



A precise scheme for detection of current transformer saturation based on time frequency analysis



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ABSTRACT

Current Transformers (CTs) are prone to saturation due to large amplitude of fault current and existence of decaying Direct Current (DC) offset. Since the CT saturation leads to mal-operation of protective relays, detection and correction of saturated currents is one of the most important challenges in the power systems protection. In this paper, a new algorithm is presented for detection of CT saturation time interval by using the Improved S-Transform (IST). Simultaneously, IST can yield a complete visualization of signal in both time and frequency domains. An index based on instantaneous power of the CT secondary current is calculated using the IST output matrix. Then, the saturation region is estimated by determining the maximum and minimum values of the proposed index in the time domain. Comprehensive simulations are implemented using PSCAD/EMTDC software. Main parameters which have direct effect on the saturation levels are considered in simulation studies. As extremum points of the proposed index are determined for detection of saturation regions, the proposed method is not affected by CT parameters. The obtained results show that the proposed algorithm can precisely detect CT saturation time intervals even in noisy conditions.

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1. Introduction

Current Transformers (CTs) play an important role in the power systems protection. The saturation of CT core can lead to an undesirable effect on the operation of protective relays. Many parameters impact on the time to saturation of CTs such as CT burden, remnant flux, Direct Current (DC) offset and so on [1,2]. Considering all above mentioned parameters in CT dimensioning causes the core becomes extremely large and its production cost increases subsequently. According to the IEEE standard, CTs should be dimensioned so that the CT cores would not be saturated for nominal burden when DC-offset-free current of the primary side increases as much as 20 times of the rated current [1]. In addition, increase of substations Short Circuit Capacity (SCC) due to changes in the network configuration such as addition of new generation units. Therefore, the probability of CT saturation increases when interconnected power system expands. Thus, it is necessary to detect and correct the saturated current prior to passing through protective relays [2].

Many methods have been presented for detection of CT saturation. In some practical applications, harmonic contents of

CT secondary currents are measured for CT saturation detection [3]. Harmonic-based techniques need at least one cycle for detection of saturation while the start and end points of saturation region are not precisely determined.

Current signal derivative functions of different order have been used in CT saturation detection schemes [4–9]. The Combination of second derivative of CT secondary current and zero crossing technique has been used for improvement of CT saturation interval detection [6]. In [9], a method has been proposed based on the distance between consecutive points in the plans formed by the secondary current samples and their difference functions.

Wavelet Transform (WT) can detect the start and end points of saturation by analyzing the signals in time and frequency domains [10–12]. In the WT-based methods, current signals are decomposed into details and approximation levels in consecutive steps using specific filter named mother wavelet. The detail level containing high frequency contents can be used for detection of CT saturation [11]. The main drawback of both WT and derivative based methods are their sensitivity to noise. So, for practical applications, the signal should be passed through a low pass filter prior to applying these methods.

In some papers Artificial Neural Networks (ANNs) have been used for detection and correction of CT saturation [13–15]. Saturated and unsaturated secondary side currents of CTs are utilized

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Nomenclature

S	output matrix of IST
g	Gaussian window
f	frequency
t	time
x	time series
δ	adjustable factor
T	sampling interval
K	correction factor
T_{end}	the saturation end time
T_{min}	the time at which the index has the minimum value
T_{max}	the time at which the index has the maximum value

List of abbreviations

AC	Alternative Current
CT	Current Transformer
DC	Direct Current
FT	Fourier transform
IST	Improved S-Transform
SCC	Short Circuit Capacity
ST	S-transform
STFT	short time Fourier transform
WT	Wavelet Transform

to train ANNs. The main drawback of ANN-based approach is that the huge amount of training data set is needed to have correct estimation of different levels of CT saturation. Besides, some of these intelligent methods require huge computational burden due to their complicated networks structures [14,15].

In [16], the difference between estimated samples before and after of the window is the base of detection method. Using variable-length window as well as variable threshold value increases the complexity of this method and reduces the detection accuracy in noisy conditions.

