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Power Transformer Differential Protection Relay Using Half Cycle Fourier Algorithm

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Abstract:

In this paper design, computational aspects and experimental results of a microprocessor based digital transformer differential relay is described. Half cycle Fourier algorithm is used to estimate current phasors. Performance of the proposed relay is tested for different faults including internal and external faults. The ability of the relay to restraint for inrush current is discussed and demonstrated. Test results of the proposed algorithm highlight the abilities of the algorithm. Test results for external fault, internal fault and inrush current are presented in the paper.

1. Introduction

As one of the most important elements in modern power systems, transformers are used in power networks transmission and distribution levels. An unscheduled repair work, especially replacement of a faulty transformer, is very expensive and time consuming. Power transformers are usually protected by percentage current differential relays based on the power frequency signal measurements [1-3].

The main aspect of differential protection is that the currents entering a device through normal paths should be equal to the outgoing currents from the device and thus this principle is considered as a method of fault detection algorithm. To provide effective protection for faults within a transformer and satisfactory security for normal operation and external faults, design and application of differential transformer protection must consider many different factors such as CT mismatch ratios on two sides of the transformer, transformer magnetizing current and transformer tap position as well as CT saturation.

Nowadays microprocessor based relays have become the basis of most protection systems [1-9]. Many different great advantages including flexibility, self-testing, multifunctional protection products and background tasks are amongst the benefits mentioned for using this digital technology [6-9]. A major portion of the present research in the power system protection continues to be in the development of new microprocessor based digital relays and algorithms [10].

One major part of digital relays is their software and their signal estimation algorithm. The microprocessor based relay is software controlled and estimates the amplitude and phase of its input signals using different types of filters.

Filter data windows are frequently used in different applications such as automation and digital protection. In differential protection schemes, input and output current signals should be estimated. Various algorithms such as Fourier, Walsh and Least Square Error (LSE) could be used to process the current signals.

The basic assumption used in Fourier method is that the waveform that results from a fault condition (voltage and/or current) is assumed to be periodic within the interval. This assumption enables the waveform to be expanded by Fourier series. The desired components are extracted and then used for relaying.

The application of full cycle Fourier data windows might involve time-consuming computations for the processors due to the many multiplications which should be performed. In this paper digital relaying algorithm based on half cycle Fourier analysis is presented.

Design and test of a half cycle Fourier algorithm based relay that operates quickly for internal transformer faults and at the same time dose not operate for any other non-fault condition is the main task in this paper. In the following sections, the relay characteristic design and the principles of the proposed algorithm are described. The performance results of this algorithm are also presented.

2. Differential Relay Design

Differential protection works on the basis that no differential current flows into the relay if the currents at each end of the device are equal, but if they are not equal e.g. due to an internal fault, then a differential current equal to the difference between the currents will flow in the relay, causing it to operate and trip the transformer circuit breakers.

For a power transformer, several practical issues must be considered before a workable differential relay can be implemented. The differential relay is extended to include the introduced errors. The CTs on two sides of the transformer are selected from available standard ratios. A differential current may result because of the mismatch between the CTs ratios and transformer turns ratio. The current transformation error of the CTs on the two sides may differ from each other, thus leading to some differential current especially in case of external faults. The CTs may saturate for heavy faults and could have different transient responses to external faults. If the transformer is equipped with a tap changer, this will introduce the main transformer ratio change when the tap is changed, causing some error differential current [11].

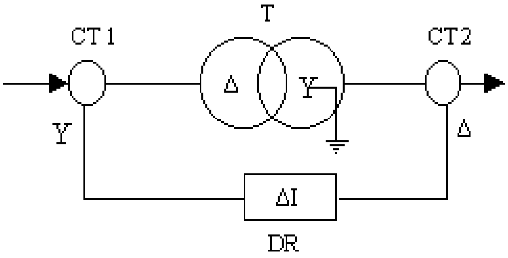


Figure 1 : Schematic diagram

In order to compensate the above mentioned errors and to ensure stability of the relay in the case of external faults, a restrained based percentage differential relay characteristic should be chosen. The proposed relay in this paper is designed for a power transformer in a sub-station. The specifications of the transformer are given as:

