Abstract: This paper introduces a novel approach to differential protection of three-phase power transformer that is based on the wavelet transform and the fuzzy logic. The wavelet transform is tuned to distinguish between the magnetizing inrush and fault condition. The fuzzy logic is employed for final decision making. The proposed algorithm is tested off-line using data collected from a model which is simulated in the EMTP/ATP software.

Keywords: power transformer, differential protection, magnetizing inrush current, wavelet transform.

INTRODUCTION

The main concern in a transformer protection is the accurate discrimination between magnetizing inrush and different internal faults currents. It is evident that relaying protection should be initiated in response to internal fault but not to inrush current. To avoid the needless trip by magnetizing inrush current, many different restrain methods are proposed in recent years. The proposed schemes are based on some special characteristics of advanced signal processing techniques.

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. The ratio of the second harmonic of differential current in excess of a preset threshold is interpreted as a present of magnetizing inrush. However, the second harmonic component may also be generated during internal faults in the power transformer. This may be due to CT saturation or the presence of a capacitor in a transmission line to which the transformer may be connected. Moreover, it was found that in certain cases, the second harmonic generated during internal faults in transformers is relatively large, which impairs the ability of this kind of the criterion. Further, in the traditional algorithms, the magnitude of the second harmonic and fundamental are computed by discrete Fourier transform (DFT) [5]. However, it is well known that DFT is not accurate if the current is contaminated by interharmonics, especially if the data window is very short. Consequently, the commonly used conventional differential protection technique based on the second harmonic restraint, will thus have difficulty in distinguishing between an internal fault and an inrush current. Therefore, discrimination between an internal fault and a magnetizing inrush current still remains as a challenging power transformer protection problem.

This work puts forward the techniques of wavelet analysis [1, 2, 4] and fuzzy logic [3, 5] methods for transformer protection. Magnetizing inrush currents and fault currents are simulated in the ATP-EMTP program. Then using wavelet, the transient fault current and magnetizing inrush current are differentiated. The final decision about tripping transformer is making by the fuzzy logic sets.

FOURIER TRANSFORM (FT)

The main “traditional” signal processing method is the continuous Fourier transform (CFT) [5] and its discrete transform (DFT) are described by (1) and (2):

\[ F(j\omega) = \int_{-\infty}^{\infty} x(t)e^{-j\omega t} dt \]  
(1)

\[ F(k) = \sum_{n=0}^{N-1} x(n)e^{-j\omega n\pi/N} \]  
(2)

This is a powerful and useful tool but in transforming signals to frequency domain, time information are lost, that is, one cannot tell when a particular frequency takes place.

The short time Fourier transform (SFT) [5] was developed aiming to obtain information about time. The transform function is shown in equation (3).

\[ F(k, m) = \sum_{n=0}^{N-1} x(n)g(n-m)e^{-j2\pi km/N} \]  
(3)

The basis function \( g(n-m) \) is used to window the signal. SFT can obtain same information about time, however, the information is limited, which is decided by fixed size of the window.

WAVELET TRANSFORM (WT)

A new tool for signal processing is the wavelet transform (WT) [5, 6]. This tool is very wide applied for signal processing, because it doesn’t have disadvantages of the Fourier transform like loosing information about time. The WF is based on different analysis functions (more complicated than sine). The continuous wavelet transform of signal \( x(t) \) is described by (4).

\[ Wf(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)g^*(\frac{t-b}{a})dt \]  
(4)

where: \( g(t) \) - mother wavelet,  
\( a \) - scale parameter of \( g(t) \),  
\( b \) - time parameter controls \( g(t) \).

Values of \( a \) and \( b \) factors gives us the similarity between signal and a set of translated and scaled version of a mother wavelet. The mother wavelet has an average value of zero and with limited duration. Therefore, unlike the smooth and predictable sinusoidal functions extending from minus infinity to plus infinity in FT, wavelet functions \( g(t) \) are irregular and asymmetric (Fig.1).
The results of wavelet analysis is a phase space which consist of time and frequency. WF can reflect time and frequency features but not only the frequency character of the signal like FT. On figure 2 is showed the phase space of wavelet transform and for high frequency, shorter widows are adequate and for low frequency longer windows are necessary.

Like in FT here we can write a discrete form of WT which is described by (5):

$$Wf(j,k) = \frac{1}{\sqrt{|a_0^j|}} \sum_{n} x(n) g\left(\frac{k-nb_0a_0^j}{a_0^j}\right)$$  

(5)

where:  
- $g(n)$ - mother wavelet,  
- $a$ - scale parameter of $g(n)$,  
- $b$ - time parameter controls $g(n)$.

A result of this transformation is a signal’s representation in space where time has a logarithmic scale. This transformation can be used as a filters bank (Fig.3). The $cd_i$ is a detail of a signal on the $x$-frequency level and $ca_i$ is an approximation of the signal on the $x$-frequency level. DWT can be interpreted as low-pass and high-pass filters.

![Fig. 3. Multiresolution wavelet filter.](image)

**WAVELET VS FOURIER TRANSFORM**

The mathematical proposes of DFT and DWT are similar. As result, them can be viewed as a rotation in function space to a different domain. The domain contains basis function there are sines and/or cosines for the DFT and more complicated basis functions for DWT. Other similarity of the two transform is that basis functions are localized in frequency. This feature makes power spectra useful at picking out frequencies and similarity of signals.

