Transient Behaviour of Conventional Current Transformers used as Primary Transducers and Input Elements in Protection IEDs and Stand Alone Merging Units

HOLST, S*  
ABB AB  
Sweden

ZAKONJŠEK, J  
Relarte Ltd  
Slovenia

Summary

The transient behaviour of a conventional current transformer (CT) is characterized by the performance before and after CT saturation. Before saturation the transient behaviour is defined by the transfer function and the frequency response. The transient behaviour related to CT saturation is more or less decided by the time to saturation.

Different types of CTs have different transient behaviour. Conventional CTs do not have the ability to continuously reproduce a DC component. However, the different types of CTs have more or less capability of reproducing the DC component for a limited time. Especially CTs with big airgaps have poor ability of reproducing DC components. Mixing this type of CT with other types of CTs for a differential protection can be a potential risk of unwanted operations.

Conventional CTs are the most used analogue input elements in protection IEDs so far. In contrast to primary CTs it is much more common to use CTs with big airgaps, or core material that behaves the same, as input elements. In protection systems based on IEC 61850-9-2 process bus the analogue current values will be supplied to the protection as sampled values from Non-conventional CTs and Numerical Merging Units or from combinations of Conventional CTs and Stand Alone Merging Units (SAMUs). The analogue input channels of the SAMUs will probably be designed with different types of input elements that have different frequency response and different ability to reproduce low frequency and DC components. Protection IEDs shall be able to be connected to SAMUs produced by different manufacturers and of different design. To be able to guarantee correct operation of all major protection functions, requirements on the transient behaviour must be carefully specified. In this respect the transient behaviour of input CTs of SAMUs is important and must fulfil specified requirements. Requirements on the frequency response are proposed.

Due to extremely low burden of input CTs in modern protection IEDs and SAMUs, saturation of input CTs often behaves differently compared with saturation of primary CTs. The secondary currents after saturation sometimes can be mixed up with the normal secondary current from CTs with limited ability to reproduce DC components. Requirements on the transient behaviour in this case cannot be specified related to the frequency response. In this case the requirement must be specified as a transient dimensioning factor to guarantee a minimum time to saturation.

Keywords

Analogue current input elements, protection IEDs, Conventional CTs, Transient response, Stand alone merging unit, CT saturation with extremely low burden, Cigre WG B5.24

* stig.holst@se.abb.com
1. Introduction

The transient behaviour of a conventional current transformer (CT) is characterized by the performance before and after CT saturation. Before saturation the transient behaviour is defined by the transfer function and the frequency response. The transient behaviour related to CT saturation is more or less decided by the time to saturation and the performance after saturation.

Even if conventional CTs are specified according to many different classes and standards, in principle there are only three different types of conventional CTs. These types are related to the design of the iron core and the presence of airgaps. Particularly the properties of the remanent flux are affected by the airgaps in the core. The following three types of CTs can be specified: High Remanence (HR) type, Low Remanence (LR) type and Non Remanence (NR) type. The HR type is a CT with closed core (e.g. TPX, P). The LR type CT has small airgaps in the core (e.g. TPY, PR) and the remanence is limited to 10% of the saturation flux. Finally the NR type CT has large airgaps (e.g. TPZ) and the remanent flux is zero. The different types of CTs have different transient behaviour. No conventional CT has the ability to continuously reproduce a DC component in the primary current. However, different types of CTs have more or less capability of reproducing the DC component for a limited time. Especially the NR type of CT has a poor ability of reproducing DC components. Mixing NR CT type with other types of CTs for a differential protection can be a potential risk for unwanted operations. Requirements regarding the frequency response are not specified in existing international CT standards. The use of NR type of primary CTs is limited to some utilities in relatively few countries and the relay manufacturers and the utilities have by experiences learnt about eventually restrictions of mixing CTs of different types.

Conventional CTs are the most used analogue input elements in protection IEDs so far. In contrast to primary CTs it is much more common to use NR type CTs as input elements. As all analogue input channels have the same transient response this solution achieves acceptable protection performance for most protection functions. In protection systems based on IEC 61850-9-2 process bus the conditions will be completely different. The analogue current values will be supplied to the protection as sampled values from Non-conventional CTs and Numerical Merging Units or/and from combinations of Conventional CTs and Stand Alone Merging Units (SAMUs). The analogue input channels of different SAMUs will probably be designed with different types of input elements like for example shunts, Hall elements, Rogowski coils or different types of conventional CTs. These elements have different frequency response and different ability to reproduce low frequency and DC components. Protection IEDs shall be able to be connected to SAMUs produced by different manufacturers and of different design. To be able to guarantee correct operation of all major protection functions, requirements on the transient behaviour must be carefully specified. In this respect the transient behaviour of input CTs of SAMUs is important and must fulfil specified requirements.

Saturation of input CT often behaves differently compared with saturation of primary CT. The saturated currents from the input CTs can look similar to and be mixed up with normal not saturated secondary currents from NR type CTs with limited ability to reproduce DC components. Requirements on the transient behaviour related to saturation of the input CTs must be specified separately.

