INTRODUCTION OF AN EASY METHOD TO ANALYZE THE INFLUENCE OF CT SATURATION ON THE PROTECTION SYSTEM

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INTRODUCTION

Almost all protective relays used in power systems rely on phase current information for their operation, typically provided by the secondary winding of conventional current transformers (CTs). Although several modern alternatives to iron-core CTs exist (e.g. Rogowski coil, several other approaches to unconventional transformers) the iron-core type is by far the most common. Due to commercial or space limitations, CTs are often selected for proper steady-state current replication but with little reserves regarding transient fault conditions. Thus the primary-side sine-shape currents with a transient DC component during fault occurrence may result in secondary distortion as shown in this recorded example:

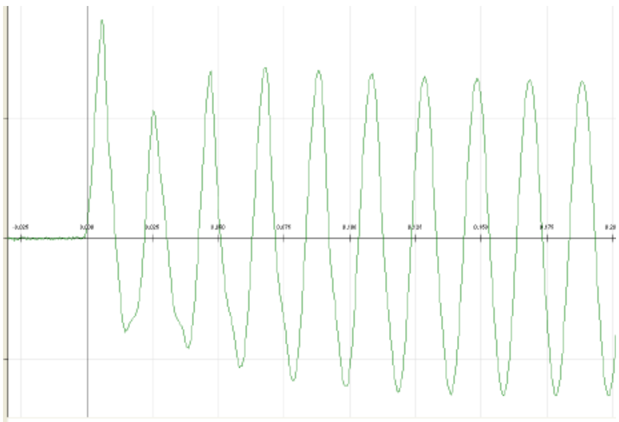

Fig. 1: Transient CT saturation (recorded)

Depending on the type and power of the CT and the connected burden (including the wiring between CT and relay(s) and the burden of the relay input circuit), CT saturation may corrupt the transformed currents up to a point where proper relay performance is impaired, especially during the first few cycles where fast and reliable operation is expected.

There are well-known calculation methods to find out if transient CT saturation will occur for given burden and fault conditions [1], but this does not help much if for the above-mentioned reasons CTs are (or have to be) chosen that will saturate under adverse conditions. The question is: How will the connected relays cope with these non-ideal signals? Can a certain amount of saturation be acceptable, i.e. will the relay still trip with acceptable trip time and reach tolerance under all realistic fault conditions?

Some dedicated studies, usually done by manufacturers, partly in cooperation e.g. with universities, reveal some general correction graphs for specific relay types, but this information, if existent at all, is not easily (or not at all) accessible by the commissioning engineer, and not portable to other relay makes (possibly not even to other firmware revisions). And since the actually connected burden plays a major role, only a measurement on site will deliver reliable results.

APPROACH

Evidently a proper assessment of the reliability of the protection performance in case of actually possible CT saturation is only possible by considering all relevant conditions of the site. The one method offering the most realistic results cannot be used for obvious reasons: The primary test with injection of short circuit currents into the CTs which are assumed as critical for CT performance. The laboratory approach to thread n windings (e.g. 50) through the primary lead-through of a CT in order to multiply the output current of a testing device in this way usually is not applicable on site either due to the CT construction type or due to the insufficient space remaining with the primary conductor in place, besides it would simply take too much time during commissioning.

The solution approach presented in this paper is based on four steps:

- Measurement of the actual burden on site as seen by the CT with connected relay(s)
- Measurement of the actual CT data (e.g. on site, with disconnected burden)
- Selection of symptomatic fault data as given e.g. by the infeed conditions at the primary CT connection
- Transient simulation of the fault currents (and voltages if needed), including the transient and steady-state saturation derived from the CT and burden data.

These signals are injected into the relay in the same way as conventional stepped steady-state test currents and voltages. The relay operation may now be assessed to verify if operation is acceptable under these real-world related conditions.

The described measurements can nowadays be carried out to a large extent in an automated fashion and very efficiently. The transfer of the measured data to the test system is quite straightforward, and the actual simulation is done practically in real-time on location. The readily available equipment required for measurement and test injection is compact and lightweight for easy commissioning use.