115/13 (KV); Δ / Y(grounded) ; 40 MVA

CTs connected to the Y main winding of transformer have with 300/5 turns ratio and CTs connected to the Δ main winding have with 3000/5 turns ratio. CTs are configured in a way to compensates the phase shift between primary and secondary currents of transformers. A schematic diagram showing the power transformer and its differential relay is shown in Fig. 1. Using these specifications, the bias current and slope of the relay characteristic should be selected in a way that the relay performs correctly for internal faults and remains stable for external through faults.

3. Algorithm Estimation Method

A function of time f(t) can be represented by a Fourier series. Power system signals such as phase voltages and currents are of course functions of time and they can be consequently expanded using the Fourier series.

If we take for example, a current waveform i(t) then:

$$i(t)=\frac{a_0}{2}+\sum_{n=1}^{\infty}a_n\cos(n\omega_0 t)+\sum_{n=1}^{\infty}b_n\sin(n\omega_0 t) \quad (1)$$

$$a_n=\frac{2}{T}\int_{t_0}^{t_0+T}i(t)\cos(n\omega_0 t)dt \qquad n=0,1,\ldots \quad (2)$$

$$b_n=\frac{2}{T}\int_{t_0}^{t_0+T}i(t)\sin(n\omega_0 t)dt \qquad n=1,2,\ldots \quad (3)$$

where ω_0 is the angular frequency of the fundamental component and T is its period [7].

3.1 Half Cycle Window Algorithm

This algorithm is based on correlating the fault waveforms with sine and cosine functions having a frequency equal to that of the fundamental component of the waveform. This method uses information corresponding to only one half cycle. Let $I_{x,1/2}$ and $I_{y,1/2}$ be the real and imaginary parts of the phasor representing the fundamental component derived from a half-cycle window.

By applying equations 2 and 3 to a half cycle window the following equations are obtained:

$$I_{x,1/2}=\frac{2}{(T/2)}\int_{t_0}^{t_0+T/2}i(t)\cos(\omega_0 t)dt \quad (4)$$

$$I_{y,1/2}=\frac{2}{(T/2)}\int_{t_0}^{t_0+T/2}i(t)\sin(\omega_0 t)dt \quad (5)$$

It is possible to express $I_{x,1/2}$ and $I_{y,1/2}$ in terms of waveform samples S_j, and their corresponding weighting factors $W_{x,j}$ and $W_{y,j}$ (j = 1, 2 ,…, N/2) such that:

$$I_{x,1/2}=\frac{4}{N}\sum_{j=1}^{N/2}W_{x,j}S_j \quad (6)$$

$$I_{y,1/2}=\frac{4}{N}\sum_{j=1}^{N/2}W_{y,j}S_j \quad (7)$$

Using a similar method, digital filters for other frequency components, e.g. second and fifth harmonics could be designed.

For a typical three phase three winding power transformer 10 different phase and ground current signals should be sampled and estimated. In power transformer differential relay design, moreover to the fundamental frequency component, second and fifth harmonic components should be estimated to prevent relay maloperation in case of inrush and over voltage cases. Therefore a high sampling rate is necessary for estimating 1^{st}, 2^{nd} and 5^{th} harmonics of the signal. In the proposed digital relay scheme, the input signals were sampled at the rate of 1440, i.e. 24 samples per cycle of 60 Hz system frequency.

For a sampling rate of 24 samples per cycle and for estimating the fundamental, the second and fifth harmonic contents of the signal, a large number of multiplications should be performed within every sampling interval. For example, using sine and cosine orthogonal functions, 3×2 digital filters should be considered for three harmonics with the total number of $3\times2\times10\times24$ multiplications per sampling interval of $\frac{1}{24\times60}$ sec. A digital relay using half cycle Fourier algorithm can reduce the burden on the processor.

