MODELING OF CURRENT TRANSFORMERS UNDER SATURATION CONDITIONS

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Summary During a short circuit the input signal of the relay can be distort by the magnetic core saturation of the current transformer. It is useful to verify the behavior of CT by a mathematical model. The paper describes one phase and three phase models and it presents some methods of how to analyze and classify a deformed secondary current.

1. INTRODUCTION

All kinds of protection relays in MV or HV networks process signals from instrument transformers. In most cases transformers are current transformers (CT) and the relays work on overcurrent, differential or impedance principle. The quality of input signals is very important for these relays to ensure correct functions. Protection relays have to detect failures - in most cases short-circuits. During a short circuit the input signal of a relay can be distort by magnetic core saturation of the current transformer.

It is very useful to create a mathematical model of a current transformer. The model can be used to analyze transformer behavior during high fault current or when the fault current contains a DC component. Verification of CT can by done by using the model without costs of the short-circuit tests or other expensive experiments.

The purpose of the work is to develop a model of the current transformer which is given only by commonly accessible data of the CT. For example it is not always simple and quick to get data from the manufacturer about the magnetizing characteristic or dimensions of the magnetic core. The mathematical model works only with rated values and with the excitation characteristic, which is commonly measured and got as a part of the receiving report.

2. ONE PHASE MODEL

The algorithm of the CT modelation comes from its circuit scheme (Fig. 1). The scheme is the same as in normal transformer.

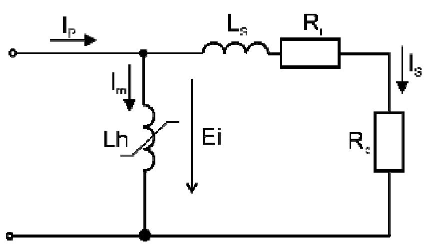
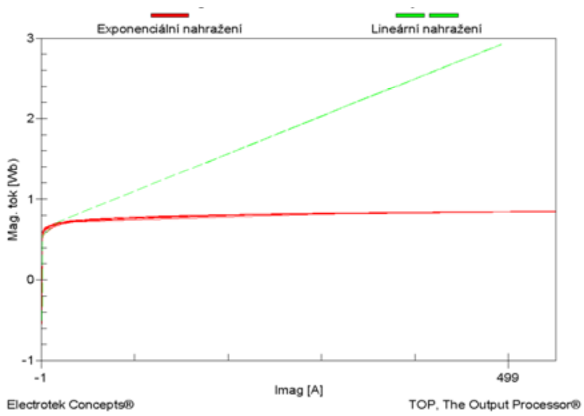


Fig. 1. One phase model of a CT

Current transformer can be described using the circuit of a normal transformer [1, 2]. In such circuit primary elements and magnetic core resistance can be ignored because they have only slight influence on behaviour. The magnetizing inductance has to be non-linear and can be described by the magnetizing characteristic. It can be determined from the measured excitation characteristic. The circuit is described by the differential equation and it is numerically solved. First results showed that the linear approximation of the magnetizing characteristic in the saturated area is not correct. It is the reason why the last part of the characteristic (values above the last measured point of the characteristic) was described using the exponential function.

The approximation is given by the last two points of the magnetizing characteristic. The characteristic is described linearly in the range of the measured values (Fig. 2), and it is described by the exponential function above the measured values:



$$\phi = a \cdot I^b \tag{1}$$

Fig. 2. Exponential (green) and linear (red) magnetizing characteristics

The following picture (Fig. 3) shows result of the one-phase model with linear characteristic shape in the saturated area and Fig. 4 shows result with exponential shape in the saturated area. The computed wave (red) is compared with measured wave (black). There is also the wave of the magnetic flux in the picture (blue). We can see in the Fig. 3 that the measured secondary current is dramatically different from the modelled secondary current.

There is no deformation of the current and of the flux by the saturation.

