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NEW METHOD OF CT SATURATION DETECTION

A new method for detection of CT saturation is presented in this paper. The presented algorithm applies a new, innovative methodology mapping first order derivative of phase current signals into coordinates of a 3D vector. The comparison of proposed algorithm with standard one based on secondary current signal's second derivative is conducted and some of simulation results are presented to show the proposed algorithm effectiveness.

1. INTRODUCTION

The inductive current transformers with solid iron ferromagnetic core (TPX) are nowadays still the most widely applied, in power systems, to provide the transformation of primary currents into secondary ones. They possess good transformation properties and guarantee high accuracy and reliability of secondary currents in most conditions. But even if selected properly according to [1] their magnetic cores can sometime experience saturation because of too large magnitude of a primary current or/and its exponential component. As CT saturation phenomenon can result in significant distorting of secondary current waveform, it may bring in serious inaccuracies into measurement results or decision-making procedures which may become unreliable or clearly wrong [13]. Thus power system reliability is jeopardised by maloperation of protection devices or/and controls.

The correct operation of protective relays depends on the quality of secondary current signals delivered into relay's inputs by current transformers. To guarantee it even in periods when the CT magnetic core gets saturated it is necessary to properly recognize

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the beginnings and ends of deformations of a secondary current signal in order to block or rearrange the operation of automatic systems [7,14]. It is also possible to undertake actions aiming at reconstructing the correct waveform of a secondary current.

The corrupted secondary current affects badly not only the work of on-line systems but can change results of fault location algorithms which run both in an on- or off-line manner as well [12].

The problem of a secondary current deformation because of CT saturation still is very important one to be solved. There are many reports available discussing this problem and proposing different way of dealing with it. [4,7,10,14] cover the design of protection devices cooperating with CTs. Hardware oriented ones include [3]. A method dedicated to CT saturation detection and presented in [7] was assumed here as a reference one for testing the new proposed herein algorithm. One other report [5] recommends application of secondary current third derivative for that purpose. Among compensating algorithms for secondary currents [6] might also be mentioned. There are also reported other methods for detecting occurrence of current transformer saturation applying other approaches like artificial neural networks [11, 9] or wavelet transformation [8] for that purpose.

The new proposed in this paper method for detecting occurrences of current transformer saturation is developed within a project investigating a new method of secondary current waveform restoration. The paper is aimed at introducing new methodology basics and description of the algorithm for detecting periods of current transformer saturation. Results of current transformer saturation detection obtained in simulation tests of a current transformer modelled in ATP-EMTP are provided to show the effectiveness of the new proposed method.

2. METHODOLOGY FOR NEW ALGORITHM DESIGN

A phase current signal flowing in a power system lines can be described with general model as

$$i(n) = i_m \cos(\omega n T_s + \varphi) + \Sigma_h i_h(n) + \Sigma_T i_T(n) + d(n) \tag{1}$$

including beside the fundamental component fluctuating with rated frequency also higher harmonics, exponentially decaying with different time constants T components and other usually random disturbances. The actual content of current signal's components depends on the state of a power system and in case of higher harmonics it is limited by power quality standards as long a power system is in normal quasi steady state operation. During transients, especially following the inception of a fault, there appears an abnormal current with exponential components which together with augmented value of its fundamental component can originate a substantial enough shift of magnetic flux to make CT magnetic core saturate. In those conditions, the secondary current waveform can suffer distortions which intensity reflects the degree (depth) of CT saturation. The fundamental component $i_{S1}(n)$ of it can be considered to be a superposition of the not deformed one and nonlinear component $i_N(t)$ equal to missing secondary current

$$i_{S1}(n) = (I_{Sm} + i_N(n))\cos(\omega n T_s + \varphi') \tag{2}$$

This decomposition of secondary current into symmetrical and asymmetrical parts allows for designing a very efficient algorithm for CT saturation detection within a framework of the new 3D methodology.

The key step of the method is that the samples of *ABC*-phase currents are considered to be the *xyz*-coordinates of a 3 dimensional Cartesian space vector called the line current vector as below