The benefits of this 'virtual primary injection test' are the greatly increased knowledge and resulting trust in the actual worst-case relay behavior as affected by the conditions on site. The commissioning staff will know if the possibly unavoidable CT saturation will be acceptable with regards to the relay performance, or if additional measures have to be taken.

This approach is valid for distance protection as well as for overcurrent protection. It is also applicable for differential protection in order to verify the proper settings of stabilizing functions against false tripping due to CT saturation.

MEASURING THE ACTUAL CT BURDEN

The compact CT Analyzer [2] supports the measurement of both burden and CT data. As a first step the secondary circuit of the currentless CT is disconnected at the CT terminal and the burden circuit is connected to the analyzer as shown in Fig. 2.

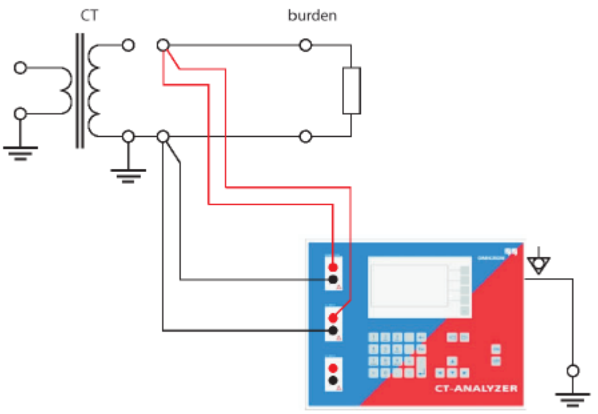

Fig.2: Connection for burden measurement

In this way the full external burden (including leads and relay input curcuit) is included in the measurement, the CT analyzer injecting the test current with one pair of terminals and assessing the voltage drop with a second pair.

The result is a complex impedance. Its angle, though usually fairly small, substantially influences the transient saturation devolution and should be taken into account for the subsequent simulation.

It must be noted that a precondition for this simulation approach is the linearity of the system under investigation, i.e. the burden should not change its impedance with varying injected current. The leads fulfill this requirement, same as all current input circuits of relays with auxiliary power supply ('static' / electronic and numeric). This is not necessarily true for electromechanical and other self-powered relays.

MEASURING THE CT DATA

The electrical data of the CT are assessed with the CT analyzer device in a similar fashion. The CT - burden circuit stays interrupted and the analyzer is connected to the CT (see Fig. 3).

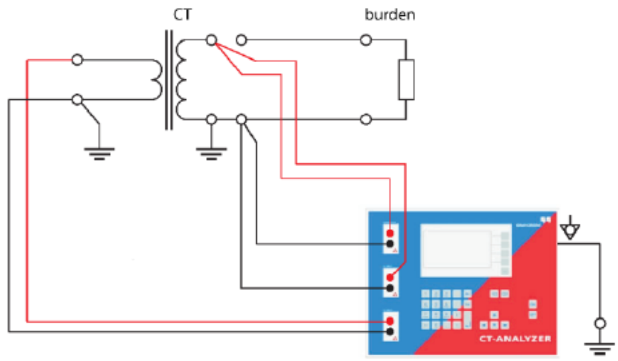

Fig. 3: Connection for CT measurement

The underlying CT model considers nonlinear real and inductive impedance components and remanence to properly evaluate the CT data (see Fig. 4).

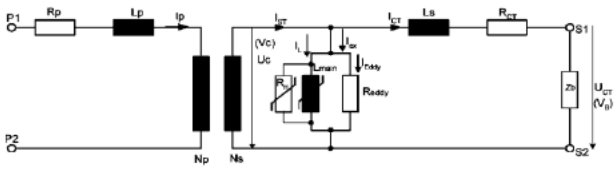

Fig. 4: CT model in CT Analyzer

As opposed to the measurement of the actual burden which always depends on the related mounting location, it may suffice for CTs from standard type series, depending on the series spread, to measure just one sample unit (e.g. not on site so no special precautions have to be taken when connecting the primary side). Especially it might be enough to measure just one of three identical single-phase CTs of a feeder.

