Overcurrent Time Protective Relay

Measurement unit

The three secondary phase currents are the input signals of the measurement unit. The measurement unit filters and rectifies these signals.

Filtering is only considered at the fully dynamic model level (EMT level), as the other model levels assume perfect sinusoidal signals. The standard filter is a second order band-pass filter, eliminating both the high frequency transients and DC components. Alternatively, if the actual filter performance needs to be modelled in detail, digital filter algorithms can be chosen.

For the rectification, a choice between generating three rectified single phase currents, or just one output current (result of a complete 3-phase rectification) exists.

Instantaneous Overcurrent Characteristic

The IOC consists of a direct overcurrent relay with an optional time delay. The element will issue a trip output if the current exceeds the set pick-up current for longer than the set time delay.

Time-overcurrent Characteristic

For the TOC the time dependant operating characteristic has to be defined. All standard IEC and IEEE characteristic formulae are supported. Additionally, any characteristic can be specified using an analytical formula or interpolated samples. Also, the pick-up current and the time dial settings have to be defined. Both values must be in the range defined by the relay type.

For a steady state simulation, the output of the TOC is triptime, which is dependant on the magnitude of the measured current. For a stability and complete dynamic simulation, the dynamic behaviour of the TOC characteristic is represented using an integrator. With the input signal *iblock*, the TOC element can be blocked from outside.

Output Logic

The tripping signal *yout* results from the logic combination of the output signals from different stages.

The standard output logic is a simple OR combination. In modern digital protective relays the output logic is programmable. Such a programmable logic unit also forms part of the protection modelling tool box.

DIRECTIONAL UNITS

For modelling the directional unit, a phase comparator or power measurement technique can be chosen. The polarization method used is specified as part of the relay type. Methods available are:

- Fault voltage, i.e. self polarized
- Un-faulted voltage, i.e. cross polarized
- Current
- Negative sequence voltage (V_2)
- Positive sequence voltage (V_1)
- Dual polarized

DISTANCE PROTECTION

For distance relays both Mho characteristics, as well as quadrilateral characteristics, are supported.

Different algorithms are used to realize the impedance characteristics. For Mho characteristics, the "dynamic" response is realized using a phase comparator model. The polarization methods supported are:

- self polarization (faulted phase)
- cross polarization (healthy phase)
- memory polarization (pre-fault voltage)

Figure 3 illustrates the difference between a static (self polarized) and a dynamic Mho characteristic in the R/X plane. The dynamic characteristic provides a much more secure fault identification for faults close to the relay location, as well as better fault coverage in the fourth quadrant, as required for series-compensated lines.

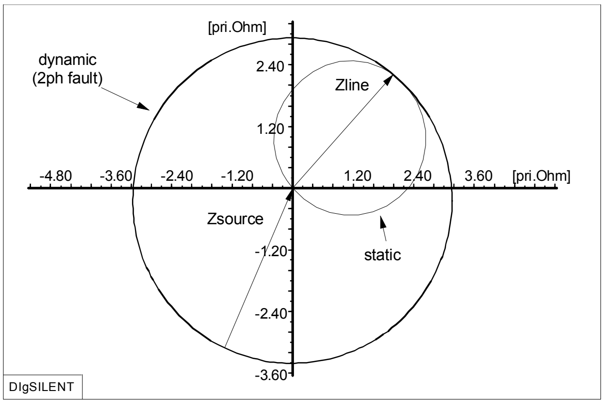

Figure 3: Dynamic and Static Mho Characteristic

EXAMPLE

The network configuration shown in figure 4 has been chosen for demonstrating some features of the protection analysis environment of the DIgSILENT PowerFactory software, which integrates the described protection modelling tool box:

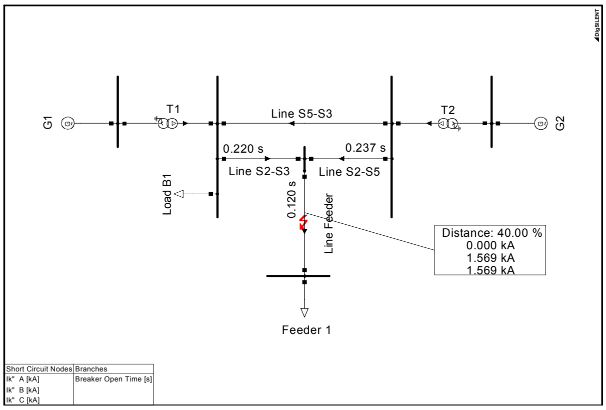

Figure 4: Example Network

A parallel line is fed from sources on both sides. A T-off branch is connected to one of the parallel lines. Every line section is protected by an impedance relay. A quadrilateral characteristic is used for earth fault detection.