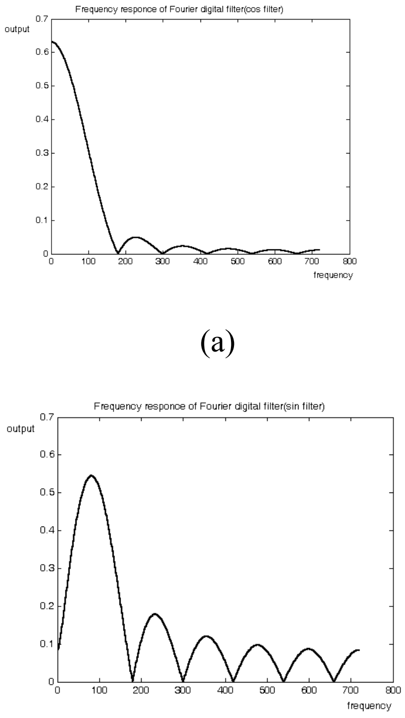
When a fault happens on power system, the fault voltage and current signals often become noisy and contain high order frequency components. In addition, fault signals may develop a decaying dc offset component whose magnitude depends on many factors which are random in nature.

A simple wide band pass 2^{nd} order filter has been used to attenuate dc component and high frequency harmonics and noise. Current signals are processed by this pre-filtering stage before being fed to Fourier filters. This analog filter acts as the anti-alias filter as well.

The filter is centered at the nominal system frequency and its pass-band is chosen to be about 200Hz. This value allows considerable reduction of the high frequency and dc components with a small time delay. Frequency response of the Fourier and band pass filters are shown in Figs. 2-4.

3.2 Inrush Restraint

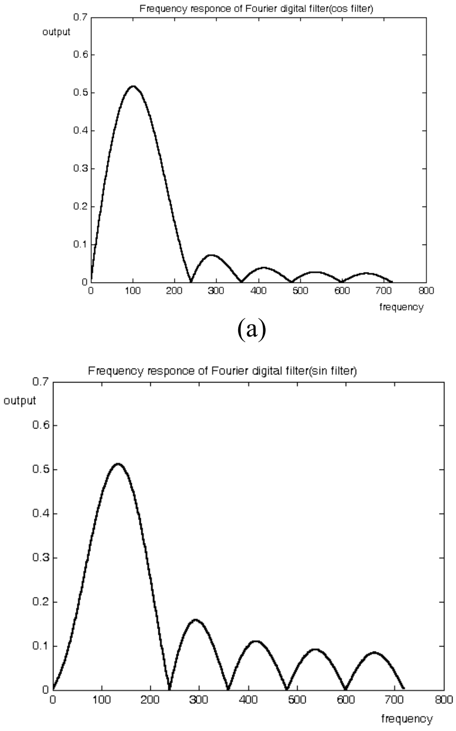
During energization of a transformer, abnormal current may flow in the winding, which is being energized. This current is known as the magnetizing inrush current, caused by the saturation of the transformer core for portions of a cycle. Depending on the point of switching as well as the magnetic state of the transformer, the magnitude of inrush current varies. Since the inrush current flows just in the energized winding, false operation of the differential relay may result due to the differential current. Therefore, algorithms for the protection of power transformers must be designed to operate correctly in the presence of magnetizing inrush current, which appears to be an internal fault to the percentage differential relay characteristic [10,13].



(a)

(b)

Figure 2: Frequency responses of cos and sin Fourier filters for fundamental harmonic



(a)

(b)

Figure 3: Frequency responses of cos and sin Fourier filters for second harmonic

This problem could be overcomed using the so-called harmonic restraint method. Inrush currents usually contain considerable amount of harmonics, of these the second harmonic is usually predominant under energization condition [7]. In this design, the second harmonic content is used as a pattern classifier to distinguish between inrush and internal fault currents [12].

The harmonic-restrained digital differential relay calculates the fundamental as well as the second harmonic signals. Sum of the magnitudes of three phase current components are estimated using:

$$I_{H2} = |I_{da2}| + |I_{db2}| + |I_{dc2}| \tag{8}$$

$$I_{H1} = |I_{ra1}| + |I_{rb1}| + |I_{rc1}| \tag{9}$$

where I_{da2}, I_{db2}, I_{dc2} are the second harmonic differential currents and I_{ra1}, I_{rb1}, I_{rc1} are the fundamental harmonic restraint currents of phase A, B and C, respectively.

