A Methodology For Assessing The Influence Of Instrument Transformer Characteristics On Power System Protection Performance

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Abstract - This paper presents a new methodology for evaluation of the influence of instrument transformers (ITs) on performance of protection system. Instrument transformers are responsible for delivering accurate power system current and voltage replicas to protective relays. However, both theoretical research and field application have shown that, due to their characteristics, conventional ITs may degrade relay performance significantly. So far, various studies investigated many aspects of the mentioned influence. The methodology presented in this paper takes systematic approach to the problem: it examines possible criteria and defines procedure for evaluation of the influence. An application of the methodology is presented, along with the results. Suggestions for the improvement of application of conventional instrument transformers are also given.

Keywords - Instrument Transformers, Protection System, Protective Relays, Performance, Evaluation

1 INTRODUCTION

INSTRUMENT transformers should deliver accurate replicas of power system current and voltage signals irrespective of their characteristics. Accurate replicas ensure proper response of power system protection to different system conditions, such as faults and disturbances. However, both theoretical research and field application have shown that conventional instrument transformers can influence the performance of protection system adversely. This influence manifests itself through signal distortions at the output terminals of instrument transformers. There are cases when the influence is significant enough to degrade performance of protection to unacceptable levels (such as misoperation of the protective relays, incorrect fault location determined by the fault locators and similar). Mentioned signal distortions are due to instrument transformer characteristics. Three most notable characteristics are: 1) accuracy, 2) frequency response, 3) transient response.

Accuracy is defined by certain standards, given in references [1], [2]. Frequency response is investigated in reference [3]. Transient response of the instrument transformers is evaluated in references [4] and [5]. There are studies that focus on influence of the mentioned characteristics on the performance of some aspects of the protection system [6], [7], [8], [9]. The mentioned studies gave considerable insight into the instrument transformer behavior, as well as some understanding of how that behavior may affect protection system. However, there is no systematic solution to evaluation of the mentioned influence. Such a solution is necessitated by emerging new applications of instrument transformers (such as use of instrument transformers with multi-function IEDs) and by emerging novel instrument transformer designs (such as advanced optical transformers [10]). Novel applications and designs of instrument transformers should be verified for correct supply of current and voltage signal replicas before being commissioned.

Approach to the problem, presented in this paper, is to define a criteria and methodology that does not *directly evaluate* characteristics of instrument transformers, but rather evaluates them in *context of functions* of protection system. There are well-defined performance indices for protection system functions [11], [12], [13], [14]. These indices can be adapted to serve as indicators of the influence of instrument transformer characteristics on the power system protection performance.

This paper also proposes a new methodology for evaluation of influence of instrument transformers characteristics. The methodology will be defined by providing answers to the following questions:

- How can the influence of instrument transformer characteristics be identified ?
- What are the means for quantifying the influence ?
- What is the best procedure for finding the quantitative values of the influence ?
- What is the meaning (interpretation) of the quantitative values ?

Section II of this paper investigates possible criteria for the evaluation. Section III defines an evaluation methodology. The results of the methodology application are presented in section IV. Suggestions on how application of conventional instrument transformers can be improved is given in section V. Section VI summarizes the new methodology.

2 EVALUATION CRITERIA

2.1 Functional elements of protective relays

Functional elements of a typical protective relay are shown in Figure 1. The elements in figure may be complex, consisting of sub-elements. Data acquisition unit is the front end that performs filtering, sampling and digitalization of the analog input current and voltage signals. Measurement unit extracts desired quantities, such as power network current and voltage phasors, transmission line impedance or power. Decision making unit relies on basic operating principles to derive trip, alarm, control or data signal.

Overall performance of a protective relay is a function of performances of the above-mentioned elements. Different sets of performance indices are defined to evaluate performance of the measuring algorithm and performance of the decision making algorithm. Data acquisition elements is evaluated as a part of the measurement.