2. Transient Behaviour of Conventional 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 behaviour 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](image)

![Figure 2. Simplified magnetization curve](image)

To achieve a small error of a CT the relative amount of magnetizing current \(I_m\) shall be minimized. The magnetizing impedance shall be as large as possible and the impedance in the secondary circuit shall be as small as possible. As long as the flux density is below the saturation level the magnetizing impedance is very high and the CT measuring error will be very low.

The magnetization curve can be assumed to be approximately linear up to the saturation level and the flux density is proportional to the secondary e.m.f. If the secondary e.m.f. reaches the saturation level due to high current and/or high burden, the magnetizing impedance will decrease considerably and the secondary current will be short-circuited by the magnetizing impedance during some time interval of each cycle and the error is considerable. The CT operates in a non-linear condition.

The transient behaviour of the CT is completely different in the case without saturation or the case with saturation. The two cases have to be analysed separately.

### 2.1 Transient Behaviour of CTs before saturation

For operation in the linear part of the magnetization curve the transfer function for the simplified CT model (Figure 1) can be defined. The transient behaviour can then be shown as the frequency response illustrated as Bode plots. The Bode plot is usually a combination of a Bode magnitude plot and a Bode phase plot that describes the transfer function as magnitude and phase angle versus frequency.

If \(R_m\) is neglected and \(R_s = R_{ct} + R_b\), the transfer function can be written as follows:

\[
H(j\omega) = \frac{I_p(j\omega)}{I_p(j\omega)} = \frac{j\omega \cdot L_m}{R_s + j\omega \cdot L_m} = \frac{j\omega \cdot L_m}{R_s} \cdot \frac{1}{1 + j\omega T_{ct}}
\]

where \(T_{ct} = \frac{L_m}{R_s + R_b}\)

The \(T_{ct}\) is the secondary time constant of the current transformer.
Introducing airgaps (gapped core) will decrease the magnetizing inductance and the secondary time constant will decrease. The amplitude and phase errors will increase. A HR type CT typically has a secondary time constant of several seconds. For a LR type CT the secondary time constant is around 0.5 – 1 second. A NR type CT has a secondary time constant of 60 ms at the maximum allowed phase error limit according to the IEC 61869-2 standard for current transformers. This means that a DC component in a fault current will be damped very rapidly and the CT has a poor ability to reproduce the transient.

The transfer function shows that a CT can be seen as a first order high-pass filter. As the simplified CT model does not have any capacitors the limitation of the CT regarding high frequency is not shown. Figure 3 shows typical Bode plots for the magnitude (expressed as dB of gain) and the phase angle.

Figure 3. Bode magnitude and phase plots for different CT types

Figure 4 shows secondary currents and errors for different CT types in case of a primary current with full DC offset and a primary time constant of 120 ms. It can be seen that the error from a HR CT type is almost negligible and of no importance for protection applications. Even in differential protection applications there should not be any restrictions to mix current input channels from different SAMUs with HR CT type inputs or other non-conventional input elements capable of reproducing DC components. On the other hand, if an input of NR CT type is mixed with inputs of HR CT type and other input elements it is obvious that there is a risk of unwanted operations or unacceptable limitation of the sensitivity of a differential protection.
The error from a LR CT type is not negligible. In the example in Figure 4 the instantaneous error reaches 10 % after approximately 50 ms (the limit of the transient error for a TPY CT according to IEC 61869-2). However, experiences from mixing primary CTs of HR and LR types in differential protection applications have shown that there are no critical limitations.

The conclusion is that input elements of a SAMU or protection IED that shall be possible to be mixed with other input elements should have a frequency response with the lower cutoff frequency ≤ 0,3 Hz. This corresponds to a secondary time constant \( T_{ct} \geq 550 \) ms.

The strong frequency dependence of the phase error for the NR CT shall also be observed. This means for example that a NR CT type sensor is not suitable for protection functions that shall be able to measure phase angles with high accuracy even if the frequency deviates from the nominal frequency. Reverse power protection for generators is an example of such protection function.

### 2.2 Transient Behaviour of CTs after saturation

Normally, when a current transformer goes into saturation the magnetizing impedance is much smaller than the total resistance of the secondary circuit. This means that the saturated secondary current will be very small (practically zero) during some time interval of each cycle. The saturation of the CT is very distinct. In some case CT saturation can look different. For example if the resistance in the secondary circuit (secondary winding resistance \( R_{ct} \) and the burden \( R_b \)) is extremely low, the saturated magnetizing impedance does not manage to short-circuit the secondary circuit completely. There will be a current distribution between the total secondary resistance and the saturated magnetizing impedance. The saturated secondary current can be of considerable magnitude. Input CTs of modern protection IEDs or SAMUs can have extremely low burden and operate in such conditions. Figure 5 shows an example of a saturated secondary current in case of an extremely small secondary resistance. The current is 3 p.u. and the CT saturates after approximately 50 ms. Figure 6 shows the unsaturated secondary current from a CT with limited ability to reproduce DC components (NR CT type).