The data from the burden and CT measurements may be saved as XML file for subsequent easy reuse by the test system (see below).

SELECTION OF THE TEST CASES FOR SIMULATION

For all simulations in question it is advisable to use a portable, simplified simulation package for ease of use during commissioning, with CT saturation simulation capability being indispensable, e.g. OMICRON Test Universe and its NetSim test module. This allows the physically correct calculation of transient fault quantities with a minimum of data input, i.e. reduced grid data for the short-circuit impedance with the time constant of the decaying DC component resulting from the complex impedance values. The calculated transient primary currents are passed through the CT simulation in the same calculation sequence by using the burden and CT data from the measurements mentioned above, resulting in realistic secondary currents with saturation similar to the original CT according to the actually connected external burden. In this way the relay is exposed to test signals that closely relate to secondary currents that would have been achieved by primary short-circuit tests.
The following NetSim time signal view shows a sample of such a simulation that clearly shows the saturation effect of the CT model in the simulation (see Fig. 5).

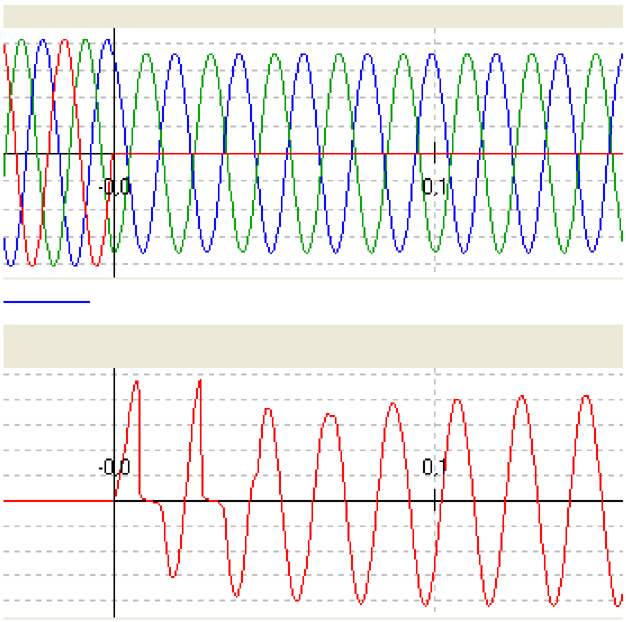

Fig. 5: Transient CT saturation (NetSim simulation example using measured CT and burden data)

The internal calculation algorithms for CT used by NetSim are closely related to the methods used by e.g. the Advanced Transients Program ATP [3], one of the market standards in versatile transient simulation. Extensive tests with differing algorithms showed that for the majority of CT cores this approach is very good. For some core types NetSim automatically uses a different, Spline-based approach to achieve satisfying results. The verification was done by injecting primary currents in sample CTs (using multiple primary turns to achieve the necessary magnitude) connected to reference burdens, recording the secondary current through the burden and comparing the resulting secondary currents, distorted by CT core saturation, with simulations by ATP and by NetSim, both using the measurement results from CT Analyzer. The comparison showed the good alignment of the simulated results with the primary-injection measurement for the sample cases.

A typical case of critical CT behavior is an auto-reclosure which recloses after the occurrence of a high-current fault with full DC offset in one phase and the subsequent dead time in a way that DC offset occurs again with the same polarity at reclosure. If the CT shows substantial remanence then it will quickly reach the saturation limit at the reclosure onto the fault due to the remaining flux, and will show extreme transient saturation.

In general, these are problematic conditions:

- High fault currents
- High burden as related to the nominal CT burden
- Large DC offset
- Iron core remanence

For proper selection of simulation test cases this implies that with given burden and CT conditions you first focus on high-current faults (fault location close to the CT connection location, grid topology with strong infeed conditions) and choose the fault occurrence time for high DC offset in one phase.