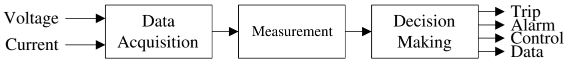


Figure 1: Functional elements of a protective relay

2.2 Criteria based on the measuring algorithm

Measuring algorithm is the basis of the measurement unit of a protective relay. Measuring algorithm extracts desired feature of the input signal. Common desired features are signal amplitude, phase angle, frequency, etc. These features are based on phasor representation of current and voltage in power systems. However, input signal may deviate significantly from the phasor representation i.e. 60 Hz (in the United State, or 50 Hz in Europe) sinusoidal waveform. Measuring algorithm should extract desired features regardless of the shape of the input signal. The extent to which a measuring algorithm fulfills this requirement can be illustrated using a time or frequency response of the measuring algorithm. Typical time response of a measuring algorithm is shown in Figure 2.

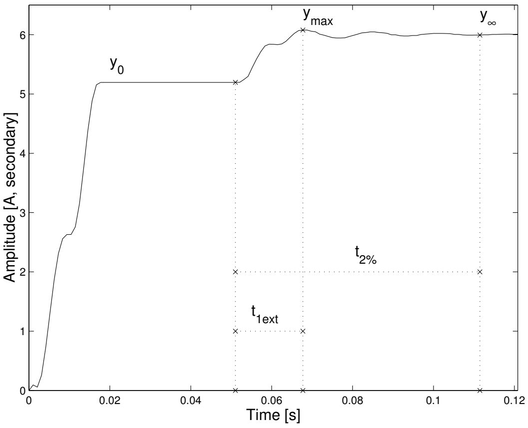


Figure 2: Time response of a measuring algorithm

Reference [14] defines a set of performance indices for measuring algorithms. These indices are used in this paper for evaluation of influence of instrument transformer characteristics on the measuring algorithm. According to reference [14], measuring algorithm indices are defined as:

- **Settling time**, $t_{2\%}$, is a time point after which the measured value remains within interval $[0.98 \cdot y_a, 1.02 \cdot y_a]$, where y_a is the actual (accurate, true) steady-state value of the estimated quantity
- **Time to the first extremum**, t_{1ext}, is a time point when in which the measured values reaches its extremum (maximum or minimum, denoted y_{ext}) for the first time after the start of measurement (measurement start is denoted by the time point $t = 18.7ms$ in the example shown in Figure 2)
- **Overshoot/undershoot**, $\Delta y_{\%}$, defined as:

  $$\Delta y_{\%} = \frac{y_{ext} - y_{\infty}}{y_{\infty}}$$

  where y_{∞} is the estimated value of y_a
- **Normalized absolute error index**, e_{abs}, defined as:

  $$e_{abs} = \frac{1}{M \cdot (y_{\infty} - y_0)} \sum_{k=L}^{L+M} \left| y_{(k)} - y_a \right|$$

  where $y(k)$ is the digital sample with index k. Index e_{abs} is computed in the window of M samples starting from the L-th sample. The purpose of this L sample offset is inclusion of transient monitors, which are present in some protective relays. Transient monitors are used to postpone assertion of a trip signal until the transient period of the input current and/or voltage signal has passed, and the signal has settled to a steady-state.

Difference in the values of the indices between:

1. The measuring algorithm exposed to signals supplied by the referent instrument transformer
2. The measuring algorithm exposed to signals supplied by instrument transformer under investigation

may be used as an indicator of the influence of a particular instrument transformer characteristics on the measuring algorithm performance. The referent instrument transformer can be an instrument transformer with characteristics proven in the practice as the best possible (high accuracy, wide frequency bandwidth and distortion-free transient response). The meaning and the interpretation of the difference depends on the choice of the particular indices used as criteria. It is possible to choose a particular set of indices to *target evaluation of a particular characteristic*. For example, if the influence of the CT transient response needs to be evaluated, criteria may consist of: 1) overshoot, 2) time to the first maximum (extremum). Tests can be conducted (by exposing the instrument transformer or its model to various power system conditions) to calculate the values of the indices. If the saturation occurs, with the increase of the level of saturation, overshoot is expected to decrease while time to the first maximum is expected to increase, in comparison with the time response of the referent instrument transformer.

