A novel approach to detect CT saturation using standalone CT measurements

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Abstract

The requirement for reliability and security in power system is increasing every passing day with the increase in complexity of the power system. To ensure highest level of reliability, protection relays have to receive correct measurements. One of the most important measurement that is needed by a relay as an input is current. However, current measurements received from current transformer (CT) can become inaccurate due to a phenomenon called CT saturation. This Master’s thesis objective is to build a novel algorithm for the protection relays to detect CT saturation. The algorithm should be based on a stand-alone method that is able to detect CT saturation within 1-2 ms for a sampling frequency of 4 kH.

This project comprises a study of the background about CTs and CT saturation. The related work done to detect CT saturation is also studied. Later, major existing methods used in the industry to deal with CT saturation are investigated in detail and modelled in Simulink. A novel method is proposed to exclusively detect CT saturation, keeping in mind the strict requirements, set in the beginning of the project. The proposed method is implemented in Simulink and HiDraw (in-house software in ABB to create C code for protection functions). Lastly, the proposed method and the existing methods are tested in Simulink for more than 1300 test cases based on different power system conditions, IEC-60255-187-1 and real current recordings from relays.

The results of the tests showed that the proposed method successfully detect CT saturation and was better than the existing methods in terms of speed and accuracy. It was concluded that the proposed method successfully detects CT saturation and hence, can be used with any protection function in a relay where there is a need to detect CT saturation.

Keywords: CT, CT saturation, Power system protection
Abstrakt

Kraven på tillförlitlighet och säkerhet i kraftsystem ökar varje dag i samband med allt högre komplexitet i kraftsystemet. För att uppnå den högsta nivån av tillförlitlighet behöver reläskydden ta emot korrekta mätvärden från kraftsystemet. Ett av de mest viktiga mätvärdena som behövs för ett reläskydd är ström. Emellertid, kan mätvärden från en strömtransformator bli felaktiga på grund av ett fenomen som kallas strömtransformatormättnings. Målet för detta examensarbete är att skapa en ny algoritm för reläskydd som detekterar strömtransformatormättnings. Algoritmen ska baseras på en fristående metod som klarar av att detektera strömtransformatormättnings inom 1-2 ms för en samplingsfrekvens på 4 kHz.


Resultatet av testerna visar att den nya föreslagna metoden framgångsrikt detekterar strömtransformatormättnings och gör det bättre än existerande metoder med avseende på snabbhet och noggrannhet. Det konstaterades att den nya föreslagna metoden framgångsrikt detekterar strömtransformatormättnings och därför kan användas för vilken reläskyddsfunktion som helst i ett reläskydd där behovet av att detektera strömtransformatormättnings finns.

Nyckelord: Strömtransformator, Strömtransformatormättnings, Reläskydd i kraftsystem
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Nomenclature

**ALF** Accuracy Limit Factor

**ANN** Artificial Neural Network

**ANSI** American National Standards Institute

**COMTRADE** Common format for Transient Data Exchange for power systems

**CT** Current Transformer

**DC** Direct Current

**DFT** Discrete Fourier Transformation

**FOCT** Fiber Optical Current Transformer

**IEC** International Electro-technical Commission

**IED** Intelligent Electronic Device

**IEEE** Institute of Electrical and Electronics Engineers

**P** Protective Current Transformer without Remanent flux limit

**PR** Protective Current Transformer with Remanent flux limit

**PSRC** Power System Relaying Committee

**p.u.** Per Unit

**PX** Protective Current Transformer of Low-Leakage Reactance without remanent flux limit

**SV** Sampled Value

**TPX** Protective Current Transformer for Transient Performance without remanent flux limit

**TPY** Protective Current Transformer for Transient Performance with remanent flux limit
TPZ Protective Current Transformer for Transient Performance with a specified secondary time-constant
Chapter 1

Introduction

1.1 Problem Definition

The importance of reliability and security provided by the protection system is ever increasing with the expansion and increase in the complexity of the power system. One of the most important component on which the functioning of a protection relay or an Intelligent Electronic Device (IED) is based on, are measurements from the current transformers (CT(s)). It is important that the measurements from the CT(s) are as accurate as possible since they are one of the most common input for any protection function. However, fault currents, much greater than the rated current of the CT and non-symmetrical faults often cause distortion in the secondary side of the CT because of CT saturation. Distorted secondary currents leads to inaccuracies in current measurement and as a result can cause maloperation of protective relays and devices that uses current from the CT as an input [1].

Several methods to detect CT saturation phenomena have been developed in the past and all of them have their own advantages and disadvantages. Majority of the methods that have been developed are usually based on the protection function they are associated with. However, limited work has been done on a standalone method to detect CT saturation exclusively using the CT measurements.

1.2 Objectives

The main objective of this Master’s thesis is to develop a novel method for CT saturation detection based on measurements taken exclusively from the affected current transformer (single source). This implies that an algorithm is developed which is reliable enough to detect CT saturation just using measurements from a single CT. Thus, the algorithm developed is independent of the type of protection function application.

Initially, several available methods to detect CT saturation are studied and compared
using available literature as well as Simulink. Once in-depth knowledge is acquired, as well as results are obtained from the existing methods, a new algorithm is formulated and implemented in Simulink and HiDraw (In house tool used for protection function development in ABB). Once implemented, the algorithm is tested and compared with the existing methods. Conclusions are drawn based on the observations and results of the tests and the comparison from the existing methods.

1.3 Outline of the Thesis

The Master’s thesis is broadly divided in six chapters including this chapter. Chapter 2 talks about the basics of CT and CT saturation. Chapter 2 also deals with the pre-study of the available literature in the domain of CT saturation and its detection algorithms. Thus, this chapter provides background knowledge of the topic as well as existing methodologies to solve the problem in hand. The next chapter describes the existing methods and studies them in detail. The methods selected in chapter 3 are based on the fact that they are stand alone in nature and/or have been used in the industry or are highly cited in academic literature. Later in chapter 4, the methodology used to build the new algorithm is described. In this chapter, implementation of the proposed novel algorithm is also illustrated. In chapter 5, different test scenarios used for verification and validation of the existing methods as well as the proposed method are described. In the same chapter, the results are also demonstrated and compared. In the end a discussion on future work is illustrated as well as a conclusion is drawn, which encompassed the results of the thesis.
Chapter 2

Background

In this chapter, theory about CTs has been explained. In addition, the phenomena of CT saturation is also elucidated. Later, the concept of power system protection is briefly described and the importance of CT measurements power system protection applications have been defined. Lastly, the related work done in the domain of CT saturation detection is analysed as well as some methods used to tackle CT saturation problem in the industry are explained.

2.1 Current Transformer

Current transformers are a type of transformers that are generally used to reduce a high level current of the power system to a low level current with a magnitude that can be handled by relays and instruments. Thus, CTs can be considered as a prime equipment used for measuring the currents of the line where it is connected.

2.1.1 Current Transformer Basics

For an ideal CT, the following equation is valid.

\[ \frac{I_p}{I_s} = \frac{N_s}{N_p} = n \]  

(2.1)

where

- \( I_p \) is the current flowing in the primary side of the CT
- \( I_s \) is the current flowing in the secondary side of the CT
- \( N_p \) is the number of turns in the primary side of the CT winding. In many cases, \( N_p \) is equal to 1 for CTs
- \( N_s \) is the number of turns in the secondary side of the CT winding.

The primary side of the CT is connected in series with the network to measure the current flowing in the network. This means the primary and the secondary currents are stiff and
are not affected by the secondary burden [2]. This also helps in using a current source while making an equivalent circuit of a current transformer. However, not all current passes from the primary side to the secondary side. Some of it is also consumed by the core of the CT. The core of the CT have active power and reactive power losses represented by the resistance of the core, $R_m$ and reactance of the core, $X_e$ respectively. Figure 2.1 shows a simple circuit diagram for a CT with core components included. In figure 2.1 $R'_p$ and $X'_p$ is the primary winding resistance and reactance respectively referred to the secondary side. Furthermore, $R_s$ and $X_s$ is the secondary winding resistance and reactance respectively. $R_b$ is the rated value of the secondary connected resistive burden.

![Figure 2.1: Simplified equivalent circuit of CT referred to the secondary side](image)

The current passing through the core of the CT is also known as exciting current, $I_e$. This current consists of both real and imaginary parts. Hence, errors are introduced and would appear both in the phase and amplitude of the measurements of the secondary current. The error in the amplitude of the secondary current is called ratio error while the error in the phase of the secondary current is known as phase error or phase displacement. These errors are quite small and are declared by the manufacturers of CT as well as standardized by IEEE and IEC as accuracy class [2].

Similar to any transformer, CTs also have magnetizing characteristics. The magnetization curve (B-H curve) showing a typical hysteresis loop is shown below in figure 2.2. In figure 2.2, $B$ is the flux density and $H$ is the magnetic field strength. In a symmetrical, periodic magnetized condition, when $H$ is zero, the flux is known as residual flux density [3].
When a fault is cleared, the primary current of CT is set to zero. However, some magnetic flux is not removed from the magnetic circuit. This residual magnetic flux is known as remanence. Remanent flux is equal to the residual flux density in a non-gapped core CT [2]. Remanence plays a vital role in influencing CTs level of saturation. This is also discussed in details in section 2.2.

