Impact of transient saturation of Current Transformer during cyclic operations – Analysis and Diagnosis

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1.0 Introduction:

Current and voltage transformers provide instrument level signals to protective relays. Protective relay accuracy and performance are directly related to the steady state and transient performance of the instrument transformers. Protective relays are designed to operate in a shorter time than the time period of the transient disturbance during a system fault. Large instrument transformer transient errors may delay or prevent relay operation. Any numerical protection relay performance is depending on the quality of analog input signal and 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, but this does not help much if for the above-mentioned reasons CTs are 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? In the Present scenario of NTPC, as we are going for the Cyclic operation of unit's load variations will be there and results in Frequent switching on and off of motors and other electrical equipment's. Whenever motor starting happens, there is a heavy inrush which causes the current transformer to Saturate and sometimes results in the malfunction of the equipment.

2.0 Transient Behavior of Current Transformers

A current transformer can be represented with the simplified equivalent diagram according to Figure 1. The properties of the magnetic core have a major influence on the performance and behavior of the CT. The iron core is used to carry the flux linking the secondary current with the primary current. A secondary current can only be achieved by a change in the flux. If the flux cannot be changed the secondary current will disappear. The magnetizing curve gives the relation between the flux density (B) and the magnetizing force (H). A simplified magnetizing curve is shown in Figure 2. The magnetizing force is related to the magnetizing current and the slope of the curve is proportional to the magnetizing impedance of the CT.

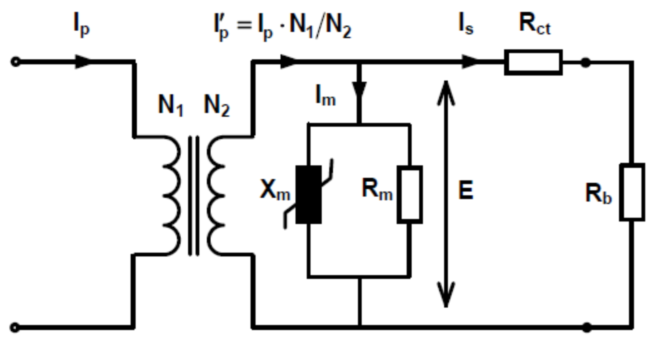


Figure 1. Simplified equivalent diagram of a CT

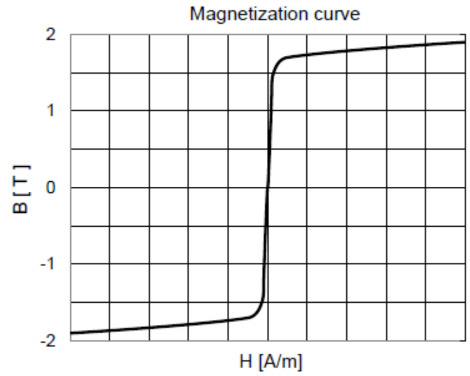


Figure 2. Simplified magnetization curve

CT output is impacted drastically when the CT operates in the nonlinear region of its excitation characteristic Operation in this region is initiated by:

• Large asymmetrical primary fault currents with a decaying dc component.

• Residual magnetism left in the core from an earlier asymmetrical fault, or field-testing, if the CT has not been demagnetized properly.

• Large connected burden combined with high magnitudes of primary fault currents.

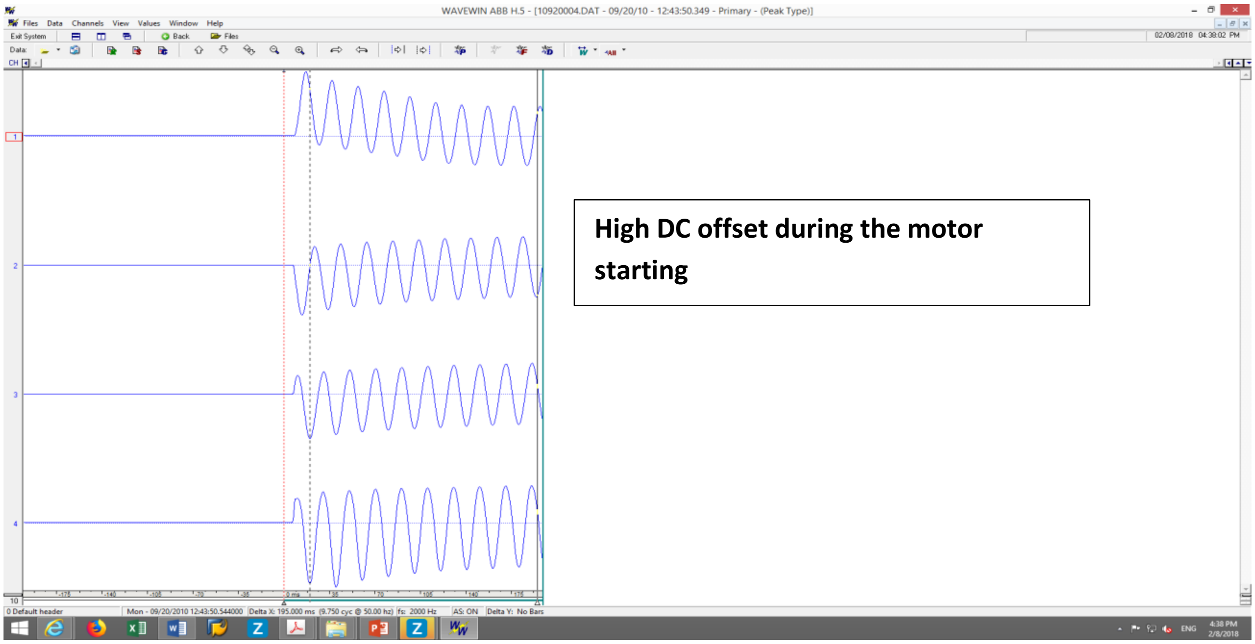
When the CT saturates because of the dc component, it can do so in the first few cycles of the fault. Long dc time constant offset faults can cause CTs to saturate many cycles after a fault. The fidelity of the transformation is reasonably good until saturation takes place. Instantaneous CT secondary current (Is), as the sum of the instantaneous burden (Ib) and the magnetizing current (Im).