If this leads to substantial transient (or even steady-state) CT saturation this may already lead to valuable findings when exposing the relay to these signals. On the other hand it may well be that also less dramatic saturation degrees are problematic for the protective function due to the changed signal response in time and shape. So, if the relay passed the first test, it might be of interest to test examples with less current amplitude or reduced DC offset.

Knowledge about the specific grid and a certain amount of experience thus prove helpful for this approach.

TRANSIENT SIMULATION

When the measurements have been carried out and the basic conditions for the test are established then the actual test can be executed with a proper test system running the compact network simulation. Since we deal here with high currents at a multiple of the secondary nominal CT current the test set should be able to generate currents well above 20 amps per phase, such as CMC 356.

Depending on the device under test it may suffice to inject a single-phase current, allowing to combine the output channels of the test system for even higher resulting test current (e.g. for 5 amp relays) if the test set supports paralleling of the output currents in software and hardware, e.g. CMC 356 allowing up to 128 A (more than 20 times nominal current for 5 A Cts). Configurations with 3 voltages and one current phase for the fault current, generated with the combined current outputs of the CMC, are supported by NetSim. And since we are talking about symptomatic tests it might be sufficient to test just one of the three phases as faulted phase to assess the saturation effect.

First a suitable grid simulation has to be selected. For the discussed purposes the default 'Short circuit single line' test case usually is already sufficient. According to the gathered grid conditions the infeed and line data are to be entered, with circuit breaker B always open. If needed, a more complex basic grid (e.g. tapped line or double line) may be chosen and parameterized.

The next step is the entering of the CT and burden data. The CT Analyzer measurement results may be directly imported into NetSim, see Fig. 6.

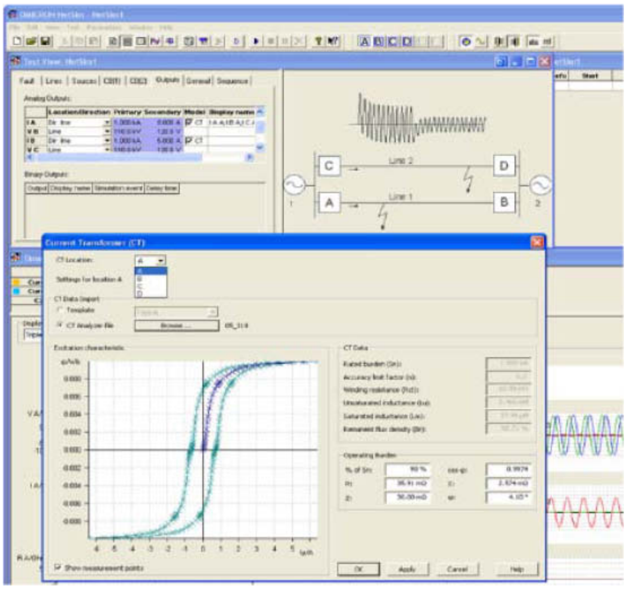

Fig.6: Importing CT data in NetSim

Finally the CT simulation has to be activated by ticking 'CT' in the Model column on the Outputs tab of the Test View. Now the test is basically configured. One more step remains:

Defining the fault conditions (occurrence on the timeline, i.e. resulting DC offset; fault type and location). The effect of each change is instantly shown as preview in the Time Signal View.

The system is now ready for 'live' transient signal generation. Compare the result (e.g. relay tripping time) with that of a simulation without CT saturation (by either deactivating the CT model or by lowering the assumed burden) to judge if the relay performance is within acceptable limits.