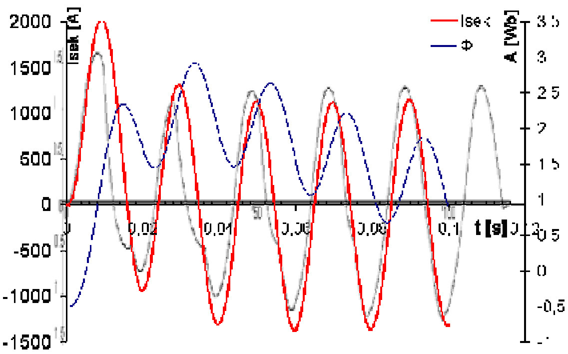


Fig. 3. Results with linear magnetising characteristic

We can see in Fig. 4 that the model with exponential shape in the saturated area is more accurate and the resulting wave agree more with the measured wave. The secondary current is deformed by the saturation

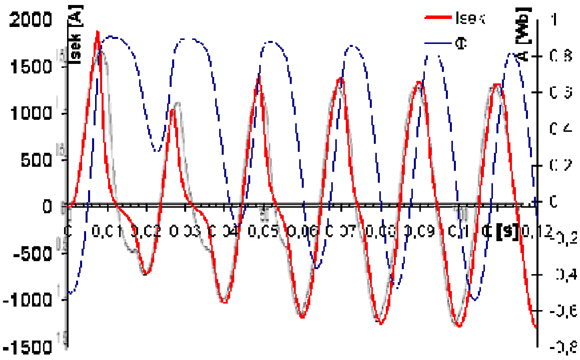


Fig. 4. Results with exponential magnetising characteristic

The described model was made as a macro of the program EXCEL. The results show that the model is accurate enough, if we consider how simple the model is. The model could be made more accurately, but it would cause its bigger complicacy and the necessity of the more complex input data of the CT (e. g. the hysteresis curve).

The input data of the one-phase model are the parameters of the secondary burden of the CT and the parameters of the short circuit current. It is considered, that there was no current in the CT before the fault.

3. THREE PHASE MODEL

The model of three CT in the star connection was developed base on older one-phase models. This model represents the common connection of the protection relay into the three-phase network. The model is based on the circuit scheme of thee one-phase current transformers (Fig. 5.). This circuit was described by the system of differential equations and it was solved using the method Runge-Kutta.

It is considered the following general shape of the primary current in phase k in time of t >0:

$$i_{kp} = \mathrm{Im}ax \cdot (Off_k \cdot e^{-t/\tau} - \cos(\omega t + \varphi(k) - \alpha) \qquad (2)$$

Where k ... Number of the phase (k = 1 - 3)
Off_k ... Ratio of the DC component in time of t = 0 in the phase k [-]
φ (k) ... Phase angle of the phase k
α ... Phase shift

System of differential equations is following:

$$L_{h1}\frac{di_{1p}}{dt} - (L_{h1} + L_1)\frac{di_{1s}}{dt} - R_1 \cdot i_{1s} - u_E = 0 \qquad (3)$$

$$L_{h2}\frac{di_{2p}}{dt} - (L_{h2} + L_2)\frac{di_{12}}{dt} - R_2 \cdot i_{2s} - u_E = 0 \qquad (4)$$

$$L_{h3}\frac{di_{3p}}{dt} - (L_{h3} + L_3)\frac{di_{3s}}{dt} - R_3 \cdot i_{3s} - u_E = 0 \qquad (5)$$

$$-u_E + R_E \cdot i_E + L_E\frac{di_E}{dt} = 0 \qquad (6)$$

Magnetizing inductances L_{h1} up to L_{h3} are considered as non-linear. The properties are given by the magnetizing characteristic i-ϕ as it was considered in the one-phase model. The system of differential equations is solved by the Runge-Kutta method.