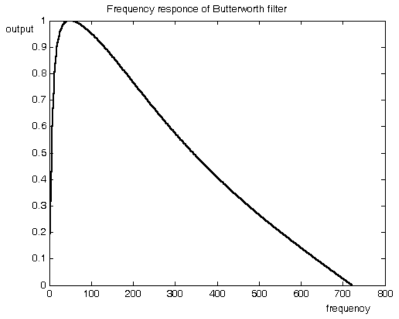
The relay is designed so that it is restrained from tripping if the following equation is satisfied:

$$I_{H2} > \beta \times I_{H1} \tag{10}$$

where β is a constant chosen based on the transformer characteristic.

4. Simulation Results

Testing the performance of a proposed digital relay algorithm is quite important [4, 14]. To demonstrate the operating performance of the applied algorithm and to determine the proposed relay accuracy and speed, the designed relay is tested. Based on the structure of the designed differential relay, appropriate software was programmed using MATLAB package.



(a)

Figure 4: Frequency response of Butterworth filter (pre filtering)

Three separate single phase differential relay are considered for the three phase transformer. The length of the window is 24 samples and the calculations are updated on the arrival of new samples and the tripping command is decided online.

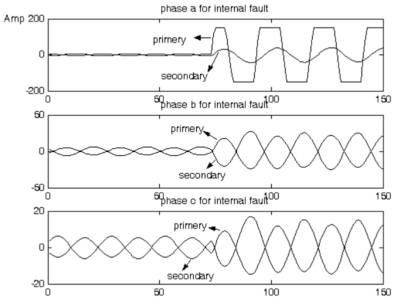


Figure 5: Primary and secondary currents, internal

The differential and bias currents for each phase could be calculated using the above mentioned computed data The performance of the proposed relay was checked in playback mode using the transformer recorded data. The relay was tested with a set of three different cases including internal fault, external fault and inrush current.

4.1 Simulation of Internal Fault

Primary and secondary test data currents of the transformer are depicted in Fig. 5. According to this figure, it seems that a fault is occurred on phase A. Three separate single phase differential relays corresponding to each of the transformer phases, calculate the differential and restraint currents for the received data.

Differential current versus restraint current of phase A is shown in Fig. 6. The differential relay characteristic is also depicted in this figure. An initial trip decision is activated if the current enters the operating region of the relay. This trip decision signal is passed through an averaging filter. If this signal remains high for at least three consecutive samples, the final trip signal is activated.

Harmonic components of the current signals defined in equations (8) and (9) as well as the ratio of the second harmonic to the first harmonic is calculated and depicted in Figure 7. As shown in this figure, the second harmonic to first harmonic ratio is initially high after the occurrence of the fault but after some samples it decreases. The β constant is chosen 0.3. Since the relay should distinguish well between

