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Evaluation of numerical time overcurrent relay performance for current transformer saturation compensation methods

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ABSTRACT

Current transformer (CT) core has non-linear magnetic characteristics and may achieve high flux values when exposed to high fault currents. In this case, the CT primary current is not fully reflected in their secondary side and the relay cannot operate in the desired time. Several papers have been published about computational methods to compensate saturation of CTs due transient conditions. However, the use of CT simulated signal for practical tests in protection relays is rare. This paper presents an environment that allows performing secondary tests in physical relays when computational methods are applied to minimize the effects caused by CT saturation. The CT model and saturation compensation methods are implemented in MATLAB. The secondary signals resulting of this modeling are converted to COMTRADE format to be loaded into injection test device in order to evaluate the overcurrent numerical relay response for each CT saturation compensation method presented.

1. Introduction

The expansion of the electric power system due to the growing demand for energy causes an increase of the fault currents levels. Greater attention is needed with the protection devices to ensure their proper operation in this case. These devices require an accurate measurement of the current magnitudes in the power system. So, the current transformers (CTs) are key components in this system, since they provide access to high currents of the power system through reduction of the primary current on the secondary side, allowing timely and correct identification of faults and disturbances by protective relays [1,2]. Thus, the correct operation of the protection system is dependent on the CT accuracy. In opposition to this desirable feature, the CT core has nonlinear excitation characteristics. When exposed to high fault currents, the CT core retains high levels of flux density and can saturate [2–5]. As a result, the secondary current feeding the protective relays can be reduced and distorted causing misoperation of these devices.

Aiming to minimize the effects of CT saturation, two conventional methods are known: (i) increasing the cross section of the core or (ii) reducing the burden connected to the CT secondary. The first method is expensive and the second can be difficult to implement. Both options can affect the cost. For these reasons, compensation techniques to minimize the effects of CT saturation protection relays have been discussed over the years.

To ensure proper operation of the protection system, mathematical and computational tools have been developed to carry out studies on the CT behavior under transients and to identify the saturation interval, so that it can be compensated for errors due to CT saturation. In practice, these compensation methods of CT saturation are integrated into the algorithm of numerical relays.

On the CT modeling for transient analysis, many mathematical CT models with iron core have been published in recent years. Most published studies have considered the use of ATP (Alternative Transients Program) to model the CT under transient conditions [6–10].

Regarding to identifying the saturation interval, the authors in Reference [11] proposed to use difference functions of the sampled signal. In Reference [12] the authors propose a method for detection of saturation interval through the third derivative of the secondary current signal.

After detection of the saturation interval, it is necessary to compensate the distortion of the current waveform to improve the relay response. In Reference [13] the authors use the saturation compensation technique based on curve fitting by least squares. In Reference [14] the authors describe the CT saturation compensation method based on linear regression. In both References [13,14], the authors warn on the importance of testing relays in CT saturation conditions. However, the use of simulated CT signals to

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practical tests on protective relays is rare. Thus, this paper presents an environment that allows performing secondary tests in physical relays when computational methods presented in the literature are used to reduce the effects caused by the CT saturation.

Beyond the methods presented in References [11–14] cited in the above paragraphs, other relevant techniques based on the use of Artificial Neural Networks (ANNs) for detection and correction CT saturation effects can be found in the literature [15–19]. However, it is not part of the scope of this paper to describe these techniques, since ANNs have low application when referring to relay algorithms.

The use of high-tech equipment to test protective relays is becoming increasingly common [2]. Currently, the market offers high precision relay test devices which generate analogical signals of voltage and current, but it is not possible to model some devices accurately, such as CTs, in that test devices. However, these devices allow loading COMTRADE files [20] to reproduce a signal from a simulated program. Using this type of test device, the response of a numerical overcurrent protection relay is investigated when receiving CT secondary signal from simulation. The difference compared to conventional test is how to obtain the CT secondary data. Firstly, a mathematical CT is implemented in MATLAB based on the theory published by the IEEE Power System Relay Committee (PSRC) [21]. This algorithm is a model for many types of conventional CTs considering all the factors that may cause its core saturation, resulting in the secondary current signals (ideal and saturated). Numerical methods are applied to these signals to detect [11] and to compensate [13,14] the CT saturation interval. Then, the secondary signals (ideal, saturated and compensated) resulting from this computational implementation are converted to COMTRADE format to be loaded in the test device, so that it is evaluated the time response of the numerical overcurrent relay (ANSI 51). The main results are presented.

