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# Mathematical morphology for discrimination between internal faults and inrush currents in power transformers

*This paper proposes a method for discrimination between internal faults and inrush currents in power transformers based on mathematical morphology (MM), a well-established theory in computer vision. Here, the feature extraction property of MM is used for the discrimination. It is shown that mathematical morphology (MM) is as efficient as that of wavelet technique in discriminating inrush and internal fault currents and enjoys much less computational complexity than wavelet technique. Extensive simulations have verified that this method is more reliable and simple for various load conditions and over excitation condition.*

***Keywords**:* Mathematical morphology, Internal fault, Inrush current, Decision logic



## 1. INTRODUCTION

Large power transformers are a class of very expensive and vital components of electric power systems. Since it is very important to minimize the frequency and duration of unwanted outages, there is a high demand imposed on power transformer protective relays. This includes the requirements of dependability associated with no mal-operations, security associated with no false tripping, and operating speed associated with short fault clearing time. Thus protection of large power transformers is a very challenging problem in power system relaying.

Discrimination between an internal fault and a magnetizing inrush current has long been recognized as a challenging power transformer protection problem. Since a magnetizing inrush current generally contains a large second harmonic component in comparison to an internal fault, conventional transformer protection systems are designed to restrain during inrush transient phenomenon by sensing this large second harmonic [1]. However, the second harmonic component may also be generated during internal faults in the power transformer. In certain cases, the magnitude of the second harmonic in an internal fault current can be close to or greater than that present in the magnetizing inrush current. Moreover, the second harmonic components in the magnetizing inrush currents tend to be relatively small in modern large power transformers because of improvements in the power transformer core material [2]. Consequently, the commonly employed conventional differential protection technique based on the second harmonic restraint, will thus have difficulty in distinguishing between an internal fault and an inrush current thereby threatening transformer stability. Alternatively, improved protection techniques for accurately and efficiently discriminating between internal faults and inrush currents have to be found.

The wavelet transform is a relatively new tool in the analysis of the power transformer transient phenomenon because of its ability to extract information from the transient signals simultaneously in both the time and frequency domain. A decision-making logic method for discrimination between internal faults and inrush currents in power transformers is given by Mao [3] based on wavelet transform. However, the wavelet transform (WT) is to be applied on the sampled data of the signal, which covers a certain period of time to reveal the periodic characteristics of the signal. Therefore, the extraction of disturbance features requires the use of a window of adequate length and a high sampling frequency to ensure

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that the detail is extracted. This increases the computational burden and reduces the attractiveness of the technique. This paper proposes a method to exploit the capability of MM in the efficient discrimination between internal fault and inrush currents in a power transformer in comparison with the WT method in [3]. The present method is found to have less computational complexity than WT based method. The same decision making logic as in [3] is used in the proposed method also.

Mathematical morphology (MM) is a set theory that is widely used in computer vision applications such as image processing, image segmentation. The principles of MM and its applications were first developed by Serra (1983) [4]. In contrast to Fourier transform and WT, MM is concerned with the shape of the signal in complete time domain rather than the frequency domain. MM only involves finding maxima/minima, or the addition/subtraction of signals, thus making calculations significantly faster. MM operators have been widely used in the area of image processing, machine vision and pattern recognition for their robustness in preserving the shape while suppressing noise. Recently MM is used for power disturbance detection by S. Smith [5] where the detection and classification of various faults are achieved.

This paper proposes a MM transform for distinguishing internal faults from inrush currents combined with the decision-making logic suggested in [3]. The MM transform is applied to extract the features of the differential current signals acquired through CTs secondary, which is a time domain signal. By quantifying the extracted features, a decision for distinguishing an internal fault from an inrush current can be accurately made.

## 2. Morphological transform

The original principle of MM stems from set theory. MM provides an algebraic formulation to apply neighborhood operations on signals. The main notion of MM is the interaction between the signal under analysis and a structuring element (SE), where the signal and SE are considered as sets of points. The SE, as a probe, slides through the signal as a moving window, inspects its interaction with the signal, and detects specific features in the neighborhood of every point in the signal. Erosion and dilation are two basic operators of MM, which are derived from the definitions of Minkowski's addition and subtraction. The basic morphological operations, namely erosion, dilation, opening, closing etc. are used for detecting, modifying, manipulating the features present in the signal based on their shapes. The shape and the size of SE play crucial roles in such type of processing and are therefore chosen according to the need and purpose of the associated application. In the following, we introduce some basic mathematical morphological operators of gray-scale morphology.