The main difference between these transforms is that wavelet functions are well localized in space (time-frequency) but DFT not. This localization feature in time domain, along its localization in frequency domain, makes wavelet ideal tool for transient processing.

DFT is more sensible for stale signal analysis, DWT is more proper for transient signals, which can detect sudden change of waveform.

One of the most popular analysis function in DWT is the Daubechies wavelet used to analyzing electrical signals. This wave is very robust and suitable for signals with DC and aperiodic component (e.g. fault current signal).

**EMTP MODEL**

The signals for testing are generated by EMTP-ATP software [7]. The modeled system is shown on Figure 4.

Transformer data:  
- power rating: 32MVA  
- rated voltage: 115/22 kV  
- rated current: 160.7/839.9A  
- short-circuit voltage: 11%  
- excitation loses: 280kW

Systems data:  
- $Z_H$: 0.133 $+ j$3.3Ω  
- $Z_L$: 0.2 $+ j$4.0Ω

CTs data:  
- $CT_H$: 200/1A, 20VA  
- $CT_L$: 1000/1A, 20VA

Faults are simulated inside transformer (between nodes ND04 and ND05) and out of protected area (ND03 and ND06). There are simulated different types of transformer’s state:  
- turn-to-turn fault,  
- interwinding short-circuit,  
- stationery over-excitation of a transformer core due to short-term steady-state overvoltage,  
- transformer energizing,  
- external faults combined with transformer and CTs ratio mismatch.

The sampling frequency of this model is 4kHz. The current signals $I_H$ and $I_L$ are filtered by a low-pass filters which a cutoff frequency is settled on 2kHz. All data are loaded into the MATLAB and there is implemented an algorithm which is described below.

**ALGORITHM**

The differential current $I_D$ and $I_F$ are calculated from the input signals $I_H$ and $I_L$. They are depends on a connec-
tion group of the transformer, and for Yd11 are calculated by equations (6) for phase A:

\[
\begin{align*}
    i_{D-A} &= (i_{H-A} - i_{L-A}) + w_p i_{L-A} \\
    i_{T-A} &= (i_{H-A} - i_{L-A}) - w_p i_{L-A}
\end{align*}
\] (6)

Next step there is filtering differential current for all phases by wavelet filter bank which is based on the Daubechies wavelet. After decomposition of the differential current signal \( I_D \) there are 7 levels which corresponds to frequencies:
- 1 level: 2kHz – 1kHz (higher harmonics),
- 2 level: 1kHz – 500Hz,
- 3 level: 500Hz – 250Hz (7th and 9th harmonics),
- 4 level: 250Hz – 125Hz (3rd harmonic),
- 5 level: 125Hz – 62.5Hz (2nd harmonic),
- 6 level: 62.5kHz – 31.25Hz (fundamental comp.),
- 7 level: less than 31.25kHz (DC component).

For inrush detection is used 1st and 5th level of decomposition. On Fig. 6. there is showed output of the wavelet filter bank at the 1st level. Lower graph shows 1st level detail of the decomposition signal in phase C. Every disturbances shows the moment of saturation. The highest peak is recognized as the saturation beginning or end.

When saturations are in all phases its mean that the core of the transformer is saturated but when only one or two phases are saturated its mean about the CT’s saturations.

Output of block “Inrush current detection” is connected to decision block \( DET \). The decision is based on fuzzy logic sets. Input signals are differential currents \( I_D \), through currents \( I_T \) and saturation detector \( DET \).

All calculation are made in the MATLAB using The Wavelet Toolbox [6].

SIMULATION

Digital simulation of the proposed algorithm are made by using the model system described earlier. All testing signals are generated in the ATP-EMTP program. The transformer model is a 3-phase model modified to possibility simulate all state of transformer [8]. Here are examples of current signal decomposition on Fig. 7-8.
CONCLUSION

Proposed algorithm is worked out still, but using of wavelet extraction naturally emphasize the difference between fault and inrush current since their frequencies are different. This paper demonstrates the application of wavelet decomposition of signals can be use for recognition fault and inrush current. The next step of the algorithm is to suit fuzzy sets to making decision. This part is in progress.

LITERATURE


Fig. 7. Decomposition of the currents during simultaneous C-G fault and CT’s saturation

-0.2 -0.1 0 0.1 0.2 Amplitude

-4 -2 0 2 4

1st level

-4 -2 0 2 4

4th level

0 0.1 0.2 0.3 0.4 0.5 Time [s]

0 -0.2 -0.4

0 0.1 0.2 0.3 0.4 0.5 Time [s]

0 -0.2 -0.4

0 0.1 0.2 0.3 0.4 0.5 Time [s]

0 -0.2 -0.4

0 0.1 0.2 0.3 0.4 0.5 Time [s]

0 -0.2 -0.4

0 0.1 0.2 0.3 0.4 0.5 Time [s]

0 -0.2 -0.4

0 0.1 0.2 0.3 0.4 0.5 Time [s]

0 -0.2 -0.4

0 0.1 0.2 0.3 0.4 0.5 Time [s]

0 -0.2 -0.4

0 0.1 0.2 0.3 0.4 0.5 Time [s]

0 -0.2 -0.4

0 0.1 0.2 0.3 0.4 0.5 Time [s]

0 -0.2 -0.4

0 0.1 0.2 0.3 0.4 0.5 Time [s]