2.1.2 Current Transformer during Transient

Transient condition or short interval response of the CT during fault is of prime importance especially for protection systems. A transmission system, without considering any load, is mostly inductive. When a short circuit occurs in a power system, the fault current, neglecting the shunt admittances, is given by [4][5]

$$i_p(t) = I_{\max}[\sin(\omega t + \beta - \theta) + \sin(\theta - \beta)e^{-\frac{R}{L}t}]$$  \hspace{1cm} (2.2)

where

$I_{\max}$ is the peak value of the sinusoidal steady-state fault current and is given by

$$I_{\max} = \frac{E_p}{\sqrt{R^2 + \omega^2 L^2}}$$  \hspace{1cm} (2.3)

$E_p$ is the peak value of the e.m.f

$R$ is the resistance of the system

$\omega$ is the system frequency in radians/sec
\( L \) is the system inductance

\( \beta \) is the inception angle of the supply voltage

\( \theta \) is the power factor angle of the system and is given by

\[
\theta = \tan^{-1} \left( \frac{\omega L}{R} \right)
\]  

(2.4)

Considering zero power factor i.e. \( \theta = \frac{\pi}{2} \), (2.2) can be written as

\[
i_p(t) = I_{\text{max}} [\cos(\omega t - \beta) - \cos(\beta)e^{-\frac{R}{L}t}]
\]

(2.5)

(2.5) consists of steady state part and transient part. The transient part is responsible for asymmetry in the primary waveform. The ratio \( \frac{L}{R} \) is the primary time constant, \( T_p \). It is defined as the time taken by the DC component to completely decay from the network. However, CT also have its own secondary inductance and burden that further effects the transient behavior of the current when seen from the secondary side of CT. According to [6], secondary loop time constant, \( T_s \) of a CT is calculated by dividing the sum of magnetizing and leakage inductances and the secondary loop resistance. Thus, \( T_s \) is given by the following equationc[5]

\[
T_s = \frac{L_e R_m + L_e (R_s + R_b)}{(R_s + R_b) R_m}
\]

(2.6)

where

\( L_e \) is the magnetizing inductance resulting in reactance, \( X_e \)

After knowing \( T_s \), the secondary current, \( i_s(t) \) reflected by a CT can be found. \( i_s(t) \) of a CT can be given by

\[
i_s(t) = Ae^{-\frac{t}{T_s}} + Be^{-\frac{t}{T_p}} + C \sin(\omega t - \beta - \varphi)
\]

(2.7)

The constants seen in (2.7) are as follow [5]:

\[
A = I_{\text{max}} \cos \beta \left( \frac{R_m}{R_m + (R_s + R_b)} \right) \left( - \frac{T_p}{T_s - T_p} + \sin \varphi \cos \varphi \tan \beta - \cos^2 \varphi \right)
\]

(2.8)

\[
B = I_{\text{max}} \cos \beta \left( \frac{R_m}{R_m + (R_s + R_b)} \right) \left( - \frac{T_s}{T_s - T_p} \right)
\]

(2.9)

\[
C = I_{\text{max}} \cos \beta \left( \frac{R_m}{R_m + (R_s + R_b)} \right) \left( - \omega T_s \frac{\cos \varphi}{\cos \beta} \right)
\]

(2.10)

where

\( \varphi \) is defined by the following

\[
\varphi = \tan^{-1}(\omega T_s)
\]

(2.11)
2.2 CT Saturation

A CT is said to be saturated if the primary current is not faithfully reproduced in the secondary side of the transformer. If Kirchoff’s current law is applied in figure 2.1, the following equation is obtained

\[ I_s = \frac{I_p}{n} - I_e \]  

(2.12)

During normal operations, \(I_e\) is only a small percentage of total current. However, saturation of the CT leads to high current passage from the core, thus, \(I_e\) increases. This reduces the secondary current as per (2.12).

During faults, the current magnitude may be much larger than the rated CT current. The fault current might also have substantial amount of DC components as well as there could be remanent flux in the CT [5]. All these factors contribute to CT saturation. Figure 2.3 shows a typical secondary current wave with saturation as recorded by an IED.

![Figure 2.3: Secondary side current recordings of CT from IED](image)

IEC 61869-2 defines some important terms associated with CT saturation. It is necessary
to define these terms for a better understanding of CT saturation. These terms are described below [6].

- **Saturation flux**, $\phi_{sat}$ is the maximum value of secondary linked flux in a current transformer, which corresponds to the magnetic saturation of the core material.

- **Remanent flux**, $\phi_r$ is the value of secondary linked flux which would remain in the core 3 min after the interruption of a magnetizing current of sufficient magnitude to induce saturation flux.

- **Remanence factor**, $K_R$ is the ratio of the remanent flux to the saturation flux, expressed as a percentage.

- **Accuracy Limit Factor** or ALF is the ratio of the value of primary current up to which the CT will comply with the requirements for composite errors to the rated primary current.

There are different reasons that leads to CT saturation as well as influence time to saturation. These reasons can be high remanent flux in the CT core, high primary current, high DC offset primary current, or high secondary burden [7].

As discussed in section 2.1, remanent flux is the residual flux left when CT magnetization is removed. CTs can be classified based on the remanent flux they hold. The classification is described below [2].

**High remanence type CT**: This type of CT has a magnetic core without any air gap and a remanent flux might remain for almost infinite time. In this type of transformers the remanence can be up to around 80% of the saturation flux. Class P, PX, TPX according to IEC standards and class C and K according to ANSI/IEEE standards are high remanence type CTs.

**Low remanence type CT**: This type of CT is made with a small air gap to reduce the remanence to a level that does not exceed 10% of the saturation flux. According to IEC 61869-2, Class TPY is a low remanence type CT.

**Non remanence type CT**: The non-remanence type CT has almost insignificant level of remanent flux. This category of CT has comparatively large air gaps in order to decrease the remanence to essentially zero level. In the same time, these air gaps minimize the impact of the DC-component from the primary fault current. A disadvantage of this type of CT is that the measuring accuracy in the non-saturated region of operation is low due to large air gaps. Class TPZ according to IEC is a non-remanence type CT.

Primary current magnitude as well as DC offset present in the primary current influences CT saturation to a great extend. Greater the magnitude of sinusoidal component of
primary current due to transients e.g. faults, faster is the increase in CT flux at the point of saturation. $T_p$ and $\beta$ determines the degree of offset in the primary current waveform. Higher the degree of offset, greater is the DC component contribution in the primary current. This leads to an increase in flux and results in faster CT saturation.

The burden of the CT is another important factor that is taken into consideration while studying CT saturation. In order to study the effect of burden, it is necessary to define the rated knee point voltage. It is the value of the sinusoidal voltage at rated frequency applied to the secondary terminal of the CT, all other terminals being open circuited, which, when increased by 10% causes the r.m.s value of the exciting current to increase by 50% \[6\]. Thus, basically after rated knee point voltage, the CT will saturate. Knee point voltage, $V_k$ can be calculated by (2.13)

$$V_k = K_x \times (R_s + R_b + R_{cable}) \times I_{sr}$$  

(2.13)

where

$I_{sr}$ is the rated secondary current of CT

$K_x$ is the dimensioning factor. It indicates the multiple of $I_{sr}$ including safety margin occurring under power system fault condition up-to which CT is expected to meet performance requirements.

$R_{cable}$ is the resistance of the cable connected to the secondary terminal of the CT.

From (2.13), it can be deduced that the value of rated knee point voltage is dependant on the burden of the CT. Thus, it can be clearly seen that value of the CT burden is of high importance when deciding CT saturation limit.

### 2.3 Power System Protection

The described CT behaviour in the previous sections of this chapter plays an important role in the overall power system protection performance. Power system protection is an important domain within power system that deals with the protection of power system from unforeseen events that creates instability and physical damage in the power system. A protection system should fulfil the requirements of reliability, selectivity, sensitivity and speed in order to successfully protect the power system. A protection system is said to be reliable if and only if it operates all the time whenever required. A protection system is said to be selective if it disconnects only the faulty part from healthy power system. Sensitivity of the power system is defined by how accurately it respond to the change in parameters within power system. Speed of the power system is defined by the time it takes to respond whenever it detects a fault \[8\].
These requirements of a protection system are fulfilled by creating different protection functions based on the equipment to be protected, application, current level etc. Some examples of these functions are transformer differential protection, bus-bar differential protection, line differential protection, distance protection, over-current protection etc. Almost all of these functions are implemented by IED’s that need current as input from a CT. Thus, accurate measurement from CT is of prime importance.

CTs are one of the most crucial equipments in a protection system. A CT reduces the current magnitude of the line to a level that is easily accepted by the electronic devices connected with it. The CT mainly performs three functions in power system: metering, measurement and relaying. Metering function is needed for energy metering within the power system. Measurement function is concerned with measuring current for monitoring purposes. As the name suggests, relaying function of a CT is more associated with the relays or IED’s. The secondary side current from a CT is used as an input to these relays. It is therefore, extremely important that the secondary current from the CT is a good representation of primary currents received by the CT. A saturated CT may compromise the reliability of power system protection since inaccurate values of the current are transferred from the secondary side to the IED. It is therefore required that CT saturation is detected quickly so that the IED can perform necessary adjustment or correction in the protection function.