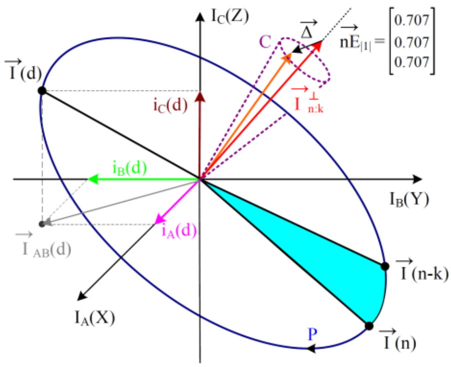

Fig. 1: Graphical presentation of relations between line current vector current perpendicular-to vector $\vec{I}^{\perp}_{n:k}$

$$\begin{cases} i_A(n) = X_{1m}\cos(\omega n T_s + \varphi_A) \\ i_B(n) = X_{1m}\cos(\omega n T_s + \varphi_B) \\ i_C(n) = X_{1m}\cos(\omega n T_s + \varphi_C) \end{cases} \rightarrow \vec{I}(n) = \begin{bmatrix} i_A(n) \\ i_B(n) \\ i_C(n) \end{bmatrix} \tag{3}$$

which rotates around the space centre scratching a closed curve corresponding to a given steady state of power system operation, see Fig.1.

Shifting the analysis of power system phenomena from a two dimensional impedance plane to a three dimensional space shows them in a new perspective and these newly observed features can be successfully applied for a power system protection purposes.

Different steady state conditions of power system operation are now mapped into closed curves in a three dimensional space. Curves are housed in planes distinguished by a current perpendicular-to vector calculated as a vector product of a actual and delayed by *k* samples line current vectors as follows

$$\vec{I}^{\perp}_{n:k} = \vec{I}(n) \times \vec{I}(n-k) = \begin{bmatrix} \vec{I}^{\perp}_{n:k}(x) \\ \vec{I}^{\perp}_{n:k}(y) \\ \vec{I}^{\perp}_{n:k}(z) \end{bmatrix} = \begin{bmatrix} \left(i_B(n)i_C(n-k) - i_C(n)i_B(n-k)\right)_x \\ \left(i_C(n)i_A(n-k) - i_A(n)i_C(n-k)\right)_y \\ \left(i_A(n)i_B(n-k) - i_B(n)i_A(n-k)\right)_z \end{bmatrix} \quad (4)$$

Compared to the line current vector (3) the current perpendicular-to vector (4) is almost steady in space. It can be shown that all normal states of power system operation can be described with current perpendicular-to vectors of different length but all of which have the same spatial orientation with reference to *xyz*-axis.

During transients current perpendicular-to vector moves from its normal position to a new one characteristic for a given disturbance and stays there as long as the disturbance lasts.

As each different state of power system can be now associated with a unique position of a current perpendicular-to vector then any deviations from them are referred to various additional abnormal conditions occurring in power system operation and are subjected to protective relaying. The investigation of those deviations allows for identifying the ones corresponding to current transformer saturation and to develop an algorithm responsible for detecting and indicating those conditions.

3. CRITERION QUANTITY SIGNAL

The criterion quantity signal used for detecting occurrences of CT saturation is a measure of spatial orientation deviations of the current perpendicular-to vector (4), which are substantial while CT saturation starts and ends, as presented in Figure 2b. Observed damped oscillations of the current perpendicular-to vector coordinates are driven by exponential components present in phase-to-phase fault current signals, see Figure 2a.

Calculating the first order derivative of current perpendicular-to vector coordinates a vector signal is obtained:

$$\Delta_d \vec{I}^{\perp}_{n:k} = \vec{I}^{\perp}_{n:k} - \vec{I}^{\perp}_{n-d:k} \approx f_t'(i_N(n)) \quad (5)$$

It carries on the information focused on changes of phase current signal disturbances in time, among which the nonlinear current component $i_N(t)$ introduced in (2) is the largest component.

As the computation process of a current perpendicular-to vector mixes the information on two different phase currents together it incorporates a natural redundancy of them into each one vector's coordinate. To bring it out a vector

$$\Delta^{\downarrow}\vec{I}^{\perp}_{n:k} = \begin{bmatrix} \vec{I}^{\perp}_{n:k}(y) - \vec{I}^{\perp}_{n:k}(z) \\ \vec{I}^{\perp}_{n:k}(z) - \vec{I}^{\perp}_{n:k}(x) \\ \vec{I}^{\perp}_{n:k}(x) - \vec{I}^{\perp}_{n:k}(y) \end{bmatrix} \approx f_t'(i_N(n)) \tag{6}$$

called a current perpendicular-to detail vector is obtained. It also carries the information focused on phase current signals' disturbances and like (5) is a function of the nonlinear current component $i_N(t)$ introduced in (2). Comparing the formulas (5) and (6) the current perpendicular-to detail vector (6) can be considered as a spatial derivative of a current perpendicular-to vector (4).

