A CT SATURATION DETECTION ALGORITHM
BASED ON THE ANALYSIS OF THE SATURATED CURRENT
USING WAVELET TRANSFORMATION

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ABSTRACT
In this paper, distorted current relaying signals due to the CT saturation are analyzed with WT (Wavelet Transformation). Daubechies 2 is used as the mother wavelet. The output level (detail) of multi-level filter banks and the sampling frequency are also analyzed. The first output level of the multi-level filter banks for the output level (detail) and the 3,840Hz of the sampling frequency are adopted. A series of test results show that the proposed algorithm detects the saturated region accurately under various faults and CT conditions of a C800 CT model.

KEY WORDS
CT Saturation, Wavelet Transformation, Filter Banks, Mother Wavelet

1. Introduction
The relay collects current signals through a CT. The CT is consisted of an iron core. When magnetic flux increases above the saturation point, the nonlinear characteristic, CT saturation is occurred [1]. Since the CT saturation condition, current signal is distorted so that problems are caused in all the equipment that uses CT for input signal. Especially, the protective relaying algorithm which calculates the phasor to detect a fault by using voltage and current signals can be affected. CT saturation may cause malfunction or delay the operation of the protective relay. Several documents have been published on CT saturation detection. The CT saturation is detected by the modal transformation in [2]. In this paper, that method requires a prerequisite with only one frequency component. However, there is not only one frequency component of the current measured from the power system. In [3], an algorithm that uses a third-order differential method to distinguish a saturation point has been proposed, but the results of this algorithm cannot detect CT saturation when a fault phase angle of more than 180° occurs. In [4-9], the algorithms detect the saturation instants using the discrete wavelet transformation. However, there is no reason why to adopt such mother wavelets, sampling frequencies, and the output levels of the multi-level filter banks in each paper, respectively.

Distorted current relaying signals due to the CT saturation are analyzed with wavelet transformation in this paper. Daubechies 2 is used as the mother wavelet. The output level (detail) of multi-level filter banks and the sampling frequency are analyzed for the accurate detection of the instants of the saturation beginning and the saturation end. To extract the fine peak feature from the output of the filter banks, the dominant frequency bands of each detail level of the filter banks are also analyzed. A series of test results show that the proposed algorithm which is determined from the aforementioned analysis is suitable to detect the saturated region accurately under various faults and CT conditions of a C800 CT model.

2. Proposed Algorithm
2.1 Wavelet Transformation
Applying a frequency-based analysis method in an attempt to isolate the transient components of a signal is useful to identify a particular phenomenon producing the transients. The signals associated with transients are typically non-periodic and contain high frequency oscillations superimposed on the fundamental frequency signals. There are a number of transformations that can be applied to obtain requisite information. One of the most of that method is the FT (Fourier Transformation). However, the FT is not suited to analyze non-stationary signal which contains abrupt change, beginnings and ends of events.

The wavelet transformation is the solution to overcome the shortcomings of FT. The window is shifted along the signal and calculates the coefficient at different resolutions. Then, this process is repeated with a slightly shorter (or longer) window. The result will be a collection of time-frequency representations of the signal, all with different resolutions. The continuous-wavelet transformation (CWT) of a signal f (t) with respect to the mother wavelet φ(t) is given below.

\[
\text{CWT}(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \varphi \left( \frac{t-b}{a} \right) dt
\] (1)

Where a and b are continuously varying scaling and translation parameters, respectively. Thus, the one dimensional (1-D) time-domain signal f (t) is mapped to a two-dimensional (2-D) function space across scale (a) and translation (b) by the CWT. The transformation coefficient CWT (a, b) represents how well the original signal f (t) matches the scaled and translated mother wavelet.
One of the well-known advantages of the wavelet function is one of the most effective tools for analyzing the singularity of the signal due to an error or switching event in a general power system because it is an advantageous localized characteristic of the frequency domain and the time domain [10-12]. In this paper, a CT saturation detection algorithm based on the analysis of the saturated current using WT is proposed.

2.2 DWT Implementing With Filter Banks

Successive approximation is decomposed in order to repeat the decomposition process. Thus, signal can be decomposed into various low-resolution components. This is called a multilevel filter banks. As a result, DWT can be easily implemented as a multilevel filter bank.