To avoid saturation, CT’s can be over-sized. But this increases cost as well as the installation area requirement. Another method is to make the protection system operate fast enough so that it can trip or block even before the saturation has occurred. However, this does not solve the problem of false tripping specially in case of differential protection where tripping is not needed in case of external faults or blocking is not needed in case of internal faults. The CT may saturate due to the external faults in differential protection leading to false tripping of the power system. Lastly, Fiber Optical Current Transformer(FOCT) can replace the conventional CTs since, FOCT does not experience saturation phenomenon. However, FOCT technology is still developing and studies show that long term operation stability of FOCT is questionable [9]. Furthermore, majority of the industries still use conventional CTs for relaying. Hence, algorithms to detect CT saturation within an IED are developed. Work done to create algorithms for CT saturation detection is briefly described in the next section.

### 2.4 Related Work

A lot of researchers, both in the industry and academia, have tried to detect CT saturation using different kind of approaches. Some of these approaches have been patented as well. In practical applications, some relay manufacturers use harmonic content of the wave to
detect CT saturation. A disadvantage of this method is that it requires at least one cycle to saturation.[10]. The method is also prone to detection around inflection points.

In industry, majority of the algorithms to detect CT saturation is based on the protection function it is associated with. For example, differential-restraining curve trajectories in the operating region of differential current versus restrain current are used to detect CT saturation during external faults in differential protection in [11].

Another method introduced in [3] uses a cosine-peak adaptive filter with instantaneous overcurrent element. The method consist of a cosine filter with a peak detector. The transition from cosine filter to peak detector occurs when current distortion reaches above a set threshold level. Current distortion is found by comparing ratio of second harmonics and third harmonics to the fundamental component of current. An inherent disadvantage of the method is that the threshold value needs to be carefully defined for the accurate operation of the algorithm. [12][14] uses different current magnitudes including differential currents, incoming and outgoing current etc. to compensate for CT saturation in busbar differential protection. [13][15] uses the fact that current waveforms during CT saturation changes drastically when compared to normal operation. The algorithm compares the behaviour of the current wave with certain predefined constants and detect CT saturation.

Several different CT saturation detection methods have also been proposed in academic literature. In [16], a method to detect CT saturation using third difference of the current is used. An advantage of the method is that it is a stand alone method and does not require much information apart from the secondary current samples. Disadvantage of the method includes sensitivity to noise and the need of careful selection of threshold limit. [17] combines second difference calculation and zero crossing detection for finding the detection point of CT saturation. ANN have been used to detect and compensate CT saturation in [18]. [19] proposes a method to detect CT saturation using Euclidean distances. Different filtering approaches in combination with difference calculation method are used in [20][21] to fulfil CT saturation detection.

Handful of other methods based on creating a variable length window [22], using impedance in bus-bar differential protection [23], calculating symmetrical components of the current [24], finding time difference [25], utilizing morphological approach [26] have also been proposed.

2.5 Methods used in the industry

Different industrial players use different kind of techniques to handle CT saturation problem. In this section, major companies that manufacture relays are taken into consideration and the methods they use to deal with CT saturation are described briefly.
ABB uses different algorithms to handle CT saturation for different functions. In transformer differential protection and line differential protection, there is no dedicated algorithm that ABB use for CT saturation detection. Instead, these protection function rely on 2\textsuperscript{nd} and 5\textsuperscript{th} harmonics blocking, which is primarily used for blocking trip during inrush conditions, over-excitation conditions and load harmonics conditions. It is found that high 2\textsuperscript{nd} order and 5\textsuperscript{th} order harmonics are seen during CT saturation, allowing this method to block the trip during CT saturation [27][28]. For bus bar differential, ABB uses a unique and patented way to compensate the CT saturation effect by utilizing incoming, outgoing, restraint and differential currents [12]. Line distance protection uses another patented method based on the line current and its derivative. This method is stand-alone and utilizes the behaviour of current wave during saturation [15].

Siemens also utilizes different methods to manage CT saturation condition. For differential protection, Siemens uses the trajectory of the fault to decide whether the CT is saturated during external fault or if it is an internal fault. Siemens also utilizes blocking method during CT saturation using harmonics similar to ABB, however they use a threshold based on current magnitude, if CT saturation is below 1 cycle to further compensate for CT saturation [10][29].

SEL uses the so called cosine peak filter to calculate the magnitude of fundamental component of instantaneous current. An adaptive peak filter is also present to calculate the peak current. Comparison between distortion index and a threshold values defines whether current from cosine filter or peak current from the adaptive peak filter is passed as an input to the protection function. Distortion is calculated as a ratio of 2\textsuperscript{nd} harmonics to fundamental component and 5\textsuperscript{th} harmonics to fundamental component [3]. So basically, SEL also utilize 2\textsuperscript{nd} order and 5\textsuperscript{th} harmonics to compensate for CT saturation.

GE uses the trajectory of the differential versus restraint curve to identify CT saturation. During external faults, the restraint current increases quite rapidly, however the differential stays quite low during linear operation of the CTs. As soon as the CT saturates, the differential current starts increasing, at the same time restraint current remains the same or even reduced. This pattern is not seen during internal faults where both differential current and restraint current increase rapidly [11].
Chapter 3

Existing Methods

In this chapter, most commonly used methods both in industry and academia are described in details. The methods illustrated here only take secondary currents from the CT as input. Hence, these methods may be considered as stand alone methods to detect CT saturation which is the main reason for selecting these methods for detail analysis. These methods are also implemented in Simulink as a part of this thesis. The results of the Simulation can be found in chapter 5. The methods to detect CT saturation that are described in this chapter are as follow:

- Detector based on Third Difference Function
- Detector based on 2\textsuperscript{nd} and 5\textsuperscript{th} Harmonic Components
- Detector based on Current and its Derivative
- Detector based on Prediction Error and Instantaneous Algebraic Flux

3.1 Detector based on Third Difference Function

This method was first introduced in details in [16]. As seen from (2.7), the secondary current wave consists of two exponential terms and one sinusoidal term. The exponential terms arises due to the presence of $T_p$ and $T_s$ within the system. Since, an IED only process the discrete values, $i_s(t)$ can be represented in discrete version as shown in (3.1)

$$I_s[n] = Ae^{-\frac{nT}{T_p}} + Be^{-\frac{nT}{T_s}} + C\sin\left(\frac{2\pi}{N}n - \beta - \varphi\right)$$

(3.1)

where

$T$ is the sampling interval

$N$ is the number of samples per cycle

$n$ is the index of the sample
The first difference of $I_s[n]$ is, thus, given by
\[ \text{del1}[n] = I_s[n] - I_s[n-1] \]
\[ = A \left(1 - e^{\frac{T}{T_s}}\right)e^{-\frac{nT}{T_s}} + B \left(1 - e^{\frac{T}{T_p}}\right)e^{-\frac{nT}{T_p}} 
+ C \left(2\sin\frac{\pi}{N}\right)\sin\left(\frac{2\pi}{N}n - \beta - \varphi - \frac{\pi}{2}\right) \]  
(3.2)

In case the CT is not saturated, the time constants are large. This makes the exponential components in $\text{del1}[n]$ insignificant. The sinusoid component’s magnitude is dependant on $N$. Higher the value of $N$, lower would be the effect of sinusoidal component. Proceeding with the similar approach, the second difference, $\text{del2}[n]$ and the third difference, $\text{del3}[n]$ can be defined
\[ \text{del2}[n] = \text{del1}[n] - \text{del1}[n-1] \]  
(3.3)
\[ \text{del3}[n] = \text{del2}[n] - \text{del2}[n-1] \]  
(3.4)

The sinusoid component of $\text{del2}[n]$ is given by $2\sin\left(\frac{\pi}{N}\right)^2C$ and the sinusoid component of $\text{del3}[n]$ is given by $2\sin\left(\frac{\pi}{N}\right)^3C$. The addition of square term in $\text{del2}[n]$ and the addition of cube in $\text{del3}[n]$ reduces the sinusoid multiple times. The reduction in the sinusoidal part is more prominent in case of $\text{del3}[n]$.

During CT saturation, the magnetizing inductance is much smaller than that before saturation. Thus, $I_s[n]$ is distorted and has points of inflection. The values of $\text{del3}[n]$ at the next instant of the beginning/end of saturation are much larger than its value during normal operations. This feature of $\text{del3}[n]$ is used to detect CT saturation. Once $\text{del3}[n]$ is calculated, its value is compared with a threshold value, $Th$ given by the following equation
\[ Th = k\sqrt{2I_{f_{\text{max}}}} \left[2\sin\left(\frac{\pi}{N}\right)\right]^3 \]  
(3.5)
where

$I_{f_{\text{max}}}$ is the maximum expected fault current

$k$ is the margin factor acknowledging the effects of a low-pass filter and the sensitivity of the algorithm

The criteria for detecting CT saturation is given by the following equation
\[ |\text{del3}[n]| > Th \]  
(3.6)

To prevent the algorithm from malfunctioning due to its sensitivity to inflection points at the start and the end of saturation, the algorithm only starts if three successive current samples exceeds three times the rated secondary CT current. An overall flowchart of this method is shown below
3.2 Detector based on 2\textsuperscript{nd} and 5\textsuperscript{th} Harmonic Blocking

This method utilises the fact that CT secondary currents are rich in harmonic contents when the CT is saturated. Traditionally, this method is used to block the trip when harmonics are detected in case of transformer differential protection in the industry. However, this method also responds to situations when CT is saturated. In order to calculate the harmonic components, the currents received from the secondary side of the CT are send as an input to a DFT algorithm to abstract 2\textsuperscript{nd} and 5\textsuperscript{th} harmonic components before feeding the current to a detector logic. The entire algorithm is described in details in the following subsections.