RELAYS EXPOSED TO CT SATURATION

So what happens when relays are confronted with secondary currents distorted by CT saturation? This greatly depends on the protective function, the implementation in the specific relay type, diverse relay settings and of course the degree of saturation and its change over time. Steady-state saturation, which is a symmetrical distortion (both half-cycles show the same shape, mirrored along the time axis) and stays present as long as the current magnitude stays at its level, should be a rare situation - normally CTs can always be selected in a way to avoid steady-state saturation. One exception could be a weak feeder from a bus bar with a small CT fitting the nominal feeder data - if several strong infeeds to the bus bar feed a fault on the weak outgoing feeder then its CT might show steady-state saturation. The problem with this is that, whatever the relay's interpretation of this corrupted signal shape is, will stay like this for the fault duration. Blocking derived from the amount of 2nd harmonic will fail since symmetrical saturation only contains odd harmonic numbers. Much more common is transient saturation, present as long as the transient DC offset - that is always present when a fault current otherwise would have to 'jump' from the pre-fault to the fault value at fault inception - has not noticeably decayed. Since this offset depends (amongst others) on the current phase angle at fault inception it will differ in the three phases for a three-phase fault, so the effect on the relay also depends on the implemented or selected inter-phase treatment (cross-blocking). For two-phase faults the effect is the same in both phases since the currents are just mirror currents to each other. Now let's have a look at some protection principles and observed effects of CT saturation that is present during the test:

1. **Definite-time overcurrent stages:** They typically trigger phase-wise on the peak value of the current. Their setting is calculated from the steady-state RMS value, i.e. for non-offset signals. Stages with threshold settings that are in the magnitude of fault currents that could cause transient saturation typically are high-set instantaneous stages. Except for extreme transient saturation, e.g. during an auto-reclosure and with a CT showing high remanence (not to be selected for this purpose in the first place), the current will always overcome the set threshold value before the transient saturation sets in.

This is especially true for three-phase faults where at most one of the three phases will show maximum DC offset so the other two behave fairly normal. Overcurrent relays are typically found in distribution grids with a short time constant (low L/R) so the effect of transient saturation lasts for only roughly 100 ms. This would be the trip time delay to be expected if the relay function is indeed impaired by strong transient saturation. Relays that do not evaluate the peak value but e.g. take the fundamental component are more prone to show trip delays, but also restricted to the mentioned time span.

2. **Overload relays with inverse-time characteristic:** For true overload assessment these relays integrate the current-time area (i^2t) to simulate the heating effect of current through a resistance (i.e. the protected object that should not overheat). Since the full signal shape contributes to the threshold integration, any 'missing part' (i.e. cut-off sections due to the CT saturation) will act as if the primary current had a smaller magnitude, thus directly prolonging the trip delay. If the time constant is as short as assumed for 1) then the trip delay will be in the same range (i.e. even for total secondary signal loss during the assumed 100 ms and steady-state short current afterwards the additional delay would be just these 100 ms). For transport grids with a greater time constant this could be a more severe impact (if the second half of one half-cycle is cut off then this equals an apparent current of 3/4 of the non-saturated current in the integration, resulting in a related trip delay), possibly leading to unselective tripping by up-stream devices with a CT/burden combination with less or no saturation. So in case saturation is to be expected it is sometimes necessary to have a look at other relays in the protection chain of the protected object as well.

3. **Distance protection:** These relays often calculate the impedance (as a measure for distance) by analyzing a sample data window of e.g. one cycle of nominal frequency and take the fundamental of voltage and current to calculate the impedance. As tests and theoretical considerations show, transient saturation leads to an apparent increase in Z magnitude while rotating the Z angle toward the R axis. During the transient phase this might even lead to an X value below the target value but at a highly increased R for a short time span. Fig. 7 shows how the impedance trajectory, for a quite heavily saturated current in the transient state, enters from the right and first reaches an X (mark 1) slightly below the steady-state fault value but at an R about 10 times as high as the steady-state fault value, then (after a time usually too short to actually trip) continues by wandering to even higher R and about twice the target X until it changes its direction toward the target (mark 2), traversing in loops that go to even higher X values. This takes about 180 ms in this example and, depending on the R and X setting of the trip zone, will lead to a trip delay of about the same duration if the upper zone boundary is not far above the steady-state X of this fault. For slightly changed data the first low-X peak might actually trip an instantaneous zone 1 while the steady-state fault impedance really is in zone 2, a kind of false trip one might not expect from a current 'reduced' by CT saturation. So for distance relays in transmission as well as distribution grids this test is really worthwhile. This example also shows how severe a transient saturation can be although there is no steady-state saturation at all.