![Structure of the general multi-level filter banks](image)

A multi-level filter banks is a set of filters. Figure 1 shows the structure of the general multi-level filter banks. In the decomposition process, H(n) is a high pass filter and L(n) is a low pass filter, respectively. Both of them are identified by the mother wavelet. Those filters separate the input signal into different frequency bands. Then the output current of the H(n) is entered into H'(n). H'(n) is a high pass filter for reconstruction.

![Figure 1. Structure of the general multi-level filter banks](image)

2.3 Adoption of the Mother Wavelet

In many applications, because of the different requirements for mother wavelet function, the adoption of the mother wavelet should be carefully considered. CT saturation detection algorithm requires the ability of detecting abruptly changing instants, therefore adopting one kind of mother wavelet to realize that purpose is necessary. Daubechies wavelet has good orthogonality, so Daubechies wavelet can be used to decompose signal effectively. In the Daubechies wavelet group, the higher of the order of mother wavelet, the frequency domain performance is better. Data window size also has to be considered because of the time delay. The window size of the Daubechies2 wavelet is only 4, it is longer than Haar wavelet but it is the shortest than other wavelets and it is also very short to analyze the frequency of the signal compared to FT’s window size. Therefore, Daubechies2 is adopted to detect the CT saturation.

![Figure 2. Frequency spectrum of the saturated current](image)

2.4 Adoption of the Sampling Frequency and the Output Level of Multi-Level Filter Banks

Each output level (detail) of the multi-level filter banks has dominant frequency bands, respectively. Thus, the frequency spectrum of a saturated current is analyzed to adopt the suitable output level (detail) of multi-level filter banks. Since it is normally very difficult to detect the CT saturation period when the CT is slightly saturated, the frequency spectrum in that case should be analyzed. Figure 2 shows the frequency spectrum of the saturated current when an A-phase-to-ground fault occurs at 0.9[PU] (27[km]) from S bus in the model system as shown in Figure 4. Fault phase angle is 0° and the remanent flux is 80%. In Figure 2, the 20th to 40th harmonics appear to have adequate information to detect CT saturation because each magnitude is higher than the other. The 25th harmonic is most dominant except fundamental frequency and low order harmonics which are close to the fundamental frequency.

![Frequency spectrum of the saturated current](image)

Table 1 shows the corresponding dominant frequency bands according to the output levels (detail) of multi-level filter banks. So that the first output level (detail) is adopted to extract dominant frequency band to detect the CT saturation. The 2nd order Butterworth low pass filter is added to the output of H’(n) of the filter banks to remove the other harmonics higher than 25th harmonic. The pass band cut-off frequency of 2nd order Butterworth low pass filter is 1,500[Hz] with the gain of 1.

If the output level (detail) of multi-level filter banks is too low, the coefficient of that level is easy to be affected by noise but if it is too high, changing characteristics of a signal are not obvious and even disappeared. Normally, with the higher sampling frequency, the features at the signal changing instants are more obvious. If the sampling frequency is too low, the sampled signal cannot have high frequency components. Thus, the WT cannot reflect its changing characteristics for a fault and
the CT saturation instants. The corresponding dominant frequency band of the each output level of multi-level filter banks depend on the sampling frequency. Based on the wavelet transformation frequency dividing characteristics, especially considering the 25th harmonic, 3,840[Hz] sampling frequency is adopted according to Table 1.

2.5 The Flow Chart of the Proposed Algorithm

![Flow chart of the proposed algorithm](image)

Figure 3. Flow chart of the proposed algorithm

Figure 3 shows the flow chart of the proposed algorithm from this paper. L(n) and H(n), those filters separate the input signal into different frequency bands. Then the output current of the H(n) is entered into H'(n). H'(n) is a high pass filter for reconstruction. The output current of the decomposition process is already down sampled in that process. That’s why it has to enter into the reconstruction process. The beginning and end instants of the CT saturation periods are detected by the output current of H'(n). To improve the performance of the proposed algorithm for the beginning and end instants of the saturation periods, the output current of the H'(n) in the reconstruction process of the filter banks is entered into a 2nd order Butterworth low pass filter.