Let *F(m,n)* denote a gray-scale two-dimensional image and *B(s,t)* denote SE. Dilation of a gray level image *F(m,n)* by another structuring element *B(s,t)*, denoted by $F \oplus B$, is defined as

$$F \oplus B(m,n) = \max\{F(m-s,n-t) + B(s,t)\} \tag{1}$$

Erosion of gray level image *F(m,n)* by another structuring element *B(s,t)*, denoted by $F \Theta B$, is defined as

$$F \Theta B(m,n) = \min\{F(m+s,n+t) - B(s,t)\} \tag{2}$$

Opening and closing of gray-scale image *f(m,n)* by gray-scale SE *B(s,t)* are denoted respectively by

$$F \circ B = (F \Theta B) \oplus B \tag{3}$$

$$F \bullet B = (F \oplus B) \Theta B \tag{4}$$

Now, the concepts of MM for 1-D signals can be defined as follows.
If S and G represent the input set and the SE respectively, dilation can be developed as $S \oplus G$; its definition is:

$$\delta_G(S) = S \oplus G = \bigcup_{g \in G} (S + g) \tag{5}$$

And erosion can be developed as $S \Theta B$, defined as:

$$\varepsilon_G(S) = S \Theta G = \bigcap_{g \in G} (S - g) \tag{6}$$

A widely used morphological filter (MF) is the morphological mean filter (MMF), which is derived from the addition of dilation and erosion. The MMF is denoted by $\Psi_G$ :

$$\Psi_G = \frac{1}{2}(\delta_G(S) + \varepsilon_G(S)) \tag{7}$$

The mathematical morphological gradient (MMG) is defined as the subtraction of erosion from dilation. The MMG is denoted by $\rho_G$ .

$$\rho_G = \delta_G(S) - \varepsilon_G(S) \tag{8}$$

MMG can detect sudden changes of waveforms. This capability of MMG is used for extracting features of inrush and internal fault currents.

## 3. MM TRANSFORM AND FEATURE ANALYSIS OF TRANSFORMER TRANSIENT SIGNALS

In this paper, MM is used to develop an analyzer, which is then applied to both the inrush and internal fault currents to extract meaningful components from the signals. An extensive series of simulation studies have been carried out to obtain power transformer transient signals for subsequent analysis. The system selected to demonstrate the effectiveness of the proposed scheme is shown in Fig. 1. The system is a three phase and two winding 100 MVA, 220/33 KV, D1yg-connected power transformer. The simulations have been carried out using MATLAB software. In each simulation of the system considered in Fig. 1, the power transformer faults and system parameters are varied, including the fault types and fault positions. For brevity, only one of the three phases is considered for the analysis in this paper. The three phases are named as a-phase, b-phase and c-phase.

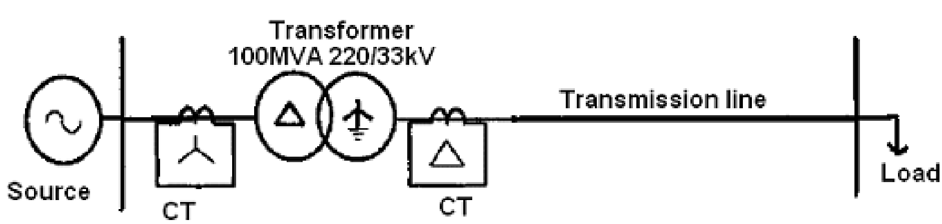


Fig. 1 Test System Considered

### 3.1 INRUSH CURRENTS

When the power transformer is energized on the primary side with the secondary side open-circuited, a transient magnetizing inrush current flows in the primary side. This current may reach instantaneous peaks of 6-8 times full-load current because of the extreme saturation of the iron-core in the power transformer. Fig. 2(a) shows typical magnetizing inrush current waveform in a-phase. As can be seen, the current waveforms are distorted quite significantly, gaps appear over the times of the inrush currents. At the edges of the gaps, the current magnitude changes from near zero to a significant value or from a significant value to near zero; this would be expected by virtue of the fact that sudden changes from one state to other different states produce little ripples, which very often are not visible from the fundamental frequency signals as apparent in Fig. 2(a). However, this can be discerned and clearly demonstrated by the MMG method. Fig. 2(b) and 2(c) show the result of application of WT and MMG respectively. The result of WT is also included to have a comparison with the method proposed in this paper.