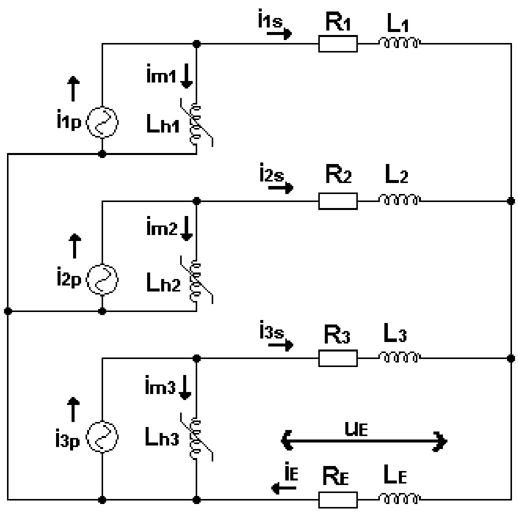


Fig. 5. Three-phase model

In the model the magnitude and the phase angle of the short circuit current can be set in each phase separately. It can be set the ratio of the DC component in the time of short circuit start (Off) in the phase A. In other phases the DC component is computed based on the given current magnitude and the phase angle of the short circuit current.

The model considers the same excitation characteristic of the all three current transformers. The parameters of all phases and of the neutral wire (inductance and resistance) can be set differently. The remanence magnetic flux of current transformers can be also set in each phase.

4. SIMULATION RESULTS

We considered a current transformer with following rated values:

CT 300 / 5 A; 25 VA; 5P20
Winding resistance: 0.1325 Ω
Load resistance: 0.08 Ω
Inductance of the secondary circuit 2 μH
Magnetic flux at t = 0 0 Wb

Tab. 1. Excitation characteristic

I [A]	0	0.055	0.104	0.2	0.68	1.18	5.37
U [V]	0	70.52	117.2	132.6	142	146	157

A protection relay with resistance of 30 mΩ was considered as a load of the CT, the relay was connected with a Cu cable 2.5 mm^2 with length of 6 m (46 mΩ). A reserve of 4 mΩ was added to the lead resistance. The resistance and the inductance parameters of the neutral wire had the same values as the phase wires parameters (80 mΩ and 2 μH).

The primary fault current was in this case considered as a tree-phase short current with 100 % DC component in the phase A. The magnetic flux at the time t = 0 was 0 Wb in all current transformers.

The following pictures (Fig 6, 7, 8) show the resulting secondary current and magnetic flux in all current transformers.

When a short circuit between phases occurred (e. g. two phase without ground or three-phase short circuit) there in no neutral component in the current and the neutral wire has no influence, because the primary current is only in the phase wires.

In the case of three phase short circuit and the star connection the load resistance and inductance take effect twice lower then in the case of one phase circuit, because there is no current in the neutral wire. This is very important by comparing the results of the one phase model and the three phase model.