3.2.1 Discrete Fourier Transform

The first step in this method is to separate fundamental component, second harmonic component and fifth harmonic component. This is done by calculating the DFT of CT secondary current. DFT converts time-based signal into frequency domain. Thus, harmonics of different order can then be easily separately.
The Fourier series for a signal, \( X(t) \) is given by the following equation [8]

\[
X(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t)
\]  

(3.7)

where

\( n \) describes the harmonic order for the signal

\( a_0, a_n \) and \( b_n \) are given by the following equations

\[
a_0 = \frac{1}{T} \int_{0}^{T} X(t) dt
\]

\[
a_n = \frac{2}{T} \int_{0}^{T} X(t) \cos(n\omega t) dt
\]

(3.8)

\[
b_n = \frac{2}{T} \int_{0}^{T} X(t) \sin(n\omega t) dt
\]

\( T \) is the time period of the signal. It is equal to \( \frac{1}{50} \text{sec} \) in case of a 50 Hz signal.

Furthermore, the amplitude and phase angle of \( n^{th} \) order harmonic is given by (3.9)

\[
|F_n| = \sqrt{a_n^2 + b_n^2}
\]

\[
\theta_n = \tan^{-1}\left(\frac{b_n}{a_n}\right)
\]

(3.9)

Since the IED works with discrete signals instead of continuous signals, (3.8) can be modified for discrete signal as [30]

\[
a_0 = \frac{1}{N} \sum_{k=1}^{N} X(k\Delta t)
\]

\[
a_n = \frac{2}{N} \sum_{k=1}^{N} X(k\Delta t) \cos(nwk\Delta t)
\]

(3.10)

\[
b_n = \frac{2}{N} \sum_{k=1}^{N} X(k\Delta t) \sin(nwk\Delta t)
\]

where

\( X(k\Delta t) \) is the discrete representation of \( X(t) \) in which \( k \) is the sample number and is a positive integer.

\( \Delta t \) is time difference between two consecutive samples. For a 4 kHz sampling frequency, \( \Delta t \) is 250 \( \mu \text{sec} \).

The signal in DFT is only processed for a defined number of samples at a time. It is known as a DFT window. The DFT window size is usually user defined based on the number of samples. Bigger the window slower is the processing speed of the DFT algorithm. Generally, the DFT window is kept equal to one full cycle of the wave. Thus, for a 4 kHz
sampling rate, the DFT window may include 80 samples in case of one cycle for 50 Hz frequency. The flowchart showing DFT algorithm is shown below.

**Figure 3.2:** Flowchart showing DFT algorithm [30]
3.2.2 Detection Algorithm

The detection algorithm is based on the magnitude of $2^{nd}$ and $5^{th}$ harmonics when compared to the magnitude of fundamental component of the signal. If a percentage of $2^{nd}$ harmonics or $5^{th}$ harmonics are above the fundamental component, CT saturation detection signal is set to True. The block diagram for the detection algorithm is shown in figure 3.3 below.

![Block diagram of detection algorithm using $2^{nd}$ and $5^{th}$ harmonics](image)

**Figure 3.3:** Block diagram of detection algorithm using $2^{nd}$ and $5^{th}$ harmonics

A threshold value, $k$ is compared with the fundamental component for the algorithm to activate detection. In practical application, the algorithm only starts once the differential current is more than the minimum set differential current based on the differential-restrain current characteristics. However, in this case since, only information available is the secondary current, a small percentage of the CT primary rated current is used as minimum current value to activate detection from the algorithm. The algorithm detects saturation
if the amplitude of 2\textsuperscript{nd} harmonics is more than some percentage of the amplitude of fundamental current (15\% in this case) or the amplitude of 5\textsuperscript{th} harmonics is more than some percentage of the amplitude of fundamental current (25\% in this case). These percentage threshold values are taken from best industrial practices. As soon as one of the detection condition is fulfilled, CT saturation is detected.

3.3 Detector based on Current and its Derivative

This is a patented method by ABB. An improved version of this method is extensively used in ABB’s line distance protection function to detect CT saturation. The method is based on secondary current behaviour. It exploits the fact that in case of saturation, the current decreases abruptly from a high magnitude to a low magnitude followed by a low rate of change in the magnitude. The algorithm uses three consecutive secondary current samples to detect this scenario as shown in Figure 3.4 below

![Current samples analyzed in derivative based algorithm to detect CT saturation](image)

\textbf{Figure 3.4:} Current samples analyzed in derivative based algorithm to detect CT saturation [15]

In order to successfully detect saturation, the following conditions are needed to be fulfilled.

\begin{align}
I_{peak} &\geq I_{min,sat} \quad (3.11) \\
I(t-2) - I(t-1) &\geq K_3 I_{peak} \quad (3.12) \\
I(t-1) - I(t) &\leq K_2 I_{peak} \quad (3.13) \\
I(t) &\leq K_1 I_{peak} \quad (3.14)
\end{align}

where

- $I_{peak}$ is the maximum value of secondary CT current after last zero crossing.
- $I_{min,sat}$ is a setting and is usually around 2 to 3 times the value of rated CT primary current, however its value can vary from 100-1000\% of rated CT primary current. It is to be noted that $I_{min,sat}$ is also multiplied with $\sqrt{2}$ to compare it with $I_{peak}$. 

$I(t-2), I(t-1)$ and $I(t)$ are three consecutive current samples at time sample $t-2$, $t-1$ and $t$ respectively.

$K_1, K_2$ and $K_3$ are constants defining the slope of the current wave.

Analysing these four equations, one can say that in order to detect CT saturation by this method [15]

- The current must be higher than or equal to $I_{\text{min sat}}$ since last zero crossing
- The difference between currents at time samples $t-2$ and $t-1$ must be higher than or equal to certain factor of $I_{\text{peak}}$ after zero crossing
- The difference between current at time samples, $t-1$ and $t$ must be lower than or equal to a certain factor of $I_{\text{peak}}$ after zero crossing
- The current at time sample, $t$ must be lower than or equal to a certain factor of $I_{\text{peak}}$ after zero crossing.

$I_{\text{peak}}$ can easily be calculated by comparing the samples and storing the maximum value among the samples in a loop. The flowchart of the algorithm to calculate $I_{\text{peak}}$ is illustrated below:

![Flowchart](image)

**Figure 3.5:** Current peak calculation algorithm

Zero crossing is an important part of this algorithm since $I_{\text{peak}}$ is reset after every zero crossing. Flowchart showing the implementation of zero crossing detection is shown in figure 3.6 below.
3.4 Detector based on Prediction Error and Instantaneous Algebraic Flux

This method is explained in [31] and has been patented by Areva. The method is based on associating two criteria for detecting CT saturation. The first criterion considers the difference between the measured secondary current value and predicted current value calculated based on a simple mathematical interpolation model. If the difference between the measured value and the interpolated value is more than a predetermined threshold, this criterion is satisfied. The second criterion takes into account the instantaneous algebraic flux. The criterion is satisfied if the instantaneous algebraic flux is more than a set positive threshold value of the flux or if the instantaneous algebraic flux is less than a set negative threshold value of the flux. Instantaneous algebraic flux is calculated by integrating the secondary current and multiplying the result by the secondary resistance of CT. The effect of remanent flux is also added in the measured flux to get the real value of flux.

3.4.1 Criterion 1

The first criterion for CT saturation detection is based on interpolating a SV using the previous two SVs. With an order of two, a SV, \( X_k \) at sample \( k \) would depend on SVs, \( X_{k-1} \) and \( X_{k-2} \) for samples \( k-1 \) and \( k-2 \) respectively and is given by the following equation:

\[
X_k = A_2X_{k-2} + A_1X_{k-1} \tag{3.15}
\]

where
\(A_1\) and \(A_2\) are fixed coefficients and are given by

\[
A_1 = 2\cos\left(2\pi \frac{T_0}{T_e}\right)
\]

\(A_2 = -1\)

where

\(T_e\) is the sampling time for the current samples

\(T_0\) is the time period for one cycle

Once \(X_k\) is calculated, it is compared with the measured value, \(X_{k_{\text{meas}}}\). During saturation, the current changes abruptly. This means that the result of the comparison would give high prediction error during the start of saturation. The prediction error, \(e(X_k)\) is thus, given by

\[
e(X_k) = X_{k_{\text{meas}}} - X_k
\]

Thus, during no saturation, \(e(X_k)\) is virtually zero or really close to zero and vice versa. The criterion is satisfied when \(e(X_k)\) exceeds a predefined threshold value. Thus, according to this criterion, CT saturation is detected if there is a sharp increase in the prediction error. However, sharp increase in the prediction error does not necessarily mean saturation of CT. There is sharp change in the current around inflection points especially during start and end of fault, which may be detected by this criterion. Furthermore, this method might not be reliable in the presence of DC component in secondary current, since the interpolation model used, is based on the sinusoidal nature of the current wave. Thus, this criterion is not 100% fool proof and requires support from another criterion to make it more reliable.