2. CT modeling

A mathematical CT is modeled in MATLAB based on CT model developed by IEEE PSRC [16]. This implementation is intended to provide an accurate indication of the ideal and the real waveforms of the CT secondary current in a specific application, such the degree of saturation can be visualized as function of time [2,21]. The conditions in the low-end region of the saturation curve are not represented in this model. The excitation current in the region below of the knee-point is a complex combination of magnetization, hysteresis and eddy current components. These parameters are usually not known in a particular case. When the excitation current reach the saturated region, the part of the current waveform in the region below of the knee-point has a negligible effect on the overall solution, thus the hysteresis and eddy currents losses can be neglected in this model [2,21]. The CT equivalent circuit which generates the mathematical model (the equations and boundary conditions) to obtain the secondary current resulting from the algorithm implemented in MATLAB is shown in Fig. 1.

By Kirchhoff's voltage law, the circuit shown in Fig. 1 is described by Eq. (1):

$$\mathrm{v_e} - \left(\frac{\mathrm{i_p}}{\mathrm{CTR}} - \mathrm{i_e}\right)\mathrm{R_t} - \mathrm{L_b}\cdot\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\mathrm{i_p}}{\mathrm{CTR}} - \mathrm{i_e}\right) = 0 \tag{1}$$

where i_p, i_s and i_e are instantaneous values of the primary, secondary and excitation currents, respectively; v_e is the instantaneous excitation voltage; CTR is the current transformer ratio; R_s is the secondary winding resistance; Z_b is the burden impedance and R_t is the total resistance equal to the sum of burden resistance and the secondary winding resistance. One set of assumptions and equations are used to solve the differential equation in Eq. (1).

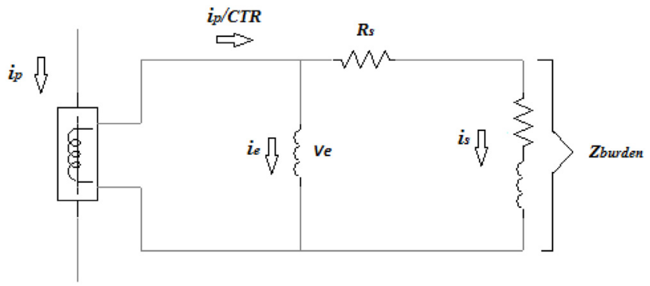

Fig. 1. CT equivalent circuit.

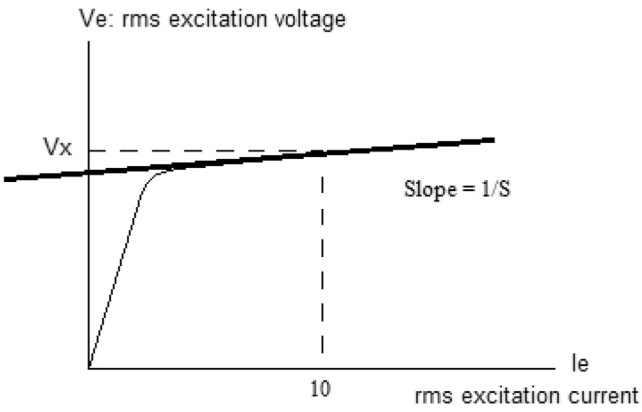

Fig. 2. Excitation curve of the CT IEEE PSRC model [21].

Considering the circuit of Fig. 1 under fault condition, the ideal secondary current ($i_e = 0$) can be expressed by Eq. (2):

$$i_s = \frac{i_p}{CTR}\sqrt{2}\left[K.e^{-\frac{t}{\tau}} - \cos\left(\omega t - \cos^{-1}K\right)\right] \tag{2}$$

where K is the factor that determines the characteristics of the secondary current waveform:

- If $K = 1$, there is an asymmetrical component in the fault current;
- If $K = 0$, there is only a symmetrical component in the fault current.

In practice, the excitation current is nonzero and its value defines how much the primary current will be reflected with distortions in the secondary side. Thus, the real current in CT secondary side is given by Eq. (3).

$$i_s(t) = \frac{i_p(t)}{CTR} - i_e(t) \tag{3}$$

So, it is necessary to find the CT excitation parameters that can be obtained from the excitation voltage versus excitation current curve (see Fig. 2). As presented by the author in Reference [21], two parameters must be extracted from the excitation curve:

- The slope of the saturated section of the excitation curve;
- The rms saturation voltage (V_x) when the rms excitation current (I_e) is 10 A. Reference [3] says that "for a CT secondary current of 20 times of CT rated current, the maximum value of saturation voltage (V_x) is defined for a excitation current of 10 A".

The straight line curve with slope 1/S shown in Fig. 2 [21] is defined mathematically as Eq. (4):

$$\log V_e = \frac{1}{S}\log I_e + \log V_i \tag{4}$$