2.3 Criteria based on the decision making algorithm

Decision making algorithm is supplied with the measured values by the measuring algorithm. By processing the measured signals, decision making algorithm derives the final output. Final output may take one of the several forms. Examples are trip signal (binary signal), fault location (numerical value) and power measurement (continuous or discrete real signal). Based on the context of the output signal, evaluation criteria for the decision making algorithm can be defined. References [11], [12], [13], [14] propose criteria for the protection functions. In this paper, the following index is used:

- **Selectivity**, s, defined as:
$$s = \frac{N_1 + N_0}{N}$$
where N_1 is the number of correct assertions of the trip command, N_0 is the number of correct trip command restraints and N is the total number of test cases. Ideally $N = N_1 + N_0$.

Differences in values of the indices between the decision making algorithm exposed to signals supplied by the referent instrument transformer (processed by the measuring algorithm) and the algorithm exposed to signals supplied by instrument transformer under investigation may be used as an indicator of the influence of a particular characteristic on the decision making algorithm performance.

2.4 Standardization of criteria

It is possible to choose a particular set of indices as a criteria to evaluate influence of a single particular characteristic. Evaluation can be done by:

1. Defining a characteristic-targeting criterion (see section 2.2 for an example)
2. Defining limits (upper and lower) for the criterion values
3. Varying the value of design elements of the instrument transformer (such as burden, capacitances, etc.) that influence characteristic under investigation (accuracy, frequency response or time response), calculating the criterion values and checking whether they conform to the imposed limits

Result of this evaluation will be a set of criteria values that corresponds to the desired IED performance. Such a set may be adopted as a standard set of values for a particular characteristic. For example, the above-mentioned evaluation of some particular relay may yield the following conclusions:

- By increasing the instrument transformer burden the settling time ($t_{2\%}$) increases
- As long as the settling time remains less than two cycles, the protective relay will correctly assert the trip command (when exposed to input signals corresponding to faults)
- When the burden is increased beyond a certain threshold point, the settling time will become longer than two cycles, which in turn would cause a relay to assert the trip command with unacceptably long delay

The example conclusion is that for the correct relay operation, the settling time has to be less than two cycles.

3 Evaluation methodology

3.1 Simulation procedure

As mentioned before, influence of instrument transformer characteristics on protective relays can be measured using performance indices. The indices may be calculated by analyzing output signals of protective relays. Options for obtaining these signals are:

- Field-recorded data
- Signals obtained from simulations

Focus of this paper is simulation-based data. Two main elements of a simulation are: 1) models, 2) scenarios. Models, that are necessary, are: 1) instrument transformer models, 2) protective relay models, 3) power network models. Models of instrument transformers should include elements that accurately represent transformer characteristics. There are several studies that discuss modelling of instrument transformers. The studies such as [15], [16], [17], [18] offer validated models of instrument transformers. References [15] and [17] offer also generic models and define elements necessary for the accurate modelling. Models of protective relays should include all the functional elements of the original devices under consideration. Output signals from functional elements of the model should be available for recording. Output signals should be recorded and stored as a database of protective relay responses. Model of the power network should be representative of the section of the power system under protection by the protective relays. Other network sections interconnected with the network section under consideration should be included in the model as Thevenin equivalents.

Protective relay responses in a simulation are initiated by input signals from different power system events (faults, disturbances, etc.). Events are organized according to simulation scenarios. The scenarios consist of: 1) timeline of events, 2) features of events. Timeline defines time points when each of the events occurs. Event is usually modelled by a sequence of switching of power network topology. Switchings allow for a modification of network topology, thus simulating faults and disturbances. The events are characterized by their features. Examples of features are: location of the event along the transmission line, associated resistances (such as grounding or line-to-line resistances), point-on-wave of fault inception and so on.