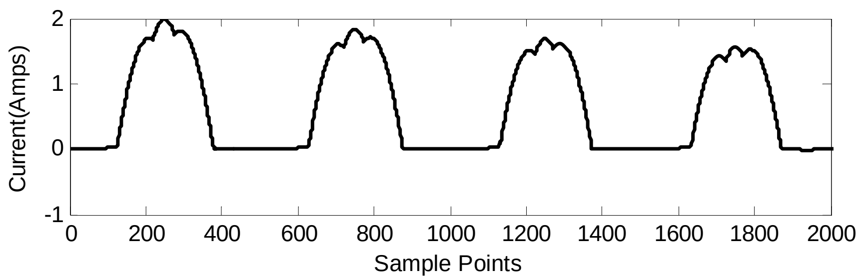


Fig. 2(a) inrush current waveform

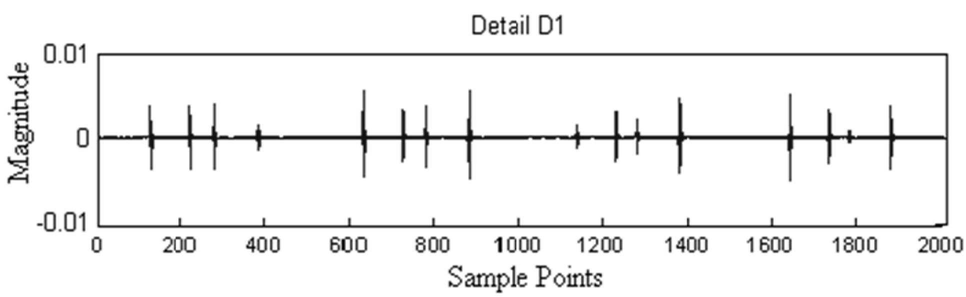


Fig. 2(b) D1 coefficient with wavelets

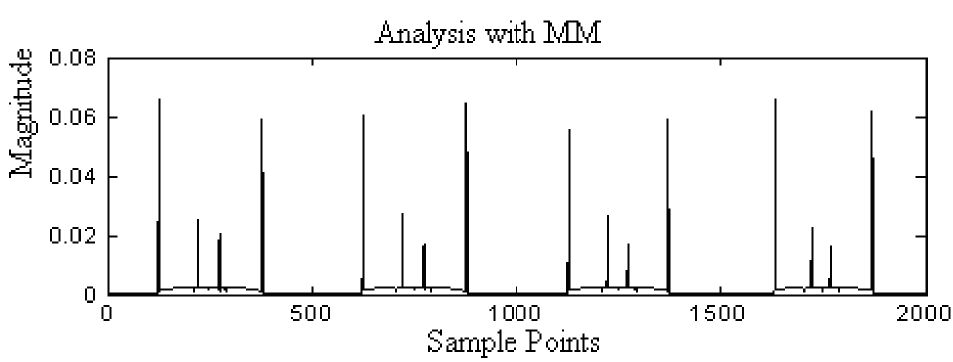


Fig. 2(c) MMG analysis

From Figs. 2(b) and 2(c), it can be seen that there are a number of sharp spikes during the period of the inrush current transient. From the foregoing analysis, a number of these arise at edges of gaps at which the inrush current suddenly changes from one state to other different states; others are produced because the primary windings of the power transformer are connected as delta, so that the a-phase differential current is in fact the difference between the a-phase magnetizing inrush current and b-phase magnetizing inrush current. This results in the nonsmooth points in the current waveforms, which in turn cause sharp spikes to appear in the MMG analysis with greater magnitudes than those with the WT analysis as shown in Fig. 2(c). The greater magnitudes resulting from MMG analysis help in better discrimination of inrush and internal fault currents in comparison with WT based method.

### 3.2 MM Transform of Internal Fault Current

Fig. 3(a) shows current signal for an internal fault that corresponds to differential currents through the CT secondary sides, under an a-b-c earth fault on the high voltage side of the power transformer considered in Fig. 1. It is apparent from Fig. 3(a) that there is a high frequency distortion in the current waveform. This is a direct consequence of the effects of the distributed inductance and capacitance of the transmission line. This can lead to a significant second harmonic in the internal fault, thereby posing difficulty in an accurate discrimination between magnetizing inrush and internal fault currents by the conventional protection method.