The CT steady-state magnetizing current (Im) is very small, as long as the CT operates in its linear region. If we assume that the exciting current is negligible, then the burden current, (Ib) is a replica of the primary current adjusted by the CT ratio. When the CT is forced to operate in its nonlinear region, the magnetizing current can be very large due to a significant reduction of the saturable magnetizing inductance value. The magnetizing current (Im), which can be considered as an error current, subtracts from Secondary current (Is) and drastically affects the current seen by the connected burden on the CT secondary winding.

The following can have a significant impact on CT saturation and should be given due consideration in a simulation study:

- DC offset in the primary side fault current.
- Remenant flux on the CT prior to the fault (if any).
- Secondary side impedance including those of the relay, connecting wires and CT secondary impedance - this parameter plays a major role in the level of saturation the CT.

Typical CT saturation during the motor starting is shown in the below graph:



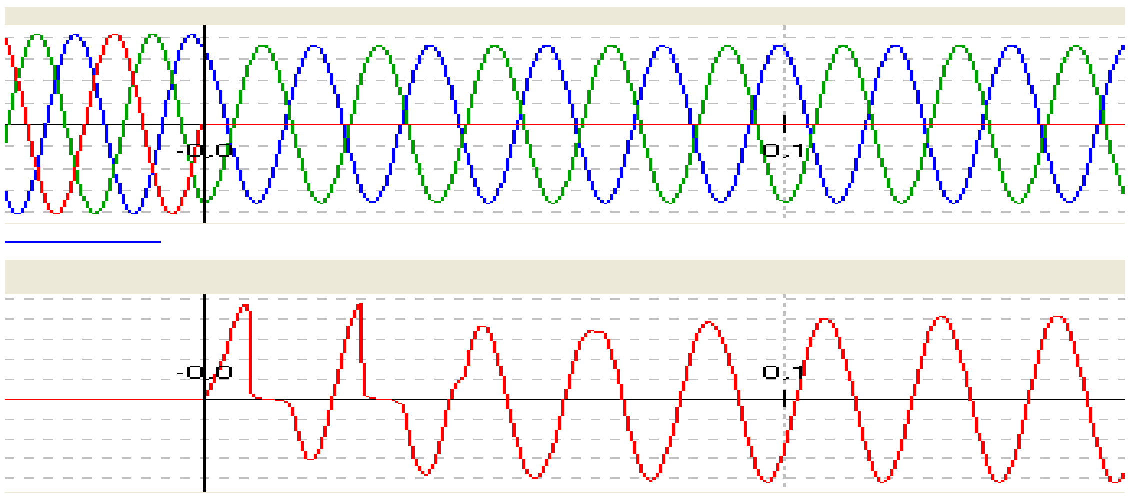
3. <u>**Approach towards the solution for transient saturation:**</u>

To understand the protection relay behavior under transient saturation condition can be approachable by carrying out Transient simulation of the fault currents (and voltages if needed), including the transient and steady-state saturation derived from the CT and burden data.

The Transient simulation is done practically in real-time in numerical test kits relay with **virtual Primary Injection Principle.** In the transient simulation, fault current level 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. For carrying out the transient simulation with variable CT Remenance factors, actual burden of the CT Shall be measured first.