The simulation procedure can be summarized by the following steps :

1. Create a database of test cases by simulating events (faults, disturbances) using a power network model
2. Replay signals recorded from test cases using either models of instrument transformer and protective relay models
3. Record relay model output signals (both from the measuring and decision making algorithm)

3.2 Simulation environment

Simulation environment was developed as an implementation of the procedural steps described in section 3.1. Main features of the environment are *automation* of the testing procedure, *comprehensiveness* of the results and *flexibility* of use. Automation means that simulations are performed with a minimal user interaction (without any loss of accessibility or modifiability of relevant simulation parameters). The comprehensiveness means a sufficient number of test cases is covered, where each case presents protection system conditions with a sufficient number of parameters. Flexibility means 1) environment can integrate any instrument transformer and protective relay model into testing, allowing the user to test and compare influence of different instrument transformer versions and designs, 2) environment generates results in the form of graphs and tables that can ne directly imported into various text processors, allowing the user to quickly and efficiently analyze the final results. Main functional elements and the flowchart of the simulation environment are shown in Figure 3.

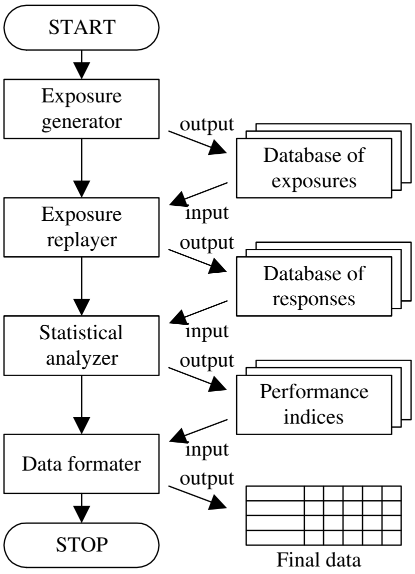


Figure 3: Functional elements and flowchart of the sim. environment

3.3 Investigation of the current transformer influence

As an illustration of the methodology application, influence of a current transformer on the power system protection was investigated using the simulation environment described in section 3.2. Objective was to determine whether transient response of a current transformer may degrade protection performance beyond acceptable limits. The current transformer models that were used are:

1. Referent current transformer model (see section 2.2)
2. Current transformer with low burden model (current transformer model #1) [16]
3. Current transformer with high burden model (current transformer model #2) [16]

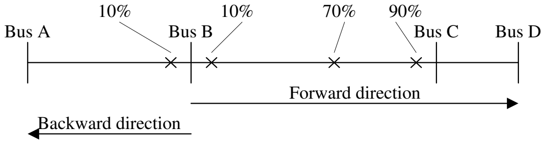
Current transformer model was taken from reference [16] (saturable, 900:5 electromagnetic current transformer). Power network was modelled according to example given in reference [19] (9-bus, 11-line, 345 kV Sky-STP section). Two protective relay models were investigated. They were taken from reference [20]. Protective relay model A represents an overcurrent protection relay. Protective relay model B represent distance relay. All the model data can be found in reference [20].

Even though a single current transformer is investigated, the two versions of the current transformer (connected to low and high burden) are denoted as different models (current transformer model #1 and current transformer model #2). Physically this is true, since their equivalent circuits and characteristics differ (which is shown and explained in the following text). Current transformer model #2 represents a real situation when a properly sized current transformer is connected to very long wiring cable, for interconnection with protective relays.

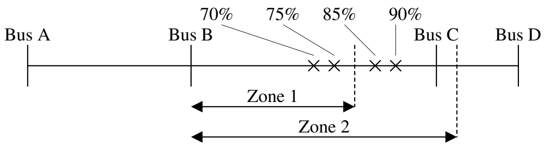
The selectivity and response time of the protective relay models was tested. The protective relay models were place at Bus B, protecting the line between buses B and C. The overcurrent relay was set to trip for the faults in the forward direction and to block tripping for faults in the backward direction. The distance relay was set to trip instantaneously for the faults in the first zone of protection (80% of protected line), and to trip with time delay of 20 cycles (333 ms) for the faults in the second zone (120% of the protected line). The zones are shown in Figure 4. The figure also shows the locations were the faults were simulated (points marked with ”x” sign, where number associated with the mark denotes position of the fault along the line). Large number of scenarios was created to simulate events along the transmission lines of the power network model. Input data for the exposure generator was:

1. fault type (AG, BC, BCG, ABC, ABCG)
2. grounding and phase-to-phase resistances $(0\Omega, 10\Omega)$
3. fault inception point-on-wave (8 consecutive points covering phase range $(0, 2\pi)$)
4. location along the transmission line (see Figure 4)

For protective relay model A total of 320 faults was simulated. For protective relay model B total of 320 faults was simulated, 160 of them belonging to zone 1, the other half belonging to zone 2.