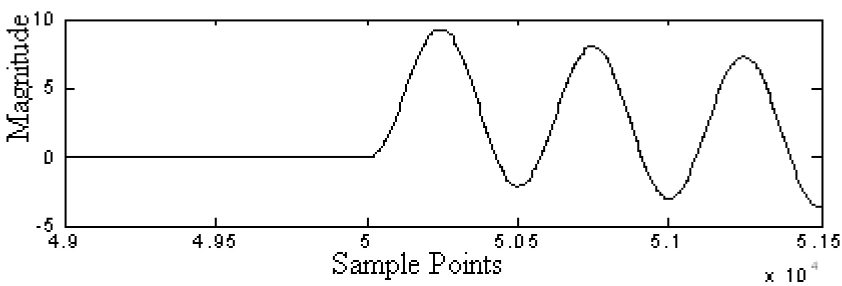


Fig 3(a) internal fault current waveform

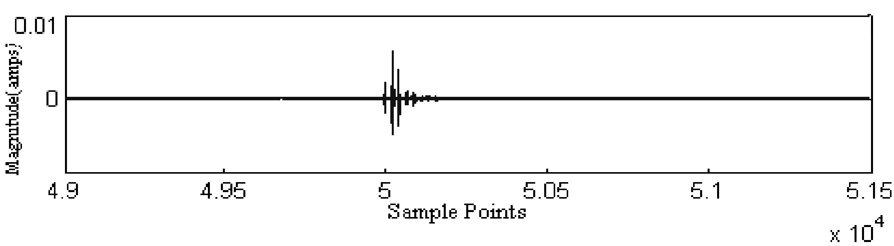


Fig. 3(b) WT analysis for internal fault current

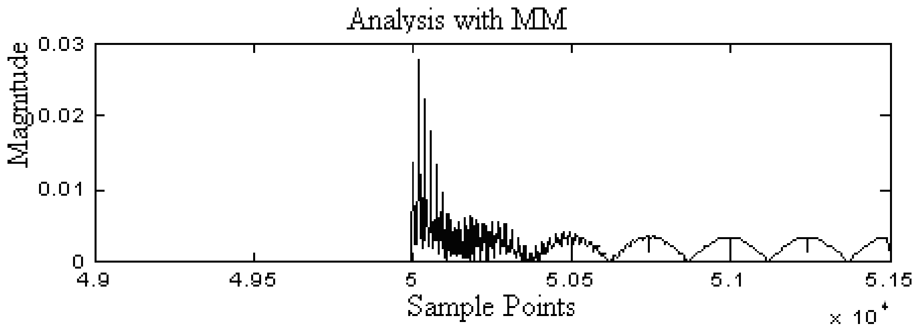


Fig. 3(c) MMG analysis for internal fault current

Magnetizing inrush currents and internal fault currents have the following different features. From Figs. 3(b) and 3(c), we can clearly see that there are several sharp spikes appearing from the inception time of the internal fault. It can also be seen from Figs. 3(b) and 3(c) that MMG method has spikes of greater magnitude than the spikes generated by WT method. The maximum value of the sharp spike appears at the beginning of the fault. However, in marked contrast to the inrush current cases shown in Figs. 2(b) and 2(c) these sharp spikes rapidly decay to near zero within one cycle, whereas those sharp spikes under inrush current cases suffer from little attenuation during the entire inrush Transient period, which can last from perhaps 10 cycles for Small transformers to 1 min for large units. It is apparent that this difference can be used as the key feature to effectively distinguish internal faults from inrush currents.

## 4. MM BASED DECISION-MAKING LOGIC METHOD

The decision-making logic used for the discrimination in the proposed method is adapted from [3]. The decision for discriminating between internal faults and inrush currents are made based on the extracted features that are quantified by a ratio in a certain MMG component, which is given by the following equations**.**

$$I_{a-ratio} = \frac{I^{k}_{a-MM,\max}}{I_{a-MM,\max}} \quad (9)$$

$$I_{b-ratio} = \frac{I^{k}_{b-MM,\max}}{I_{b-MM,\max}} \quad (10)$$

$$I_{c-ratio} = \frac{I^{k}_{c-MM,\max}}{I_{c-MM,\max}} \quad (11)$$

Where, $I_{a-MM,\max}$, $I_{b-MM,\max}$, $I_{c-MM,\max}$ respectively, represent the maximum peak values of a-phase, b-phase, c-phase of MM transform in the first window. $I^{k}_{a-MM,\max}$, $I^{k}_{b-MM,\max}$, $I^{k}_{c-MM,\max}$ represent the maximum peak values of a-phase, b-phase, c-phase of MM transform in the k$^{th}$ subsequent moving windows after the first window. The window length in this study is 1/2 cycle (10 ms in 50 Hz). The size of moving window is 1/4 cycle (5 ms in 50 Hz) and the sampling frequency is 25kHz.

### 4.1 DECISION MAKING LOGIC

The decision for distinguishing between internal faults and inrush currents is made in terms of the ratio change in $I_{a-ratio}$, $I_{b-ratio}$ and $I_{c-ratio}$ in each moving window, which is given as follows:

*If* $(I_{a-ratio} > \varepsilon \quad or \quad I_{b-ratio} > \varepsilon \quad or \quad I_{c-ratio} > \varepsilon)$ *then*

*"This is an inrush current"*

*else*

*"This is an internal fault"*

*end*

Where $\varepsilon$ represents the predefined threshold value.