3.4.2 Criterion 2

The second criterion in this method is based on calculating the instantaneous magnetic flux, \(\phi_{\text{meas}}(t)\) established on the following equation

\[
\phi_{\text{meas}}(t) = R_s \int_0^t i_s(t)dt
\]

where

\(R_s\) is the secondary resistance of CT

Since, the analysis is based on SV, (3.18) can be rewritten as

\[
\phi_{\text{meas}}(k) = \sum_{k=1}^{N} \frac{(X_k + X_{k-1})T_e R_s}{2}
\]

It is also important to add the values of remanent flux in order to find the high and low extreme flux values. However, it is not possible to find the exact value of remanent flux.
at a sample. Thus, to achieve extra reliability, extreme value of high and low remanence is added to \( \phi_{\text{meas}} \) to get high and low extreme flux values. This is given by

\[
\phi_{\text{high}} = \phi_{\text{meas}} + \phi_{\text{rem}_\text{high}} \\
\phi_{\text{low}} = \phi_{\text{meas}} + \phi_{\text{rem}_\text{low}}
\]  

(3.20)

where

\( \phi_{\text{rem}_\text{high}} \) is the highest value of remanent flux possible.

\( \phi_{\text{rem}_\text{low}} \) is the lowest value of remanent flux possible.

A maximum value and a minimum value of threshold flux is pre-set in the algorithm. If \( \phi_{\text{rem}_\text{high}} \) is more than the maximum predefined value, detection signal is set to true from this criterion. Similarly, if \( \phi_{\text{rem}_\text{low}} \) is less than the minimum(negative) predefined value, detection signal is set to true from this criterion.

The algorithm also has a flux correction method in case, the criterion 1 is not satisfied and criterion 2 is satisfied. If \( \phi_{\text{rem}_\text{high}} \) is more than the maximum predefined value and criterion 1 is false, then a difference between the maximum predefined threshold flux and \( \phi_{\text{rem}_\text{high}} \) is subtracted from \( \phi_{\text{rem}_\text{high}} \). This bring down the flux level to maximum threshold level possible. Similarly, If \( \phi_{\text{rem}_\text{low}} \) is less than the minimum predefined threshold value and criterion 1 is false, then a difference between the minimum predefined threshold flux and \( \phi_{\text{rem}_\text{low}} \) is added to \( \phi_{\text{rem}_\text{low}} \). This bring down the flux level to minimum threshold level possible. and reduces the chances of false detection. A simplified yet effective implementation is done in Simulink for this algorithm and can be seen in the flowchart shown in figure 3.7 below.
Figure 3.7: Flowchart of detector based on Prediction Error and Instantaneous Algebraic Flux
Chapter 4

Proposed Method

4.1 Principle and algorithm

The objective of this chapter is to build a stand-alone (relies only on secondary current samples from a single CT) algorithm that can detect CT saturation within 1-2 ms with a 4 kHz sampling frequency. It is required that the method works for low / high AC saturation with high DC saturation or long term low CT saturation. Additionally, the method must work under low / high AC saturation situations for all three type of load conditions (Resistive, Inductive and Capacitive). Furthermore, the method should also work for different CT remanence conditions as well as different CTs types based on remanence level. Keeping in mind these requirements a novel method is proposed in this chapter, which is mainly build on the following three fundamental characteristics of CT during saturation condition.

- Saturation can only exist when the difference in the absolute values of the consecutive secondary CT current samples is negative.
- During saturation, the second order and the third order derivatives of the secondary current are higher (more negative or more positive) than they are during normal operations.
- Saturation can only exist when the difference in the consecutive absolute values of the crest of the secondary CT current is negative.

To make sure that CT saturation is detected accurately, adaptive thresholds are defined that are based on the system parameters. The method takes secondary current measurements scaled to primary side and primary rated current of the CT as inputs. The secondary current measurement are converted in per unit values based on these inputs before feeding this current to five different parallel criteria to create a reliable CT saturation detector. These five criteria are described below:

1. In the first criterion, the method calculates the difference in the consecutive crest values
of current, $I_{\text{crest}}^n$, in an adaptive way and compares it with a small negative percentage of crest current, $I_{\text{crest}}^n$. The crest value of the current at $n^{th}$ sample is the zenith value of the $n^{th}$ sample and some percentage of $I_{\text{crest}}^{n-1}$. If $I_{\text{crest}}^n$ is more negative than a small negative percentage of crest current, $Th_{\text{crest}}$, this criterion is satisfied and output, $flag_1$ from this criterion is set to 1.

\[ I_{\text{crest}}^n = I_{\text{crest}}^n - I_{\text{crest}}^{n-1} \]  
\[ I_{\text{crest}}^n < Th_{\text{crest}} \Rightarrow flag_1 = 1 \]  
\[ Th_{\text{crest}} = -c_1 I_{\text{crest}}^n \]  
\[ Th_{\text{crest\_min}} = -c_2 \]  

where

$c_1$ and $c_2$ are constants

$Th_{\text{crest\_min}}$ is the minimum value of $Th_{\text{crest}}$

$n$ is the index of the sample

2. In the second criterion, the first order derivative of the current, $I_s^n$ calculated using the absolute value of two consecutive samples of secondary current is compared with an adaptive threshold, $Th_{FO}$, which is based on system parameters. If $I_s^n$ is less than $Th_{FO}$, this criterion is satisfied and output, $flag_2$ from this criterion is set to 1.

\[ I_s^n = |I_s^n| - |I_s^{n-1}| \]  
\[ I_s^n < Th_{FO} \Rightarrow flag_2 = 1 \]  

where

$I_s^n$ is the secondary current sample at $n^{th}$ index

$I_s^{n-1}$ is the secondary current sample at $(n-1)^{th}$ index

3. In the third criterion, the second order derivative of the current, $I_s''^n$ based on the absolute value of the secondary current is compared with a threshold, $Th_{SO}$. If $I_s''^n$ is less than $Th_{SO}$, this criterion is satisfied and output, $flag_3$ from this criterion is set to 1.

\[ I_s''^n = |I_s^n| - |I_s^{n-1}| \]  
\[ I_s''^n < Th_{SO} \Rightarrow flag_3 = 1 \]  

4. In the fourth criterion, the third order derivative of the current, $I_{sd}'''^n$ found using the consecutive sample values of the secondary current is compared with an adaptive threshold, $Th_{TO}$. If the absolute value of third order current derivative, $|I_{sd}'''^n|$ is more than $Th_{TO}$, this criterion is satisfied and output, $flag_4$ from this criterion is set to 1.

\[ I_{sd}'''^n = I_{sd}^n - I_{sd}^{n-1} \]  

\[ I_{sd}'''^n < Th_{TO} \Rightarrow flag_4 = 1 \]
\[ I_{sd}^n = I_{sd}^n - I_{sd}^{n-1} \]  
(4.8)

\[ I_{sd}^{n''} = I_{sd}^{n'} - I_{sd}^{n''} \]  
(4.9)

\[ |I_{sd}^{n'''}| > Th_{TO} \Rightarrow flag_4 = 1 \]

5. To remove undesirable cases where CT saturation is not expected, a minimum current value is compared with the crest value of current, \( I_{\text{crest}}^n \). The criterion is only satisfied, \( flag_5 = 1 \) when \( I_{\text{crest}}^n \) is more than the minimum set limit of the current, \( k \). The minimum current value is usually a small percentage of the rated primary current of the CT.

\[ I_{\text{crest}}^n > k \]  
(4.10)

The steps of proposed solution are as below. Figure 4.1 shows the overall logic diagram to describe the proposed algorithm

1. Take the sample values of the secondary current scaled to the primary side.

2. Take the primary rated CT current.

3. Calculate the secondary current scaled to the primary side in per-unit values.

4. Calculate the crest current.

5. Calculate the difference in consecutive crest currents.

6. Calculate the first order current derivative based on absolute per-unit values of the current.

7. Calculate the second order current derivative based on absolute per-unit values of the current.

8. Calculate the third order current derivative based on per-unit values of the current.

9. Compare the results from step 4 and step 8 with different thresholds defined in the five criteria described in previous section. If all the five criteria described in the previous section are fulfilled, CT saturation is detected. Otherwise, the no detection signal is issued by the algorithm.
4.2 Implementation

The proposed method is implemented, first in Simulink and then in HiDraw. HiDraw is the tool used in ABB to generate C code for their application functions, which then can be easily introduced in an IED.