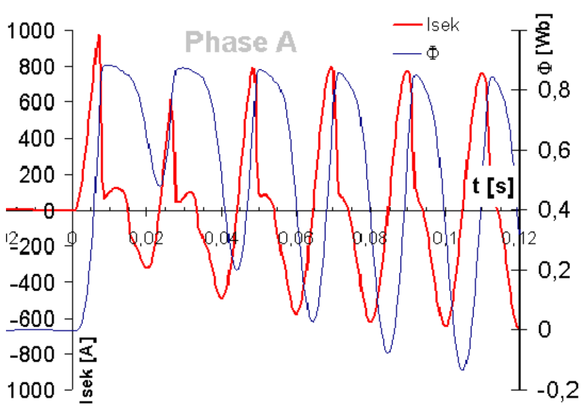


Fig. 6. Three-phase model - Phase A

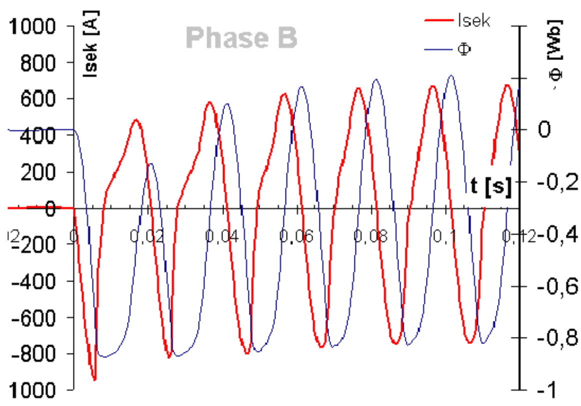


Fig. 7. Three-phase model - Phase B

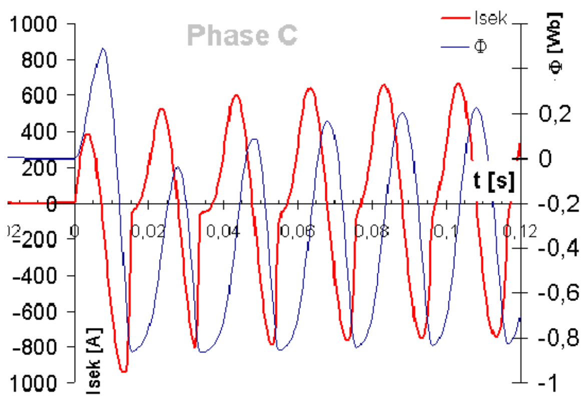


Fig. 8. Three-phase model - Phase C

The resulting secondary current in the phase A was analyzed in the postprocessor *TOP, The output Processor*. The results showed that it dramatically declined the DC component and the basic harmonic of the primary and secondary current (Fig. 6). The ratio of the secondary current over the true primary current for both components gives us an overview about the level of saturation. The level of the saturation can be classified on the base of the ratio of the RMS secondary current values over the RMS true primary current magnitude [3]. The next table shows the levels. The level could be defined also as the ratio of the basic harmonic components.

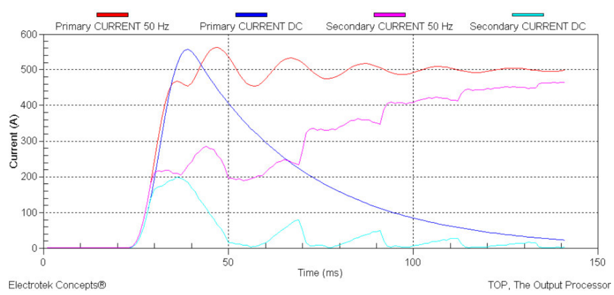


Fig. 9. Components of the primary and secondary currents

Tab. 2. The levels of the saturation

Low Saturation	Isek / Iprim = 1 – 0,9
Moderate Saturation	Isek / Iprim = 0,9 - 0,5
High Saturation	Isek / Iprim = 0,5 - 0,2
Extreme Saturation	Isek / Iprim < 0,2

It is obvious, that the deformed current contains higher harmonics. As we can expect, the level of the higher harmonics decrease with time ant with its order. The other important attribute of the deformed signal is time of the first current pulse. This time should be as big as possible so that the protection relay has ample time to process the input signal. Therewithal this time is also important regarding to number of samples, which are processed by the protection relay during this time. The more samples are processed the higher quality information about the short circuit current the relay has and the probability of the miss operation decrease. The number of processed sampled should not be lower then two that the trend of the current would be evident.

5. CONCLUSIONS

This paper describes the problem of current transformer saturation and mathematical models.

Results showed the shape of the magnetizing curve in the saturation area is very important factor.

The next work will be focused on the analysis of the secondary current when the magnetic core of the current transformer is saturated. In particular, it will be concentrated on the content of the higher harmonics in the secondary current and the time of current pulses. The behaviour analysis of some protection relay type under saturation conditions will be done. Of course the model will be kept improved and the problem will be modelled in the EMTP ATP program.

REFERENCES

[1] PROCHÁZKA M.; *Přístrojové transformátory proudu*; ZČU; Plzeň; 2005

[2] PROCHÁZKA M.; *Modelování přístrojového transformátoru proudu v programu EMTP – ATP*; In: Electro- and Information Engineering 2003: Nečtiny; ZČU 2005

[3] BENMOUYAL G., LEE T.; *Securing sequence-current differential elements*; SEL Technical Papers; SEL 2004