(a) Zones of protection, relay model A



(b) Zones of protection, relay model B

Figure 4: Zones of protection and location of faults

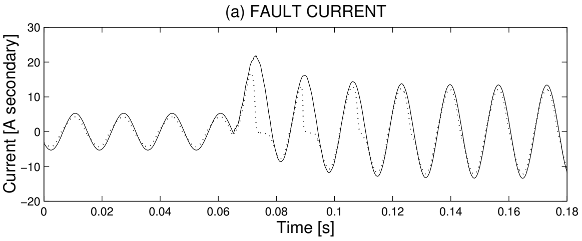
4 Results

The results from the application of methodology are given in Tables 4 through 3. Both protective relay models have the same measuring algorithm - Fourier based. Performance indices for the measuring algorithm are given in Table 4. While the settling time $t_{2\%}$, DC gain FR_{DC} and aggregated index F are similar for all the current transformer models, there is difference in the overshoot $\Delta y_{\%}$ and steady-state error $\Delta e_{\%}$.

CT	$t_{2\%}$[%]	$\Delta y_{\%}$[%]	$\Delta e_{\%}$[%]	FR_{DC}	F
Ref. model	111.5	6.95	3.37	0.025	0.035
Model 1	118.6	8.33	9.95	0.025	0.035
Model 2	116.3	1.72	18.33	0.028	0.034

Table 1: Measuring algorithm indices

The smallest overshoot is indicated when using current transformer model #2. This suggest that transient response of the current transformer model 2 experienced saturation. By inspecting current transformer output signals, the suggestion was confirmed: the current transformer did undergo saturation. Waveforms for the AG fault at 70 % of the line length are shown in Figure 5. The waveforms corresponding to both primary current (referred to secondary) and secondary fault current are shown in Figure 5(a) (note: primary current is presented with the full line, the secondary is presented with dashed line). The current amplitude detected by the measuring algorithm is shown in Figure 5(b). As can be seen, saturation caused the measuring algorithm to detect the overcurrent with a considerable delay (around two cycles).



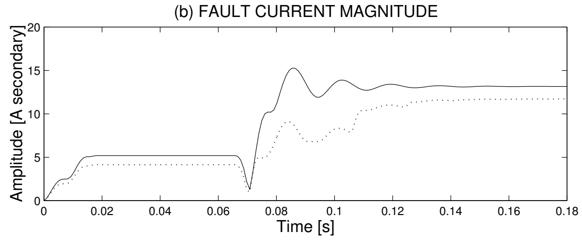


Figure 5: Fault current and its amplitude

The largest steady-state percentage error is indicated again by current transformer model 2. The reason for this is the current transformer saturation. Since the error is significant (above 18 %) it may be expected that the protective relay models may shown problematic experience with current transformer model 2.

CT	N	F_1	s [%]	t_{trip} [ms]
Ref.model	312	8	97.5	19
Model 1	304	16	95	19
Model 2	304	16	95	25

Table 2: Relay model a: decision algorithm indices

Performance indices for decision making algorithm of protective relay model A are given in Table 4. The selectivity is only 2.4 % smaller than the selectivity of the reference model. However, the current transformer model #2 has caused average trip time to increase 6 ms. Such an increase can be considered negligible. It is important to note that even when supplied with saturated signals, protective relay model A manages to maintain its performance within the acceptable limits.

Performance indices for decision making algorithm of protective relay model B are given in Table 3. In the table, N_{11} denotes number of expected trips in zone 1, while N_{12} is associated with the zone 2. F_{11} denotes total number of protective relay miss-operations (either failures to trip or trips as if the fault was in the zone 2 - delayed trip). F_{12} gives the same information for the zone 2. t_1 denotes average trip time for faults detected in zone 1, while t_2 is average trip time for zone 2 (unit for t_1 and t_2 is [ms]).