A subsystem is created in Simulink that act as a block inside which the CT saturation algorithm is implemented. The inputs for this subsystem are sample values of the secondary current scaled to primary side and the rated CT primary current. Other inputs required by the algorithm are system frequency and sampling frequency. For ease of building the model in Simulink, system frequency and sampling frequency are defined inside the algorithm whenever needed. The output of the Simulink model is a boolean which is true if saturation is detected.
CT Saturation Detector block shown in figure 4.2 consists of sub-systems that contains five criteria described above as well as the current crest calculator. A screen-shot of these block is shown in figure 4.3. It is interesting to see a unit delay after the AND gate of criterion 1, criterion 2 and criterion 3. The unit delay is added to synchronize the different binary outputs from the different criteria.

Figure 4.2: Simulink block created for the proposed algorithm

Figure 4.3: Internal Structure of the model implemented in Simulink
Chapter 5

Evaluation

This chapter describes the test cases used to evaluate the proposed method as well as the existing methods. At the same time the results and comparison of results of the different methods are also included in this chapter. Different CT saturation detection methods evaluated are based on the three different test case types as given below:

- Test Cases based on Simulink Model
- Test Cases based on IEC-60255-187-1
- Test Cases based on Real IED recordings

5.1 Test Cases based on Simulink Model

A simple 130-kV power system network is used to create different fault scenarios for creating different test cases for CT saturation detection. The network is shown below in figure 5.1

In addition to the power system model, a CT model is being used for generating secondary CT current to be used as the input for the algorithms. The CT model with the following parameters is used for generating secondary current.
Table 5.1: Parameters used for the CT model

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Burden Power</td>
<td>10 VA</td>
</tr>
<tr>
<td>Rated Current (Primary)</td>
<td>1000 A</td>
</tr>
<tr>
<td>Rated Current (Secondary)</td>
<td>1 A</td>
</tr>
<tr>
<td>ALF</td>
<td>20</td>
</tr>
<tr>
<td>Remanence flux</td>
<td>-0.75/0/0.75 p.u.</td>
</tr>
<tr>
<td>Nominal Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Power factor</td>
<td>1.00</td>
</tr>
</tbody>
</table>

This is a standard CT model used for testing purposes by ABB. Important parameters to calculate secondary current of the CT are primary current and magnetizing current. Primary current is available from the power system model. In order to find exciting current (considering $R_m = 0$), one needs flux and magnetizing inductance. The flux can be found by integrating voltage with time. General equations describing the CT model are shown below:

\[ I_s = \frac{I_p}{n} - I_e \]  \hspace{1cm} (5.1)

\[ i_e = \frac{\phi K_A(\phi)}{L_e} \]  \hspace{1cm} (5.2)

where

$\phi$ is the flux in the CT

$K_A$ is based on $\phi$ and is given by the following equation

\[ K_A(\phi) = a + b \left( \frac{\phi}{\phi_{sat}} \right)^n \]  \hspace{1cm} (5.3)

In eq. (5.3) typ. $a = 0.7$, $b = 0.8$, and $n = 14$

$\phi_{sat}$ is defined by ALF of the CT.

The sampling frequency is taken as 4 KHz for a nominal frequency of 50 Hz to run the tests. A total of $420 \times 3$ (for remanent flux of -0.75 p.u, 0 p.u, 0.75 p.u) test cases are used as functional tests to test the reliability and the performance of the algorithms. The batch of these test cases are generated for each remanent flux level, by varying the factors as seen in table 5.2 below:
### Table 5.2: Parameters to conduct functional tests

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault location</td>
<td>5 locations¹</td>
</tr>
<tr>
<td>Fault inception angle</td>
<td>-30°/-20°/0°/10°/15°/45°/60°/90°/120°</td>
</tr>
<tr>
<td>Fault Type</td>
<td>L1N/L1L2/L1L2L3N</td>
</tr>
<tr>
<td>Time Constant (ms)</td>
<td>30/50/70/150</td>
</tr>
<tr>
<td>Source Impedance</td>
<td>8 distinct values ¹</td>
</tr>
</tbody>
</table>

### 5.2 Test Cases based on IEC-60255-187-1

In these test cases, the algorithms are tested for stability during inrush conditions, stability during over-excitation conditions and stability during load harmonics based on IEC-60255-187-1. An algorithm is said to exhibit stability, if it does not detect any saturation under these test cases. The sampling frequency is taken as 4 kHz with a nominal frequency of 50 Hz to run these tests. More details about these tests can be found in the subsections below.

#### 5.2.1 Stability during inrush conditions

Stability during inrush condition is tested by generating a signal which has a similar wave shape as inrush currents. This test is mostly conducted to verify stability during inrush in transformer differential protection. The signal is generated using equations in [33]. A total of 12 cases are used for testing the algorithm based on the factor specifying the peak value of the injected inrush current, rated primary CT current and angular span of injected inrush current, α. Parameters for inrush condition test are given in table 5.3 below.

### Table 5.3: Parameters to test stability during inrush currents

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Value Factor</td>
<td>4/10</td>
</tr>
<tr>
<td>Rated Current</td>
<td>500 A/1000 A</td>
</tr>
<tr>
<td>α</td>
<td>60°/90°/120°</td>
</tr>
</tbody>
</table>

A typical inrush current wave as described in [33] is shown in figure 5.2 below.

¹See appendix for values
Figure 5.2: Power transformer inrush current waveform for a CT with 500 A rated primary current and a peak value factor of 10

5.2.2 Stability during over-excitation condition

Stability during over-excitation condition is tested by generating a signal which has a similar wave shape as over-excitation currents. The signals are generated using equations in [33] and are shown below in figure 5.3 and figure 5.4.
Figure 5.3: Power transformer over-excitation current waveforms injected from star winding for a CT with 500 A rated primary

Figure 5.4: Power transformer over-excitation current waveforms injected from delta winding for a CT with 1000 A rated primary

The two test cases have the following parameters as shown in table 5.4.
Table 5.4: Parameters to test stability during over-excitation condition

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Value factor</td>
<td>2</td>
</tr>
<tr>
<td>Rated Current</td>
<td>500 A (star)/1000 A (delta)</td>
</tr>
<tr>
<td>Winding Type</td>
<td>star/delta</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>22.5°</td>
</tr>
</tbody>
</table>

5.2.3 Stability during load harmonics

Stability during load harmonics condition is tested by generating a signal which act as a load current with harmonics superimposed on different levels. The signals are generated using equations in [33] and are shown below in figure 5.5 and figure 5.6. In figure 5.5, 5\(^{th}\) harmonic component, 7\(^{th}\) harmonic component and 9\(^{th}\) harmonic component are added to the fundamental component of the wave while in figure 5.6, 5\(^{th}\) harmonic component and 7\(^{th}\) harmonic component are added to the fundamental component of the wave.

Figure 5.5: Load current waveforms with superimposed harmonics injected on star side of a transformer for a CT with 1000 A rated primary
Figure 5.6: Load current waveforms with superimposed harmonics injected on delta side of a transformer for a CT with 1000 A rated primary

Twelve different cases are formulated based on the fundamental magnitude of current, rated primary CT current and transformer type.

Table 5.5: Parameters to test stability during load harmonics

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental Component of Current</td>
<td>0.2 p.u./0.4 p.u./0.8 p.u./1.0 p.u.</td>
</tr>
<tr>
<td>Rated Current</td>
<td>500 A (YN)/1000 A (yn0/d1)</td>
</tr>
<tr>
<td>Transformer Type</td>
<td>YNyn0/YNd1</td>
</tr>
</tbody>
</table>

5.3 Test Cases based on Real IED recordings

Apart from generating test data from Simulink for testing the algorithms, data recordings from real world IED’s are also used. The test cases mostly represents cases where the relay maloperated due to incorrect CT current measurements as a result of CT saturation. Another important thing to note is that these cases are tested at 1 kHz sampling frequency instead of 4 kHz, since the recordings are done at 1 kHz frequency. A total of 48 such test cases are analysed based on the secondary current scaled to the primary side and the primary rated current of the CT. A typical IED recording case with extremely low saturation is shown in figure 5.7 below.
Out of these 48 IED recordings, only 9 of them have CT saturation. The rest of the cases were IED recordings with disturbances present in the fundamental wave but no CT saturation. It is important to test these kind of current waves to verify the stability of the detection methods. An example of a current wave without CT saturation recorded by an IED is illustrated in figure 5.8 below.