Combining together equations (5) and (6) a criterion quantity

$$C_{3D}(n) = \Delta_d \vec{I}^{\perp}_{n:k}(z) - \Delta d\vec{I}^{\perp}_{n:k}(y) \tag{7}$$

for detecting CT saturation is created. Criterion quantity signal vector's coordinates are shown in Figure 2c. Identifying high peaks and low lows allows for detecting when CT saturation starts and ends.

4. CT SATURATION DETECTION TECHNIQUE

The design of decision-making procedure for CT saturation detection depends on how signals being components of a criterion quantity vector (7) are computed. There are two possible ways.

The first one was presented in paragraph 3. It is easy but requires complicated decision-making system analysing all three components of a criterion quantity vector (7) simultaneously. It is not to be discussed in this paper.

The other one based on the slightly modified concept of the first one and allows for considering only one coordinate of (7). In this case one criterion quantity vector with three meaningful coordinates is replaced with three criterion quantity vectors with only one meaningful coordinate. These three individual criterion quantity vectors are defined each one for different phase current signal accompanied with two virtual sine waves in place of other two real phase signals. Such a rearrangement results in a very simple decision-making scheme which additionally is almost the same as the one applied for a reference method [7]:

$$C_{3D}(n) \geq TS(n) \ \& \ CT_{SAT} = NO \rightarrow CT_{SAT} := YES \tag{8}$$

$$C_{3D}(n) \geq TN(n) \ \& \ CT_{SAT} = YES \rightarrow CT_{SAT} := NO \tag{9}$$

if only self-adapting thresholds $TS(n)$ and $TN(n)$ in (8) – (9) are kept constant.

5. SIMULATION RESULTS

Simulation research of detecting distorted, due to CT saturation, secondary current signals was performed using CT model described in [2] and proved correct operation of proposed algorithm. The proposed algorithm correctly recognised and marked periods of secondary current collapse caused by occurrence of CT saturation phenomenon.

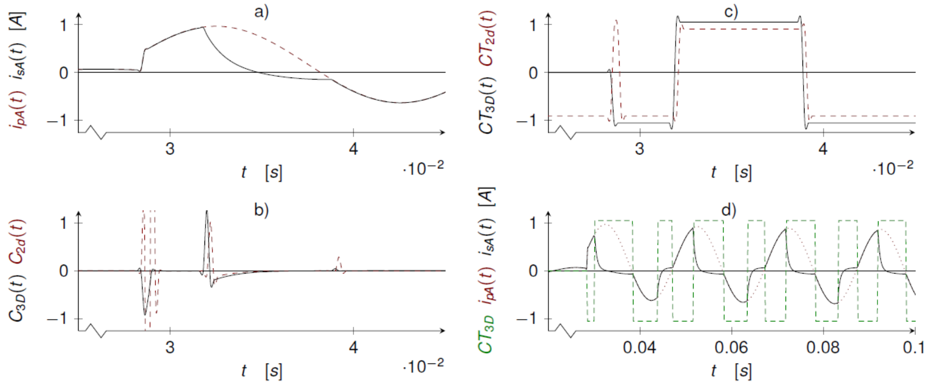

Fig. 2. Single phase fault: a) primary and secondary current signals; b) comparison of criterion signals; c) comparison of CT detection, d) Example of CT saturation detection: *CT* alarm, primary and secondary current signals

A designed criterion quantity signal's shape which is similar to the one obtained by calculating a reference measure [7], makes it possible to apply the same decision-making procedure and allowing for reliable comparing of the results obtained by both proposed and reference algorithms. Shapes of both criterion quantity signals received in case of a phase-to-ground fault, presented in Fig. 2a, are pictured in Fig. 2b. Both algorithms detected occurrences of CT saturation in a faulty phase current as shown in Figure 2c. The proposed 3D algorithm identifies the inception and final moments of CT saturation faster — without any delay— as this algorithm employs only computing of first order derivatives of current signals for the actual signal sample while the reference algorithm applying the second order derivative calculated with five-point formula lags by two sampling periods. Fig. 2d demonstrates another results of CT saturation detection achieved with the new proposed 3D method. It can be seen that all occurrences of CT saturations were correctly detected and signalled out.

6. CONCLUSIONS

A new algorithm for detecting CT saturation was presented in the paper. Simulation research confirmed high effectiveness of detecting distorted parts of secondary current signals by the new algorithm which identified them correctly and without any additional delay.

As the proposed algorithm is also based on signal's derivative calculation which results in its high sensitivity to any noises. It was found out that the decisive part of the algorithm should be reconsidered in dependence to applied model or real magnetising characteristic of a given current transformer type. Therefore further research is needed to improve the decision-making part of the algorithm by introducing some self-adapting properties to make it independent of magnetising characteristic modelling manner.

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