The problematic performance is indicated when using current transformer model 2. The selectivity is only 17 %, compared to 95 % achieved using the referent current transformer model. A large number of faults in the zone 1 was detected as belonging to zone 2 because of the the current transformer saturation.

CT	N_{11}	F_{11}	N_{12}	F_{12}	s_1	s_2	t_1	t_2
Ref.model	152	8	154	6	95	96	16	346
Model 1	136	24	138	22	85	86	15	349
Model 2	**28**	132	134	26	**17**	83	13	389

Table 3: Relay b: decision algorithm indices

5 Application suggestions

5.1 *Improvement of application of conventional instrument transformers*

The results from the previous section clearly show that even when the proper current transformer is chosen for a certain protective application, factors that may lead to performance-degrading influence of instrument transformers still exist. Current transformer model 2 is equivalent to current transformer model 1 connected to a long wiring cable. The added burden has caused the protective relay model B to miss-operate in an unacceptable large number of cases. For this particular case, there are two remedies for the problem:

1. Current transformer should not saturate when connected to a high burden

2. The wiring cable should not present a high burden for the current transformer

The conventional current transformers do not poses the above mentioned abilities. An alternative to conventional current transformers, an optical current transformer, does poses the mentioned abilities. However, it was also shown that added burden did not affect the performance of protective relay model A. If the the current transformer model represented an actual transformer installed in a substation, the results would indicate:

1. Cause of protective relay B miss-operation (low overshoot indicates possible saturation, see section 2.2)
2. The benefit of connecting protective relay B to an alternative transformer (as discussed above), while at the same time it is safe to keep protective relay A connected to the original current transformer

5.2 Limitations and benefits of the new methodology

Limitations of the new methodology (presented in this paper) are:

- The use of the methodology and the simulation environment for testing of physical devices is limited by the availability of models of devices under investigation. Currently, only a small number of commercial protective relays and instrument transformers are modelled in the available literature. In other cases, models may be available, but not detailed enough for accurate simulation.
- Output signals of the measurement unit are not accessible in most of the commercial protective relays. Some commercial relays (e.g. SEL-321) record and store some internal measurement data, which can be used to derive the performance indices.

Benefits of the new methodology:

- In the development stages of designing instrument transformers and protective relays, methodology and simulation environment can be used to identify problematic components of instrument transformers. It is presumed that in the development stages, models of instrument transformers and protective relays are available to the designer.
- Simulation environment can be used in the educational purposes. It offers a novel insight into the measuring of influence of instrument transformers on internal components of a protective relay. In turn, this insight leads into much better understanding of interaction between instrument transformers and power system protection system.

6 Conclusion

The methodology presented in this papers is defined by the answers to the questions posed in section I. The answers can be summarized as:

- *How can the influence of instrument transformer characteristics be identified ?* The influence can be identified by defining criteria *in the context* of power system protection functions. The evaluation can be done by comparing performance of protective relay functions in two cases: 1) functions exposed to signals supplied by an ideal instrument transformer, 2) functions exposed to signals supplied by a realistic instrument transformers.
- *What are the means for quantifying the influence ?* There are well-defined performance indices for protection functions in the literature [11]-[14]. These indices can be adapted to serve as an quantitative indicator of the influence of instrument transformer characteristics on the function performance (shown in sections 2.2 and 2.3).
- *What is the best procedure for finding the quantitative values of the influence ?* Statistical analysis of the performance of the protection and its functional elements. The basis of the statistical analysis methodology are available in the literature [14]. In this paper, implementation of the methodology was in the form of the simulation environment (described in section 3.2).
- *What is the meaning (interpretation) of the quantitative values ?* Quantitative values are statistical indicators of the function performance (whether it is expected or unexpected). The difference in the numerical values for the cases defined in the Question 1 is a numerical indicator of the influence of instrument transformer characteristics on function performance (shown in section 4)

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