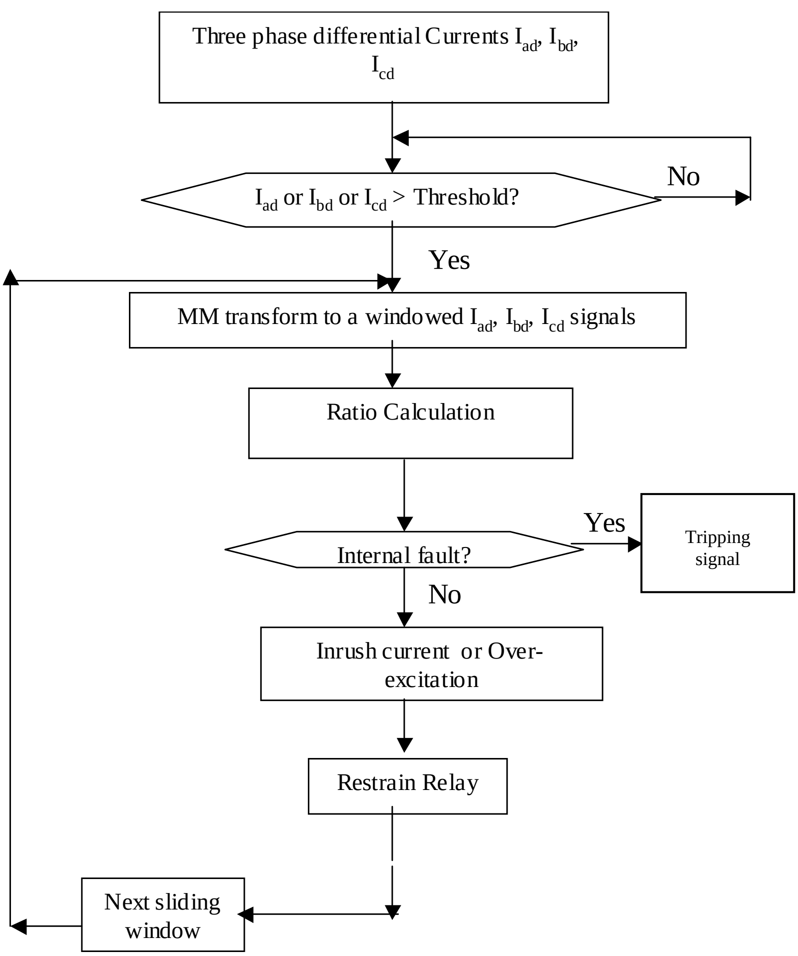


Fig. 4 Flow Chart of decision-making logic

Fig. 4 shows the flow chart for the decision-making logic used for the discrimination. In this paper, $\varepsilon$ is selected such that $\varepsilon$ is greater than 0.25, where as for WT method, $\varepsilon$ is chosen such that $\varepsilon$ is greater than 0.5. Hence, MMG method has a wide range of threshold values to choose than the wavelet transform method.

## 5. RESULTS

Extensive simulations have been done on the test system being considered for various load conditions and over excitation condition. The results obtained are as follows. For brevity, only waveforms for one of the three phases are shown here.