The information displayed in the single line diagram gives an overview of the general relay operation for a particular fault scenario. Besides currents and voltages, breaker tripping times can be displayed. The times shown consider relay tripping times and breaker delays. For a quick analysis, a network colouring technique is provided: Circuit breakers are colour coded according to their overall tripping time and lines according to state of overloading.

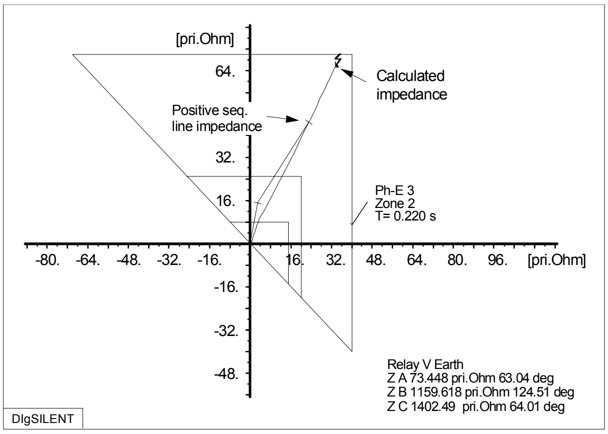

Figure 5: Quadrilateral characteristic

The R-X diagram for the earth fault characteristic of relay V, protecting line S2-S5, is shown in figure 5. It shows the simulated fault impedance, as seen by the relay for an A-N fault. In the first section of line up to the T-off point, the fault impedance corresponds to the positive sequence line impedance. For the T-off line, the relay under-reaches, i.e. the fault impedance as seen by the relay appears to be larger, due to the fault current contribution from the other leg feeding into the T-off line.

In the graphic for the operating characteristics, tripping times for each zone, and the measured fault impedances for each fault loop, are displayed.

Studying the primary and secondary power system in the time domain, again a fault on the T-off was assumed. As it was assumed that the breaker of the T-off line failed, the back-up relays on either end feeding the T-off line should clear the fault. Using the transient simulation tool and plotting the fault currents and impedances as seen by these two relays against time, the re-distribution of the fault currents after one of the relays has tripped, as well as the decrease of impedance, as seen by the other relay, can clearly be seen. When plotting the starting and tripping signal of both relays, the exact time, when each relay picks up, trips and resets, can be determined.

CONCLUSIONS

A tool box for modelling and simulating protection systems has been presented. CTs and VTs can be modelled by an ideal or a detailed model. CT saturation can be simulated using the detailed CT model and the EMT simulation function. CVT transients can also be simulated using the detailed VT model and the EMT simulation function.

Overcurrent time protection as well as distance protective relays can be modelled by combining basic building blocks. Every relay model is entered graphically by drawing a relay block diagram. A documentation set is generated at the same time. Models, valid for steady state and transient analysis, are automatically generated from the block diagram.

Powerful tools, such as overcurrent vs. time diagrams, R-X diagrams, time-distance diagrams and various analysis functions in the single line graphic display allow for a quick and efficient analysis of the protection system performance.

BIBLIOGRAPHY

1. Walter A. Elmore, ABB Power T&D Company Inc., "Protective Relaying Theory and Applications", Marcel Dekker, Inc., 1994
2. Jeff Roberts and Armando Guzman, Schweitzer Engineering Laboratories Inc., "Directional Element Design and Evaluation", SEL Webpage, 1994,1995
3. Edmund O. Schweitzer, III and Jeff Roberts, Schweitzer Engineering Laboratories Inc., "Distance Relay Element and Design", SEL Webpage, 1992, 1993
4. S.B. Wilkinson and C.A. Mathews, General Electric, "Dynamic Characteristics of Mho Distance Relays"; GE Webpage - Publication GER-3742
5. J. G. Andrichak and G. E. Alexander, General Electric Co., "Distance Relays Fundamentals", GE Webpage Publication GER-3966
6. Siemens AG, "SIPROTEC 7SA511 Digitaler Distanzschutz", Siemens AG, 1995