![Figure 5. Example of CT saturation in case of an extremely small secondary resistance](image)

![Figure 6. Example of an unsaturated secondary current from a NR CT type](image)
From the figures it is obvious that the secondary currents in the two cases have similarities and can be mixed up. The requirement on the transient behaviour for the unsaturated current is specified by means of the frequency response. The requirement on the transient behaviour for the saturated current is not possible to specify in the same way. This transient behaviour must be specified in a way that guarantees a minimum time to saturation.

A specific CT has a fixed saturation e.m.f. that specifies most of the properties regarding saturation. The equivalent limiting secondary e.m.f. \( E_{\text{al}} \) is defined as follows:

\[
E_{\text{al}} = K_{\text{ssc}} \cdot K_{\text{td}} \cdot I_{\text{sr}} (R_{\text{ct}} + R_{\text{b}}) \quad \text{where} \quad K_{\text{ssc}} = I_{\text{f}} / I_{\text{pr}}
\]

\( K_{\text{ssc}} \) is the symmetrical short-circuit current factor and \( K_{\text{td}} \) is the transient dimensioning factor. The \( K_{\text{td}} \) factor decides the minimum time to saturation if the symmetrical fault current \( I_{\text{f}} \) is \( K_{\text{ssc}} \) times rated primary current. Figure 7 and 8 show the necessary \( K_{\text{td}} \) factor for different time to saturation and primary time constants \( (T_{p}) \). Maximum DC offset is the dimensioning case for time to saturation approximately > 15 ms (50 Hz). However, for time to saturation approximately < 15 ms different inception angles give the fastest saturation. Note that the influence of the primary time constant is practically insignificant for short time to saturation \( (\leq 15 \text{ ms}) \) and \( T_{p} > 60 \text{ ms} \). For longer time to saturation also higher \( T_{p} \), than 100 ms shown in the figures, must be considered. In specific applications the primary time constants can be up to 400 ms or even more. These applications are of course very rare.

\[ K_{\text{td}} \]

\[ T_{p} \text{ [ms]} \]

\[ t_{\text{sat}} \text{ [ms]} \]

\[ T_{\text{ct}} = 3000 \text{ ms} \]

\[ T_{\text{ct}} = 550 \text{ ms} \]

Figure 7. Transient dimensioning factor for time to saturation > 15 ms

Figure 8. Transient dimensioning factor for time to saturation < 15 ms

Requirements on the transient behaviour related to saturation of the input CTs can be specified as follows. Assume that the symmetrical overcurrent range is decided to be 32 times rated current \( (K_{\text{ssc}} = 32) \). If the input CTs always must be saturation free at least for 10 ms the transient dimensioning factor must be at least 3,7 \((K_{\text{td}} \leq 3,7 \text{ for } t_{\text{sat}} = 10 \text{ ms and } T_{p} \leq 500 \text{ ms})\) and the total overcurrent factor will be \( K_{\text{tot}} = K_{\text{ssc}} \cdot K_{\text{td}} = 32 \cdot 3,7 = 118 \).

No remanent flux is considered in the \( K_{\text{td}} \) factors shown in the figures. If we assume that the input CTs (LR CT type) can have 20 % remanent flux the total overcurrent factor will be approximately \( K_{\text{tot, rem}} = K_{\text{tot}} \cdot 1/(1 - 0,2) = 118 \cdot 1,25 = 148 \).
An input CT that fulfils the following:

$$\frac{E_{\text{al}}}{I_{sr}} \left( R_{ct} + R_b \right) \geq 148$$

will also fulfil the specified transient requirement that the time to saturation is $\geq 10$ ms within the symmetrical current range 32 times rated current. $I_{sr}$ is the input CT rated secondary current. $R_{ct}$ and $R_b$ are the secondary winding resistance and the burden of the input CT.

3. Conclusions

Different types of conventional CTs have been the most used analogue input current sensors so far. In the future there will be more types of input sensors and protection IEDs must be able to operate with a mix of different sensors. To be able to guarantee correct operation of all protection functions, requirements on the transient behaviour must be specified and fulfilled.

The transient behaviour of conventional CTs is characterized of the performance before and after saturation. The transfer function and the frequency response specify the transient behaviour before saturation. Frequency responses, shown as Bode plots, for different types of CT have been calculated. To make it possible to mix different current input elements, a requirement on the frequency response has been proposed.

The transient behaviour related to CT saturation is more or less decided by the time to saturation and the performance after saturation. In case of extremely small burden the saturated secondary current can look similar to a secondary current, without saturation, from a CT with poor ability to reproduce DC components. Though the similarity, it is not possible to specify the requirement on the transient behaviour for the saturated current with the frequency response. Requirements on the transient behaviour that guarantee a minimum time to saturation has been proposed in the paper.

References

The paper is based on results of studies within the work of:

[1] Cigre WG B5.24 “Protection Requirements on Transient Response of Voltage and Current Digital Acquisition Chain”

[2] Cigre WG B5.02 “Co-ordination of Relays and Conventional Current transformers"