*Case (a): No load condition*

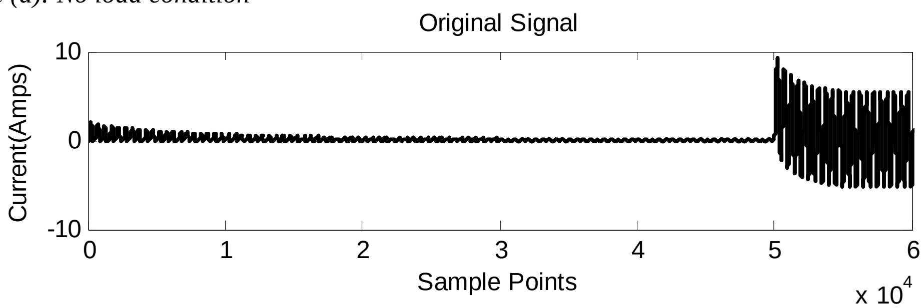


Fig. 5(a) Inrush and internal current waveform

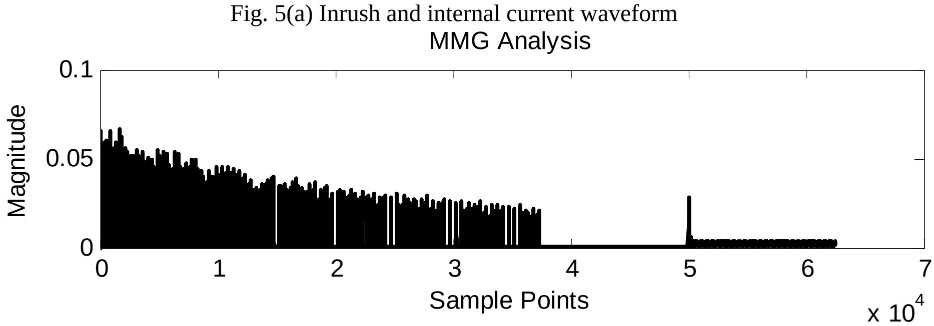


Fig. 5(b) MMG analysis for no load condition

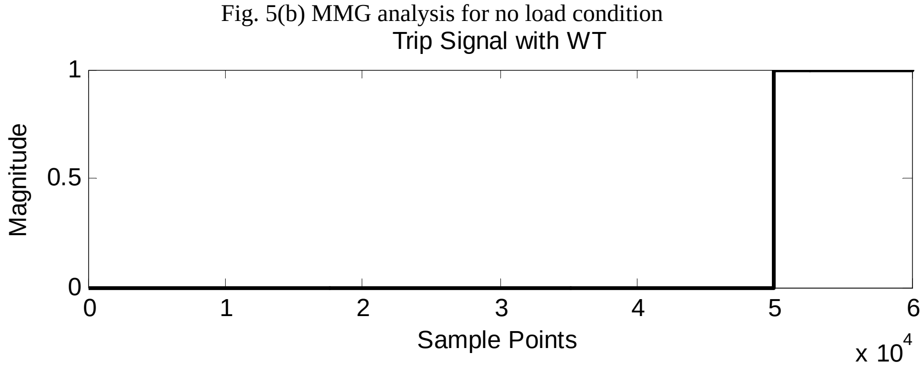


Fig. 5(c) Trip signal with MM

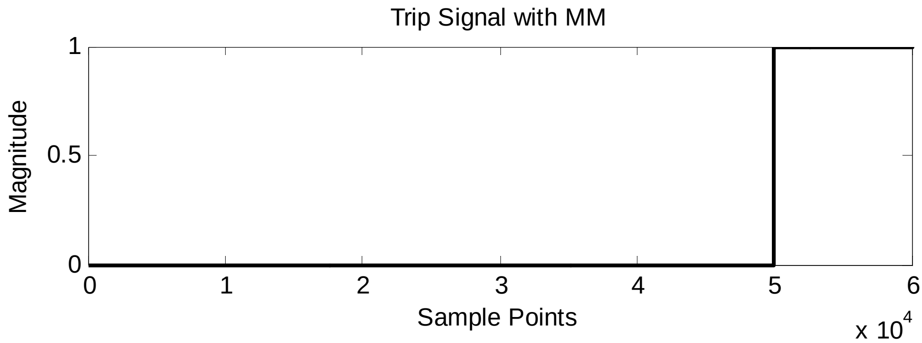


Fig. 5 (d) Trip signal with WT

*Case (b) Linear loading condition*

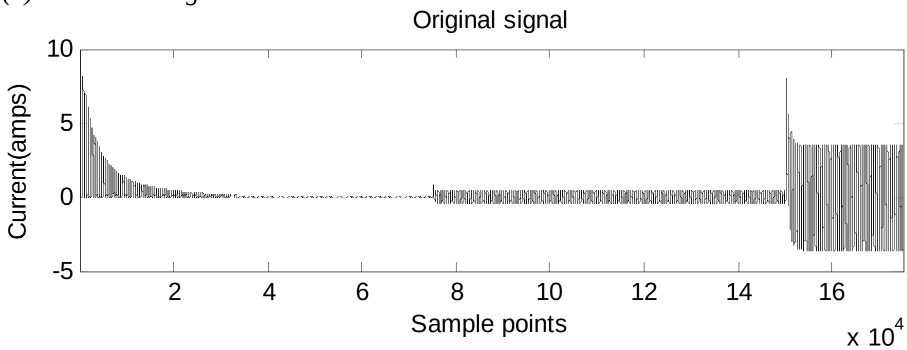


Fig. 6(a) Inrush and internal fault waveform for linear load conditions

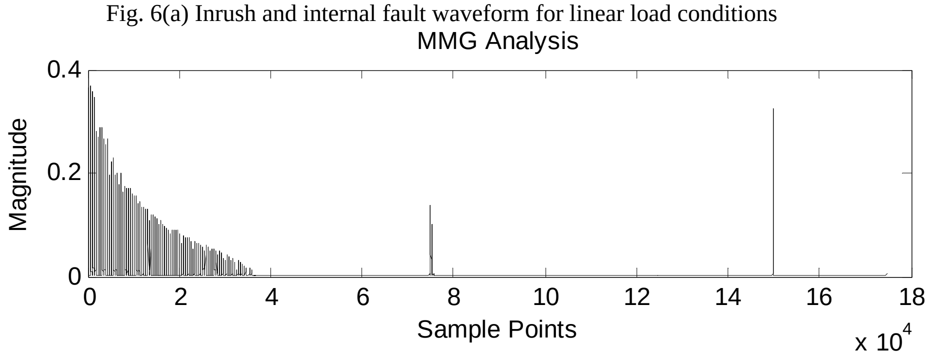


Fig. 6(a) MMG analysis for linear load conditions

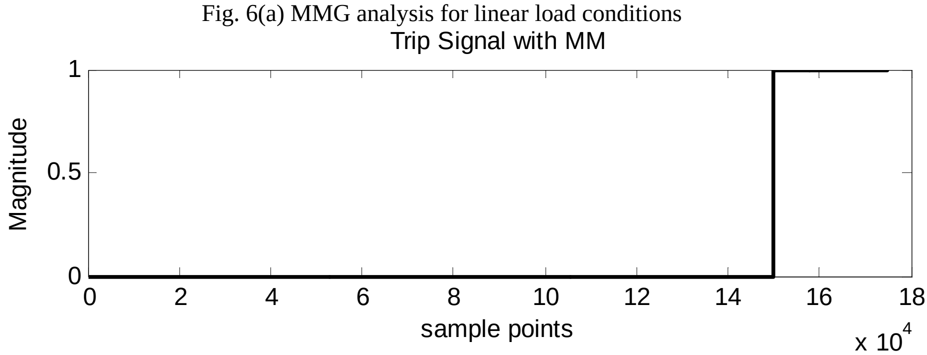


Fig. 6(c) Trip signal with MM

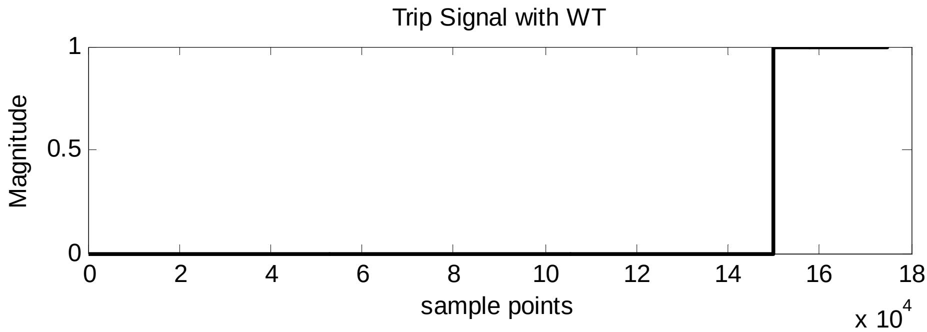


Fig. 6(d) Trip signal with WT

*Case (c) Non linear loading condition*

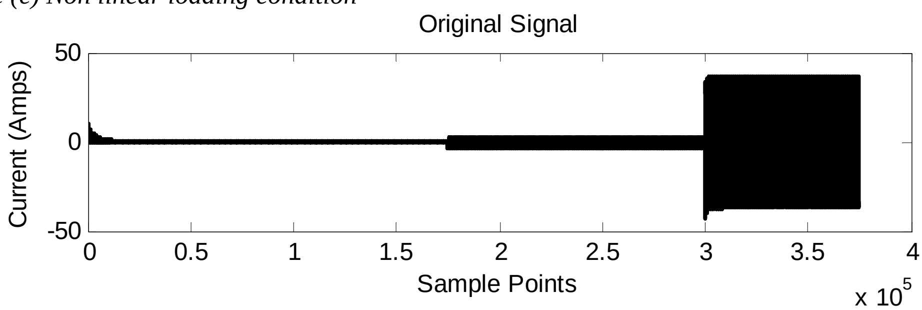


Fig. 7(a) Inrush and internal fault waveform for non-linear load conditions