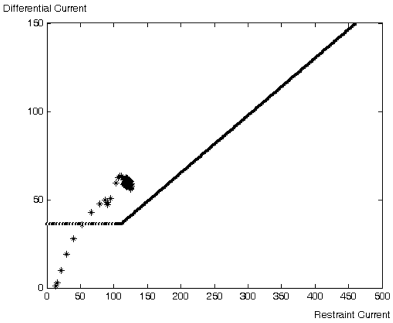


Figure 6: Differential current versus restraint current, internal

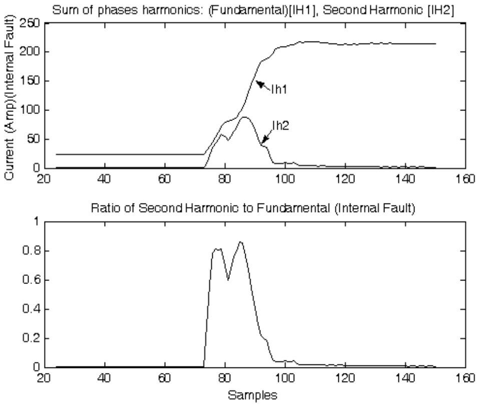


Figure 7: Harmonics components (I_{H1}, I_{H2}), internal

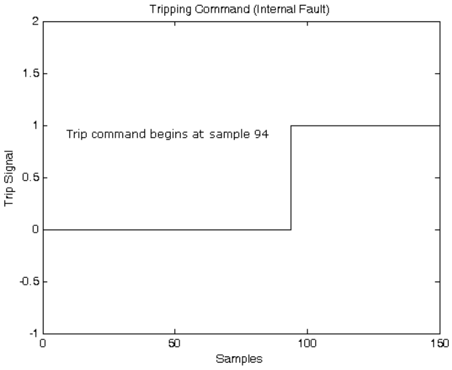


Figure 8: Tripping signal, internal

this situation and inrush, therefore the relay trip signal goes high when the ratio of second harmonic to first harmonic is decreased less than β. Phase A trip signal is commanded at sample no. 94, about 20 samples after the occurrence of the fault as shown in Fig. 8. Phase B and C trip signals remains stable.

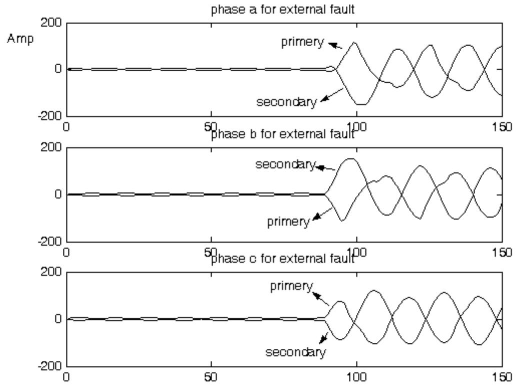


Figure 9: Primary and secondary currents, external

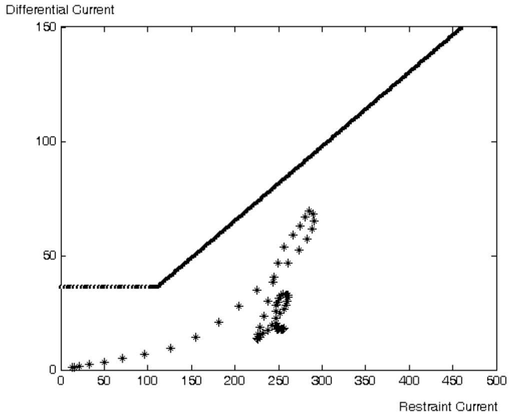


Figure 10: Differential current versus restraint current, external

4.2 Simulation of External Fault

To investigate the response of the relay to external faults, performance of the relay is tested for a typical fault. Results are indicated in Figs. (9-12). It is clear that no tripping signal is activated in this situation.

4.3 Simulation of Inrush Current

As it was mentioned earlier when a power transformer is energized, the resulting inrush current can cause a differential relay to issue a false trip signal. Transformer primary and secondary currents for an inrush case are shown in Fig. 13. Differential current versus restraint current of phase A is shown in Fig. 14. Differential currents for all of three phases enter the operating region of the relay characteristic.

However, since the ratio of second harmonic to first harmonic, shown in Figure 15 is greater than β constant, the trip signals are not activated in this case. This test verifies accuracy of relay performance and second harmonic restraint for an inrush current case.