2.6 Criteria for CT Saturation Detection

Three criteria are used for this algorithm. One of them is adopted to detect the instant of fault occurrence and other two criteria are adopted to detect the beginning and end instants of saturation periods. The CT saturation instants are detected after detecting the fault instant. The criterion value for detecting the instant of the fault occurrence can be calculated as below.

$$\text{Th}_{\text{fault}} = 0.0014215 \times I_{f \text{ min}} \quad (2)$$

Where the $\text{Th}_{\text{fault}}$ is the criterion value to detect fault instant. The scale adjustment constant, 0.0014215, is the total gain. It can be obtained as a result when the fundamental frequency component is passed through the low pass filter (for anti-aliasing), DWT process (Implemented with filter banks) and 2nd order Butterworth low pass filter in sequence. $I_{f \text{ min}}$ is the expected minimum fault current in the power system. If the instant of the fault occurrence is detected, the peak value of the output current of the 2nd order Butterworth low-pass filter is adopted as the criterion value of saturation detection at the instant of the fault. The peak value of the output current of the 2nd order Butterworth low pass filter at the beginning of saturation is always larger than the peak value of the fault instant in all cases analyzed, so the peak value at the fault instant is used as the criterion to detect the beginning of saturation. After that, half of the criterion used to detect the beginning of saturation is adopted for detecting the end of saturation.

3. Case Study

Figure 4 shows the single line diagram of the model system (154[kV], 30[km] of simplify overhead transmission system) to evaluate the performance of the proposed CT saturation detection algorithm with the relaying signals of several faults. The simulated faults are the A-phase-to-ground faults at 0.1[PU] (3[km]), 0.5[PU] (15[km]) and 0.9[PU] (27[km]) from S bus with considering the fault phase angles. The sampling rate is 64samples per cycle i.e. the sampling frequency of the algorithm is 3,840[Hz]. The remanent flux of a core for CT is also considered from -80% to 80%. A resistive burden of 8.04[Ω] is connected to a C800 CT (1200:5).

![Single line diagram of the model system](image)

Figure 4. Single line diagram of the model system

In all the figure (a)’s below, the dotted black line is the scaled primary current and the solid red line is the distorted secondary current, respectively.

![Test results](image)

Figure 5. Test results (fault occurs at 0.1[PU] from S bus, 80% remanent flux and 0° fault phase angle)
Figure 5 shows the results when the fault occurs at 0.1[PU] from S bus. The kind of fault is an A-phase-to-ground fault. The fault phase angle is 0° and the remanent flux is 80%.

![Figure 5](image1.png)

Figure 6. Test results (fault occurs at 0.1[PU] from S bus, -80% remanent flux and 180° fault phase angle)

On the contrary, Figure 6 shows the results of the case of the 180° fault phase angle and -80% the remanent flux. Other fault conditions are same with Figure 5.

![Figure 6](image2.png)

Figure 7 shows the results when the fault occurs at 0.9[PU] from S bus. The kind of fault is an A-phase-to-ground fault. The fault phase angle is 0° and the remanent flux is 80%. When the fault is occurred far from relaying point, its current is smaller than the fault that occurred closed from relaying point. Therefore, the magnitude of output current of 2nd order Butterworth low pass filter is also small. However, the proposed CT saturation detection algorithm can detect the CT saturation properly well when the CT saturation is slight as shown in Figure 7.

![Figure 7](image3.png)

Figure 8 shows the results when the fault occurs at 0.9[PU] from S bus. The kind of fault is an A-phase-to-ground fault. The fault phase angle is 0° and the remanent flux is -80%. In the Figure 8(c), after the peak of fault instant, there is no peak higher so that there is not any signal on the figure 8(d).

![Figure 8](image4.png)

The proposed CT saturation algorithm can detect CT saturation and also does not work when the CT is not saturated. Thus, the proposed algorithm can be said that is designed appropriately.

4. Conclusion

Distorted current relaying signals due to the CT saturation are analyzed with wavelet transformation in this paper. The DWT implementing with multi-level filter
banks is used to detect the instants of the fault occurrence and all saturation periods. The Daubechies2 wavelet is used as the mother wavelet in the proposed CT saturation detection algorithm. The output level (detail) of multi-level filter banks and the sampling frequency are considered for the accurate detection of instants of the beginning and end instants of CT saturation. The first level of the multi-level filter banks is adopted to extract the dominant frequency caused by CT saturation well. To improve detection performance at the beginning and the end of CT saturation, the output current of the H'(n) of the filter bank is filtered by a second-order Butterworth low-pass filter. The proposed algorithm shows the remanent flux of the CT core that determines the range of CT saturation and stable performance under various fault conditions. A chain of test simulations show that the proposed algorithm can detects the CT saturation appropriately.

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References