**Figure 5.7:** Real IED recording of secondary current scaled to primary side with low CT saturation plotted using MATLAB
Figure 5.8: Real IED recording of secondary current scaled to primary side with no CT saturation plotted using MATLAB

The IED recordings are generally available in a standardized format known as the COMTRADE file format. These files format are standard format to store data related to transient power system disturbances. The COMTRADE file format has been standardized by PSRC of the IEEE Power and Energy society as C37.111. According to C37.111-1999, COMTRADE file format usually consisting of files with following file extensions *.cfg (configuration file), *hdr (header file), *.dat (data file), and *.inf (information file). Detail information about COMTRADE file format can be found in [34]. In order to accurately view the COMTRADE file, softwares such as PQDiffractor® or Omicron’s software TransView may be used. A screen from TransView is shown below in figure 5.9.
5.4 Results

The test cases are used to measure the reliability and the CT saturation detection time delay of different CT saturation detection methods. But before starting to analyse the results, it is imperative to understand what includes reliability and how is the average detection time delay and the worst case detection time delay is calculated. Any detection before the actual CT saturates or after the CT saturation is over, is considered to be a false detection and unreliable operation by the method. This also includes detection around the inflection points at the start and at the end of fault. Furthermore, the detection time delay is the time difference from the start of the first instance where a considerable drop in current is seen (a sign of CT saturation) and the time at which the first CT saturation detection pulse is received. The average detection time delay is calculated by dividing the sum of all the detection time delays with the number of test cases considered. The worst case detection time delay is the maximum detection time delay among all the test cases considered. For a better understanding, figure 5.10 shows the start time for CT saturation used for calculating the detection time delay.
Figure 5.10: The start time for CT saturation used for calculating the detection time delay

5.4.1 Detector based on Third Difference Function

In Simulink model test cases, the method was quite accurate. Although this method is prone to false detection around inflection points, especially during the start and the end of saturation, the algorithm performs well since it doesn’t detect anything if the current is less than three times the rated CT secondary current.
The method showed stability in case of inrush current, over-excitation condition and load harmonics. However, the method is quite inaccurate when it comes to real IED cases. It was not able to detect any saturation in cases where saturation exist. Nonetheless, the method didn’t detected any saturation, in case there was no saturation in the secondary current samples for real IED recordings.

5.4.2 Detector based on 2\textsuperscript{nd} and 5\textsuperscript{th} Harmonic Blocking

The results show that a detector based on 2\textsuperscript{nd} and 5\textsuperscript{th} harmonic blocking is quite sensitive and detection was seen even if there in no saturation in case of fault. This can be viewed in one of the Simulink model case in figure 5.12
Figure 5.12: Result of a Simulink model test case for CT saturation detection for detector based on 2\textsuperscript{nd} and 5\textsuperscript{th} harmonic blocking method

This method gives detection for all the test cases based on IEC-60255-187-1. This means, the algorithm would send a signal to block the protection function. This also means that the detector based on 2\textsuperscript{nd} and 5\textsuperscript{th} harmonic blocking does not have any stability in case of inrush, over-excitation and load harmonics condition. The results seen for real IED cases showed false detection for all cases either because there was detection even if there was no saturation or detection was seen even before saturation started.

5.4.3 Detector based on Current and its Derivative

The result from Simulink model showed good results for this method. However, detection around inflection points was seen for this method as well. Thus, reducing its reliability.
The method didn’t display stability for inrush and over-excitation conditions. However, the method was stable for load harmonics test cases. As far as real IED cases are concerned, this algorithm gave poor reliability, both when there was saturation and when there was no saturation.

5.4.4 Detector based on Prediction Error and Instantaneous Algebraic Flux

In Simulink model test cases, the method was fairly inaccurate, mostly because the detection was seen at the instance of the end of fault. Thus, the algorithm showed unreliable operation during large changes in the current or at points of inflection. This can be seen in figure 5.14 which shows a detector signal during an inflection point at the end of the fault from detector based on prediction error and instantaneous algebraic flux.
Figure 5.14: Simulink result of a test case for CT saturation detection for detector based on prediction error and instantaneous algebraic flux

The method didn’t demonstrate stability for inrush. However, the method exhibits stability for over-excitation conditions and load harmonics test cases. This method, however, was most accurate among in case of real IED cases among existing method. The detection time delay was also quite fast for real IED recordings.

5.4.5 Proposed Method

The result for testing in Simulink model showed that the proposed method gives fast and accurate saturation detection for all 1260 test cases.
Among the 26 cases that were conducted based on IEC-60255-187-1 for testing the stability during inrush condition, over-excitation condition and load harmonics condition, it was seen that the method was stable for all the test scenario and no detection signal was observed. For real IED recordings, among the 9 test cases where saturation was expected, the method detected saturation in 6 test cases. However, there were 3 cases where no saturation was detected. On observing these three cases, a very small CT saturation was found. It is to be noted that these cases are quite rare in real life. These real IED recordings used were mostly a result of costumer complaint as the relay malfunctioned due to CT saturation. Still, the proposed method showed much higher accuracy than prevailing methods to counter CT saturation problem. The average detection time delay for CT saturation for these cases was 1.5 ms. Furthermore, the method didn’t detected any saturation in the remaining 39 IED recordings where no detection was expected, thus showing high reliability.

### 5.5 Comparison between different methods

This section gives a statistical view of all the test case types which means that reliability, average detection time delay and worst case detection time delay are represented in numbers and compared for the different methods studied.
5.5.1 Test Cases based on Simulink Model

A total of 1260 test cases based on Simulink model are divided in three parts based on different remanent flux levels. In figure 5.16, the reliability of different methods is illustrated. It is seen that the proposed method shows 100% reliability followed by the 3rd difference method with a reliability of little more than 90 percent. A very low reliability is seen in the 2nd and 5th harmonic blocking is seen since it is quite sensitive to inflection points and gives a detection pulse at the start and the end of the fault.

![Reliability for different remanent flux levels](image)

Figure 5.16: Reliability of different methods for various remanent flux levels in percentage

Another important parameter used for comparing the different methods is the average detection time delay. The average detection time delay for different methods is shown below in table 5.6. The proposed method has an average detection time delay of slightly more than 0.5 ms for all three remanent flux levels. An average detection time delay of 0.8-0.9 ms is seen for the detector based on current and its derivative method. The detector based on 2nd and 5th harmonic blocking showed some variation in the average detection time delay with a maximum average detection time delay of around 2 ms. It is interesting to see in table 5.6 that the average detection time delay is negative for some methods. A negative detection time delay implies that a detection pulse was seen before the first inflection point in the current wave (start of CT saturation) due to CT saturation. A detailed explanation about the negative detection time delay for various methods can be found in the appendix.
Table 5.6: Average detection time delay in ms for different methods with different remanent flux

<table>
<thead>
<tr>
<th>Remanent flux (p.u.)</th>
<th>2nd and 5th harmonics blocking</th>
<th>3rd difference method</th>
<th>Current and its derivative method</th>
<th>Prediction error and flux method</th>
<th>Proposed Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.878&lt;sup&gt;2&lt;/sup&gt;</td>
<td>-0.216&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.817</td>
<td>-0.185&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.586</td>
</tr>
<tr>
<td>0.75</td>
<td>2.148</td>
<td>-0.331&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.915</td>
<td>-0.208&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.577</td>
</tr>
<tr>
<td>-0.75</td>
<td>1.812</td>
<td>-0.308&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.843</td>
<td>-0.067&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.546</td>
</tr>
</tbody>
</table>

Finally, the worst case detection time delay is compared for different methods. The worst case detection time delay for the different methods is shown in table 5.7. It can be seen in table 5.7 that the worst case detection time delay is comparable for all the methods with detection method based on prediction error and instantaneous algebraic flux having the lowest worst case detection time delay among all the methods and detector based on 2<sup>nd</sup> and 5<sup>th</sup> harmonic blocking having the highest worst case detection time delay among all the methods.

Table 5.7: Worst case detection time delay in ms for different methods with different remanent flux

<table>
<thead>
<tr>
<th>Remanent flux (p.u.)</th>
<th>2nd and 5th harmonics blocking</th>
<th>3rd difference method</th>
<th>Current and its derivative method</th>
<th>Prediction error and flux method</th>
<th>Proposed Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.75</td>
<td>1.00</td>
<td>0.25</td>
<td>1.00</td>
</tr>
<tr>
<td>0.75</td>
<td>3.25</td>
<td>1.00</td>
<td>1.25</td>
<td>0.25</td>
<td>1.00</td>
</tr>
<tr>
<td>-0.75</td>
<td>3.25</td>
<td>0.75</td>
<td>1.25</td>
<td>0.75</td>
<td>1.00</td>
</tr>
</tbody>
</table>

5.5.2 Test Cases based on IEC-60255-187-1

Test cases based on IEC-60255-187-1 compares the stability of the different method for inrush condition, over-excitation condition and load harmonic condition. As seen in figure 5.17, the detector based on 3<sup>rd</sup> difference method and the proposed method show 100% stability in all cases followed by the detector based on the prediction error and instantaneous algebraic flux method. As expected from 2<sup>nd</sup> and 5<sup>th</sup> harmonic blocking method, detection was seen during all the cases based on IEC-60255-187-1. Thus, this method cannot be exclusively used to detect CT saturation.

<sup>2</sup>See appendix for some example waveforms and detailed explanation for negative detection time delay
5.5.3 Test Cases based on Real IED recordings

The 48 test cases available were divided into two categories.

1. Test cases where CT is saturated. A total of 9 such cases were tested.

2. Test cases where CT is not saturated. A total of 38 such cases were tested.

Figure 5.18 below shows the reliability of various methods when the CT is saturated in the data recording by the IED. The proposed method comes out to be the most reliable among all the methods followed by the detector based on prediction error and instantaneous algebraic flux. The other three methods were not able to detect CT saturation for these test cases reliably.
Figure 5.18: Reliability of different methods for real IED recordings with CT saturation in percentage

Since, detector based on 2\textsuperscript{nd} and 5\textsuperscript{th} harmonic blocking, detector based on the third difference method and the detector based on current and its derivative does not show any reliable detection, it is not possible to provide an average detection time delay for these methods. The average detection time delay was the least for the detector based on prediction error and instantaneous algebraic flux. These results can be found in table 5.8 below.