5. Conclusion

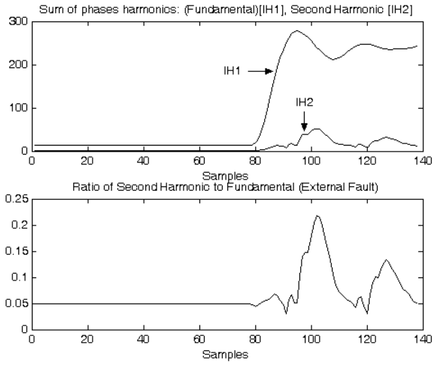


Figure 11: Harmonics components (I_{H1}, I_{H2}), external

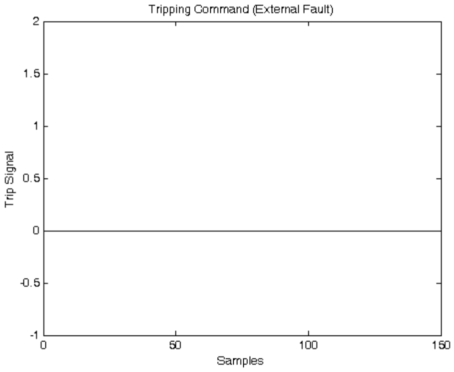


Figure 12: Tripping signals, external

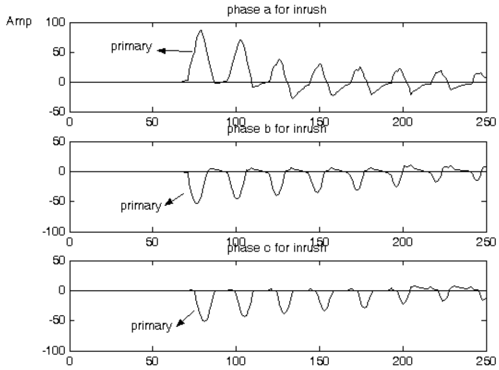


Figure 13: Primary and secondary currents, inrush

Design, practical issues, computational aspects and performance of a half cycle Fourier function based microprocessor differential relay for transformer protection are described in this paper. To make a complete x

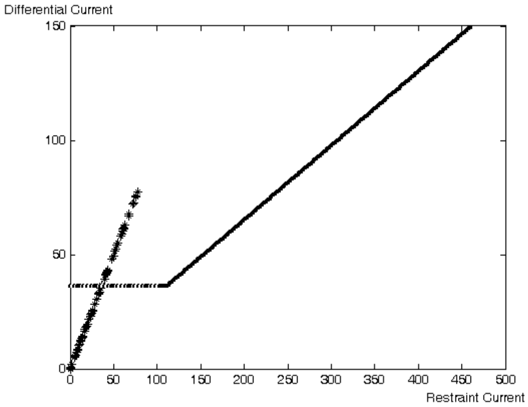


Figure 14: Differential current versus restraint current, inrush

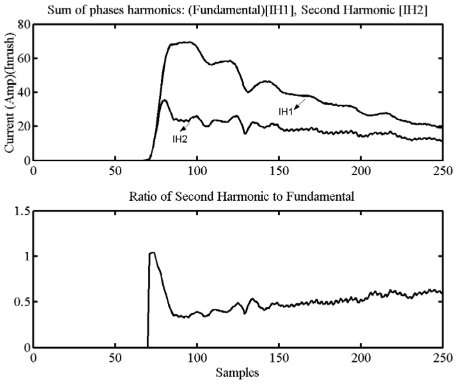


Figure 15: Harmonics components (I_{H1}, I_{H2}), inrush

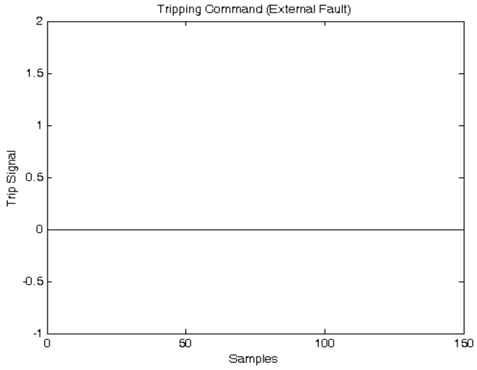


Figure 16: Tripping signals, inrush

evaluation of the proposed algorithm, the performance of the relay is checked using recorded test data currents for different cases including external fault, internal fault and inrush current. The test results indicate that the applied Fourier algorithm can provide accurate estimation. Effectiveness of the technique is verified for inrush restraint and the accuracy the whole protection is demonstrated.

6. Acknowledgement

The transformer test data for three different cases, external fault, internal fault and inrush current are provided by professor T. S. Sidhu, University of Saskatchewan, Canada.

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