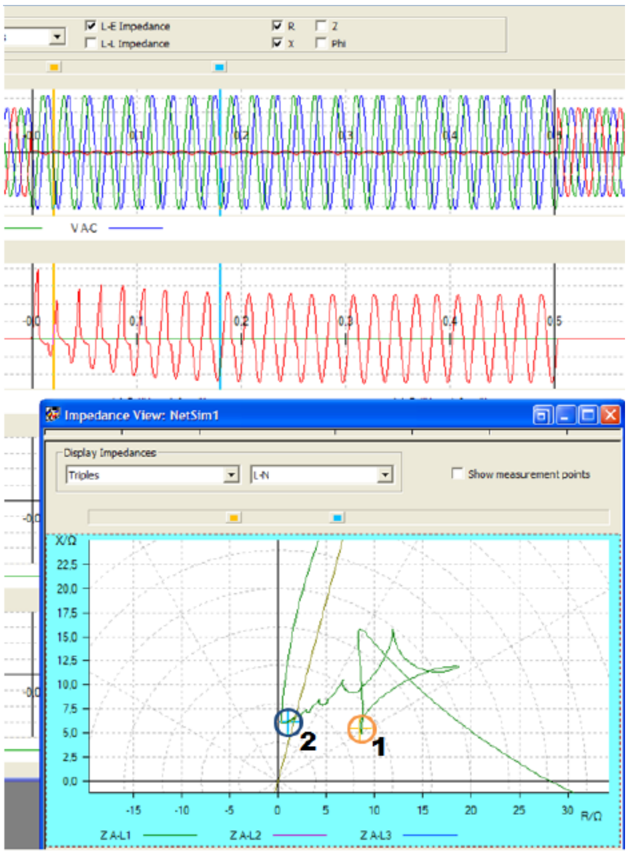

Fig. 7:Impedance trajectory, transient CT saturation

4. **Differential protection** is a special case: Since it is well-known that differing saturation at both ends during through-fault condition might lead to a false trip, those relays usually offer some sort of stabilization against false tripping. The simplest solution is an appropriately insensitive setting of the restraint characteristic parameters. Or there might be dedicated blocking functions for this case, with related parameters. But how to set these parameters? Here the described testing approach can be used to stimulate the relay with the saturation-distorted signals according to the CT and burden data at the ends of the protected zone and the grid data controlling the short current, and you can now optimize the restraining or blocking parameters of the relay to ensure stable operation at the expected worst-case through-fault conditions without setting them to inappropriately high values that might impair tripping when needed. So this is some sort of parameter testing, but not in the formerly described sense of verifying predefined parameters but to evaluate the proper parameter settings needed for the application. System-oriented testing in its core meaning: Ensure proper operation for given system conditions. There really is no other equally convenient way to do this verification.

Once the CT and burden data have been gathered the simulation test may alternatively be carried out 'in the office' with an identical relay unit with identical settings, in order to verify the saturation behavior. Of course the classical parameter and connection test still has to be done with the target relay on site.

If the result is that the saturation influence leads to unacceptable relay performance then diverse remedies can be considered, such as using a greater lead cross-section to reduce the burden of the connection between CT and relay (the leads usually contributing much more to the external CT burden than the connected relay input).

Incidentally, the expected influence of changed burden is easily studied beforehand by feeding the simulation with the assumed corrections and testing the relay with the resulting new transient data.

Auto-reclosure cycles as mentioned above can be easily simulated in the grid representation by time-controlling the circuit breaker in the simulation, allowing for simulating the mentioned worst-case scenario.

CONCLUSION

Modern measurement and test equipment enables the commissioning staff to comfortably carry out tests related to on-site conditions which also allow the assessment of relay performance under CT saturation during high-current faults. This is a complement to the parameter-oriented test and adds confidence where without this kind of test you would either have to just hope for the best accepting the possible saturation (as was often done in the past), or you would refrain from using these assets due to the expected saturation and unknown consequences.

LITERATURE

[1] IEC 60044-6

[2] CM-Line Catalog; http://www.omicron.at/en/products

[3] ATP Manual; http://www.eeug.org