A CT saturation detection method has also been proposed in [17] by estimation of the decaying DC using phasor-based computations. The performance of this method may degrade in Alternative Current (AC) saturation conditions. In some other techniques, mathematical morphology [18] and symmetrical components [19] have been used for detection of CT saturation.

In this method, a new algorithm based on Improved S-Transform (IST) [20,21] is proposed for detection of CT saturation. IST can yield a complete visualization of the signal in both time and frequency domains, simultaneously. The main drawback of the standard ST is that the Gaussian window with fixed width is used for analysis of all frequency contents.

To obtain more precise resolution in time-frequency domain, a variable width windows is introduced in IST [21]. So, more accurate analysis is obtained as compared to the WT that decomposed signals are determined in specified frequency range. Recently, ST has attracted more attention from transient analysis of signals especially in the field of pattern recognition methods [22,23].

In this study, at first, the current signals are analyzed using IST and subsequently, a new index is proposed based on instantaneous power of signal. By determining the extremum points of the calculated index, the start and end points of saturation region is specified. The accuracy of the proposed method is investigated for different saturation levels. To obtain accurate data sets, a part of Iranian power system is simulated using PSCAD/EMTDC software. In order to consider the transient behavior of CTs in different saturation conditions, the well-known Jiles-Atherton model is used in simulation studies. The proposed method can estimate time interval of different saturation levels with high detection accuracy. Also, obtained results justify the immunity of the proposed method in noisy conditions.

2. Improved S-Transform

Signal processing techniques are widely used to extract important and meaningful features of waveforms for particular application such as pattern recognition problems. The ST [20,21] can yield complete analysis of signals in both time and frequency

domains. The standard form of ST was initially introduced by Stockwell et al. in [20]. It imparts both properties of STFT and WT, simultaneously. It uses a Gaussian window whose width scales inversely, and whose height scales linearly, with the frequency. So, it provides multi resolution analysis while retaining the absolute phase of each frequency component of the signal. The original expression of continuous ST is as below [20]:

$$S(\tau, f) = \int_{-\infty}^{\infty} x(t)g(\tau - t)e^{-i2\pi ft} dt. \quad (1)$$

where $g(\tau - t)$ is the Gaussian window which is defined as:

$$g(t, f) = \frac{|f|}{\sqrt{2\pi}} e^{-\frac{t^2 f^2}{2}}$$

S denotes the output matrix of ST of x that is a continuous time series of time t ; frequency is shown by f ; and the quantity τ is a parameter which controls the position of the Gaussian window on the t -axis.

To obtain the calculation for discrete signals, $x[kT]$, $k = 0, 1, \dots, N-1$ is considered as a discrete time series, corresponding to $x(t)$, with a time sampling interval of T . The discrete version of the ST is given in [21] as follows:

$$S[jT, \frac{n}{NT}] = \sum_{m=0}^{N-1} X[\frac{m+n}{NT}] e^{-\frac{2\pi^2 m^2}{n^2}} e^{-\frac{i2\pi mn}{N}} \quad (2)$$

where j, m and $n = 0, 1, \dots, N-1$ and X denotes the discrete Fourier transform which is calculated as follows:

$$X[\frac{n}{NT}] = \frac{1}{N} \sum_{k=0}^{N-1} x[kT] e^{-\frac{i2\pi nk}{N}} \quad (3)$$

The main drawback of standard ST is that the Gaussian window has no parameter for adjustment of window width when frequency changes. This obstacle has been removed by introducing an adjustable parameter δ representing the number of periods of Fourier sinusoid contained within Gaussian window. So the corrected form of Gaussian window in time domain is given as below [21]:

$$g(t, f, \delta) = \frac{|f|}{\sqrt{2\pi}} e^{-\frac{t^2 f^2}{2\delta^2}} \quad (4)$$

And since the discrete form of IST is:

$$S[jT, \frac{n}{NT}] = \sum_{m=0}^{N-1} X[\frac{m+n}{NT}] e^{-\frac{2\pi^2 m^2 \delta^2}{n^2}} e^{-\frac{i2\pi mn}{N}} \quad (5)$$

The time resolution i.e. the start and end points of events and also frequency smearing are controlled by the adjustable factor δ . The too small values of δ yield a Gaussian window with very few

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