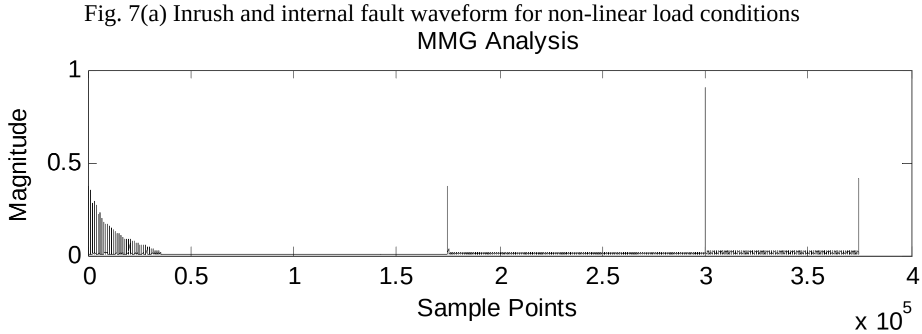


Fig. 7(b) MMG analysis for non-linear load conditions

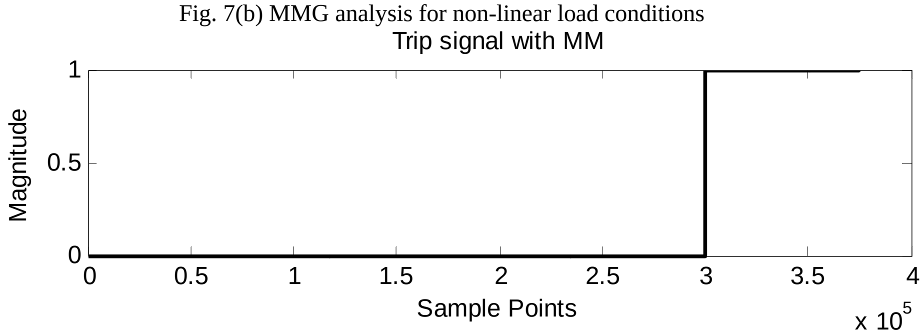


Fig. 7(c) Trip signal with MM

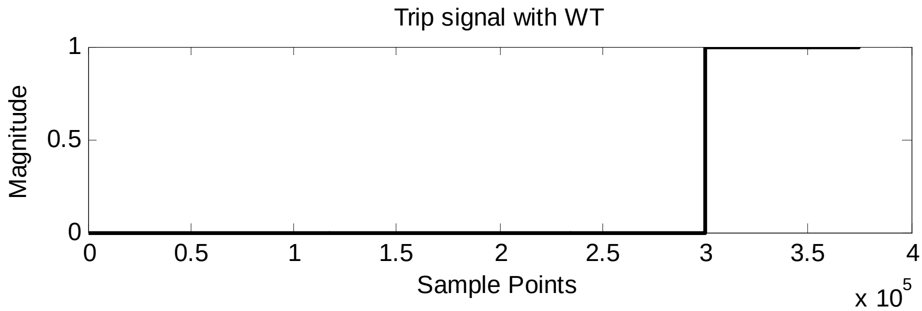


Fig. 7(d) Trip Signal with WT

*Case (d) Over excitation case*

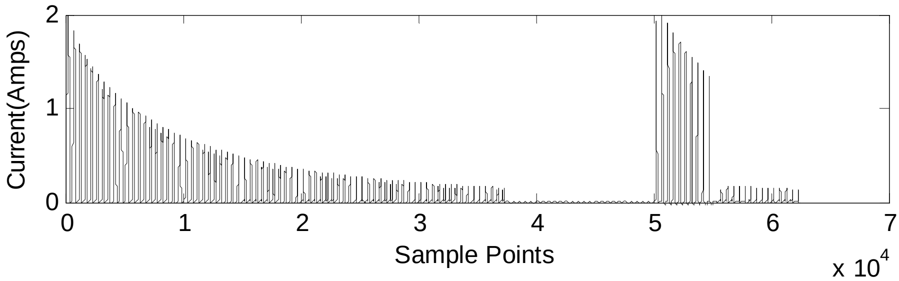


Fig. 8(a) Inrush and internal fault waveform for over excitation case

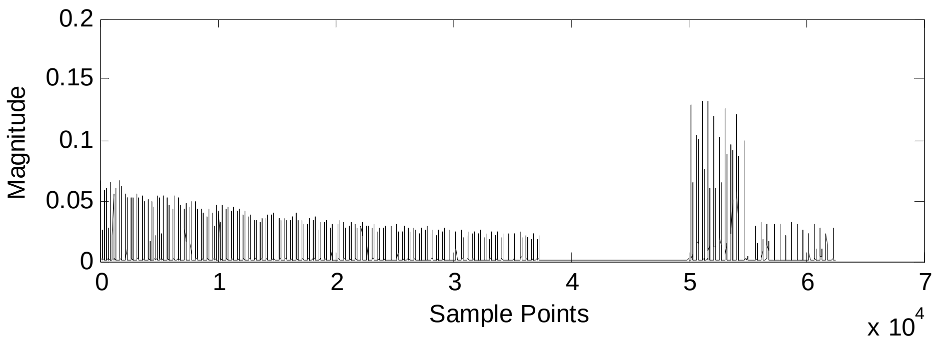


Fig. 8(b) MMG analysis for over excitation case

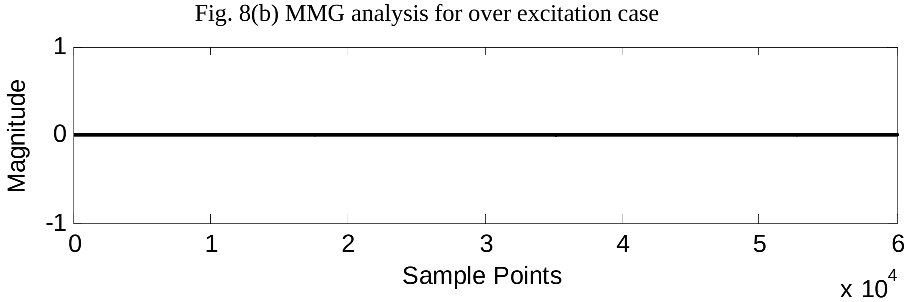


Fig. 8(c) Trip Signal with MM

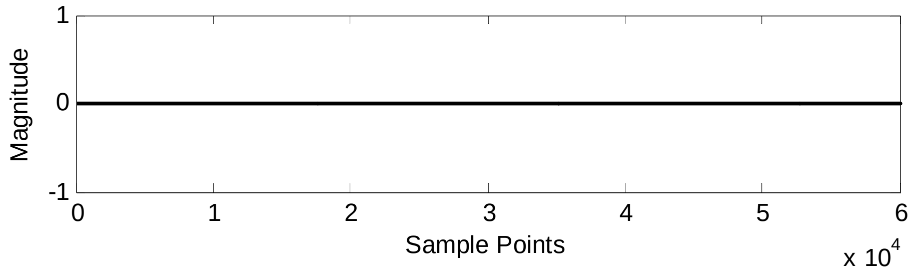


Fig. 8(d) Trip Signal with WT

From Figs. 5(c), 6(c), 7(c) and 8(c) it can be seen that the MMG technique combined with the decision-making algorithm can distinguish the magnetizing inrush currents from internal fault currents efficiently for various loading conditions and over excitation case for a particular system considered.

## 6. Conclusions

A new method has been proposed to distinguish the inrush and internal fault currents in a power transformer by using MM. Simulations have been carried out to demonstrate the effectiveness of the proposed method in comparison with the WT based method. The case studies to investigate the validity of the proposed method include different load conditions and over excitation. The results establish the reliability of the proposed method. Moreover, MM has the advantage of being mathematically less complex than wavelet transform as MM involves only finding of maxima/minima and addition/subtraction of signals. As MM itself acts as a filter, MM can perform well even in noisy environments. This aspect of MM is useful in practical situations where the signals being acquired may be corrupted by high frequency noise.

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