Table 5.8: Average detection time delay in ms for different methods with real IED recordings

<table>
<thead>
<tr>
<th>2nd and 5th harmonics blocking</th>
<th>3rd difference method</th>
<th>Current and its derivative method</th>
<th>Prediction error and flux method</th>
<th>Proposed Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The worst case detection time delay was also the least in the detector based on prediction error and instantaneous algebraic flux followed by the proposed method with a time delay of 2 ms. The worst case detection time delay was not applicable on the other methods due to unreliable detection or no detection.
Table 5.9: Worst case detection time delay in ms for different methods with real IED recordings

<table>
<thead>
<tr>
<th>2nd and 5th harmonics blocking</th>
<th>3rd difference method</th>
<th>Current and its derivative method</th>
<th>Prediction error and flux method</th>
<th>Proposed Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

For the test cases where CT saturation was not present, only the reliability of the methods is compared. A method is considered reliable if it does not detection CT saturation in these test cases. The results of this analysis is found in figure 5.19 below. As seen in figure 5.19, both the detector based on the 3rd difference method and the proposed method shows 100% reliability. This is followed by the detector based on prediction error and instantaneous algebraic flux with a reliability of 82%. The least reliable method for exclusively detecting CT saturation is the detector based on 2nd and 5th harmonic blocking, since it gave detection signals for all the test cases.

![Reliability for real IED recordings without CT saturation](image)

Figure 5.19: Reliability of different methods for real IED recordings without CT saturation in percentage
Chapter 6

Conclusion and Discussion

6.1 Existing Methods

6.1.1 Detector based on Third Difference Function

Major disadvantage of this algorithm is that it is based on a fixed threshold which is dependant on the maximum fault current of the system. Defining the fault current beforehand for a CT is almost impossible in real life.

Another disadvantage of the method is that a huge change in the third difference magnitude is seen whenever there is a large change in current i.e. transient conditions. A solution given in [16] for this is to compare three consecutive samples with three times the rated current. However, this solution offers limited advantage in providing a reliable solution. Moreover, the sensitivity of the function is reduced because any current below three times the rated current is not checked for saturation. Although not very common, CT saturation can also occur at low currents. This algorithm does not detect CT saturation in such cases.

6.1.2 Detector based on 2nd and 5th Harmonic Blocking

Disadvantage of this method include maloperation that can occur during the start of the algorithm since the algorithm waits for 1 cycle before it starts giving correct results due to the DFT window.

Another major demerit of this method is that it gives a detection signal whenever there is a large change in the current i.e. during transient conditions even if there is no saturation, questioning the reliability of this method in case of exclusive CT saturation detection. This is a bigger problem especially during the start and the end of a fault.

Output from harmonic blocking is generally seen in differential function operations during inrush, over-excitation, CT saturation, presence of load harmonics as well as start and the end of the fault. While blocking is needed in case of inrush and over-excitation
phenomenon, it is not required in case of internal faults, as well as start and end of fault. If fault type (internal/external) is not accurately detected, the method can block trip during CT saturation with internal faults. This leads to a delayed trip from the protection function and in severe case can cause damage of the equipment and as well as can be dangerous to humans, if the fault is not cleared.

6.1.3 Detector based on Current and its Derivative

The disadvantage of the method is that the algorithm is dependant of some constants that does not change with the system. Thus, these constant values do not provide reliable functionality for all networks due to the stochastic nature of power system. Since the algorithm is completely dependant on the three constants for detection, the probability of the algorithm being too much sensitive or too little sensitive is large. The algorithm also suffers the disadvantage of detecting saturation whenever there is a large change in the current e.g. start or end of fault conditions i.e. around inflection points. Thus, giving false detection even if there is no saturation in the CT.

6.1.4 Detector based on Prediction Error and Instantaneous Algebraic Flux

The disadvantage of the method is that the algorithm is dependant of some constants that does not change with the system. This makes the algorithm less reliable. This also means that it can give detection signal around inflection points.

6.2 Proposed Method

It is concluded that the method is standalone i.e. it takes only secondary CT current samples scaled to primary CT current values and the rated CT current as the inputs. An inherent advantage of the method is the speed. The algorithm is independent of Fourier analysis (which needs a moving window with a certain size creating delay in operation), making it faster. The algorithm detects CT saturation within 2-3 samples after the start of CT saturation. Since the algorithm is dependent only on the secondary CT current values and the rated current, it is possible to use this method with any type of protection function. The method is independent of Remanent flux level making it more applicable.

As seen from the test results, the proposed method detects CT saturation with almost hundred percent accuracy. The method has shown higher speed as well as reliability than the existing methods. The algorithm is capable of detecting CT saturation with currents higher than 0.1 per unit. Thus, the algorithm more sensitivity than the existing methods. Furthermore, since the algorithm presented, needs less inputs the complexity of the algorithm is reduced. This can reduce the requirement in terms of computing power.
6.3 Future Work

Future work includes testing the proposed algorithm in the hardware. This can be done by introducing this algorithm in an IED and its behaviour can be studied with and without CT saturation. Once, verified in the IED, work can be done to create an algorithm to re-construct the secondary saturated current wave which activates when CT saturation is detected using the proposed method. The design of the algorithm is universal in nature and can be used with any protection function which needs CT saturation detection. Work can be done to find different ways to fully utilize this design by combining it with different protection algorithms. It is believed that the method described, can be united with over-current protection, differential protection or distance protection to make these protection functions more reliable.

In case of CT saturation, the secondary current does not replicate the primary current and is lower in magnitude than the actual current. Thus, differential current is seen, which can be much higher than the actual differential current value. This can lead to false operation of the differential element. Combining CT saturation detection algorithm with differential element and using actions such as increasing minimum differential current pick up level when CT saturation is detected can make differential protection more reliable. Furthermore, the method is independent of harmonic components. Thus, delayed trip of the restrained differential function seen due to the traditional use of second and fifth harmonic blocking may be avoided.

Another feature that the algorithm can added in the existing protection functions is to provide an alarm signal in case of CT saturation. This will help the customer to look into the system for possible issues that lead to CT saturation and would enable the customer to take necessary corrective actions.
Bibliography


Available Online at https://library.e.abb.com/public/9f8aeefd34b9484eb1983e4cf72e73d0/1MRK505303-UEN_B_en_Technical_manual__Busbar_protection_REB670_2.0__IEC.pdf


55


[27] ABB Line Differential protection RED670 2.1 Application manual, August 2016
Available Online at https://library.e.abb.com/public/68e986369ed84f7c8bd0aa27c4c25e36/1MRK505343-UEN_A_en_Application_manual_Line_differential_protection_RED670_2.1_IEC.pdf

[28] ABB Transformer protection RET670 2.1 Application manual, August 2016
Available Online at https://library.e.abb.com/public/01f85d6c2642456eabbd8bf719d37be6/1MRK504152-UEN_A_en_Application_manual_Transformer_protection RET670_2.1_IEC.pdf


[34] *IEC 60255-24 and IEEE Std C37.111 Measuring relays and protection equipment - Part 24: Common format for transient data exchange (COMTRADE) for power systems*, Ed. 2.0, April 2013
Appendix

Values used for test cases

1. The following values are used as a fault location for testing the algorithm in simulation.
   a. Next to source A
   b. After the source impedance, $Z_A$
   c. After the source impedance, $Z_B$
   d. $0.001 \times \text{line length}$ from the relay location
   e. $0.64 \times \text{line length}$ from the relay location

1. The following values are used as a source impedance for testing the algorithm in simulation.
   0.1264
   0.2528
   1.5128
   2.0028
   3.7528
   4.0056
   5.2656
   7.5056

2. In case of third difference method, the algorithm starts utilizing third difference as soon as the instantaneous value of the secondary current becomes more than three times the rated CT secondary current. Thus, even if the current is increasing, a detection pulse may be seen showing CT saturation. This is also due to the disadvantage that this method has a pre-defined threshold. A simulink case illustrating this phenomenon is shown in figure A.1 below.
Figure A.1: ²Negative detection time as seen for Third Difference Function method

²For prediction error and instantaneous algebraic flux method, the instantaneous flux increases with the increase in fault current. This can satisfy one of the two criterion, before even saturation starts. Furthermore, the prediction error found using the interpolation method, slowly increases with the current level. It can become higher than the pre-defined threshold just before the first instance of current drop and may satisfy this criterion. This, can lead to a detection signal from the algorithm before the first instance of abnormal current drop.
Figure A.2: Negative detection time as seen for Prediction Error and Instantaneous Algebraic Flux method

Getting a negative detection time in this method is more obvious than the other methods, since this method doesn’t depends on the behaviour of the current wave. As soon as there is sufficient level of either 2\textsuperscript{nd} or 5\textsuperscript{th} harmonic component, the method gives detection. In figure A.3, it can be seen that detection starts before current drop due to the presence of 2\textsuperscript{nd} or 5\textsuperscript{th} harmonic components.
Figure A.3: Negative detection time as seen for $2^{nd}$ and $5^{th}$ harmonic blocking method.