Measuring the actual CT Burden: CT Burden can be actually measured with the help of CT analyzers nowadays available in the market. Without CT Analyzer also actual CT Burden can be calculated with an ac voltage source with current measurement. Disconnect the relay burden leads form CT and inject the rated secondary current and measure the voltage drop across the CT. The ratio of V and I gives the actual burden of the CT.

a) **Transient Simulation:** Transient simulation will be carried out in the relay with creating a single phase fault / 3 phase fault conditions with the help of numerical relay test kits. 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. To assess the relay behavior, it might be sufficient to test just one of the three phases as faulted phase to assess the saturation effect. Defining the fault conditions (occurrence on the timeline, i.e. resulting DC offset; fault type and location). The effect of each change can be recorded Time Signal View while injecting live transient signals with numerical relay test kits. 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 behavior exposed to CT saturation:

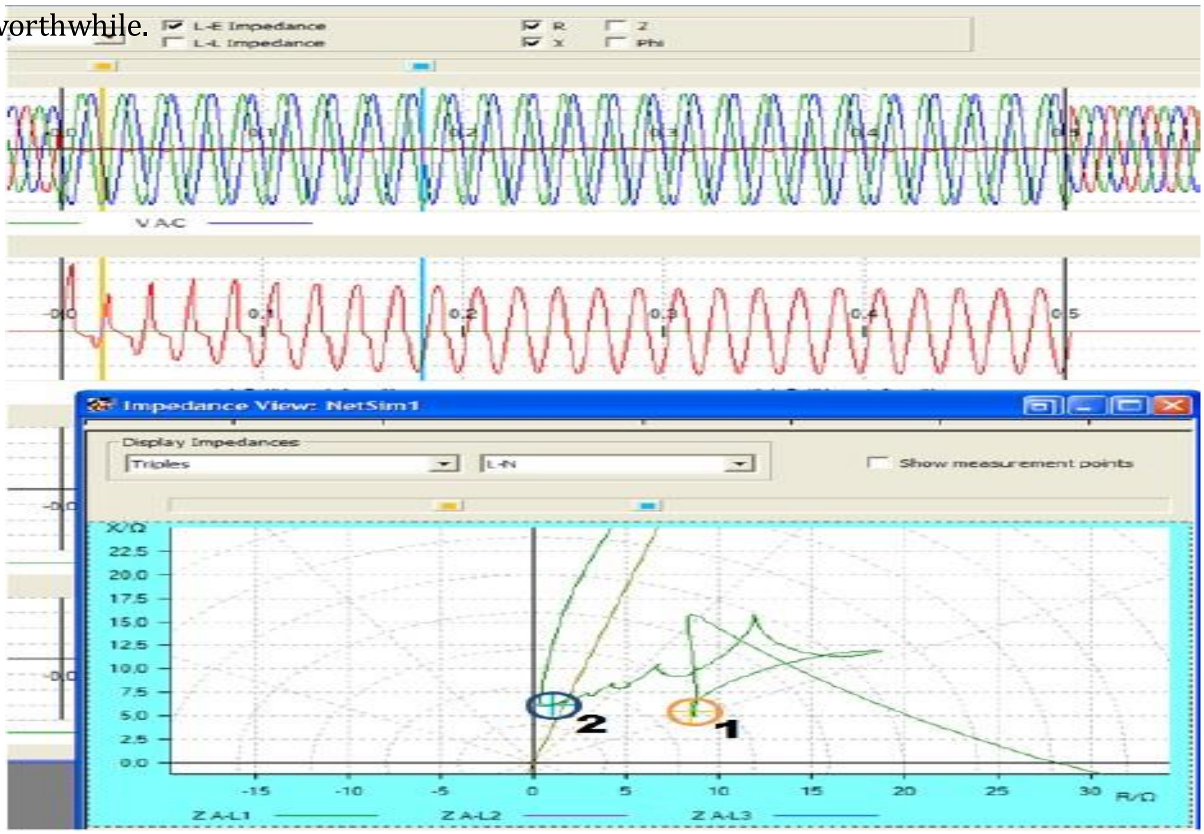
what happens when relays are confronted with secondary currents distorted by CT saturation? This greatly depends on the protective function, the implementation in the specific relay type, diverse relay settings and of course the degree of saturation and its change over time. Steady-state saturation, 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 infeed 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 on the protective relaying:

Definite-time overcurrent Relays: 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-reclose 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.

Over Current Relays with Inverse Characteristics: 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 short, 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.

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. 3 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.



Differential protection: 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? Transient simulation 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 transient simulation 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.

Conclusion:

Current Transformer saturation is not a new topic, but effect of the transient saturation behavior is to be understood. In the era of electro mechanical relays, there is no such method to check the protective relay operation due to the transient saturation of CT. After the introduction of the numerical relays, with the help of the raw data file in the disturbance recorders we could get to know the effect of transient behavior of CT. The main point to be discussed in this paper is even we know that CT will misbehave during transient condition, but no such method is there to generate the transient conditions in order to understand the relay behavior. In this paper we are introducing the Virtual Primary injection test based on simulation results for measured field data (CT secondary actual burden and CT characteristic data) can assess impact of the transient CT saturation on performance of relay and help in selecting stabilization parameter and coordination of protection setting. Modern measurement and test equipment 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.