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Design and Evaluation of a DSP Based Differential Relay of Power Transformer

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Abstract: The problem of mal operation of differential protection of power transformer due to the inrush magnetizing current has long considered as a challenging problem. Several types of protection relays have been used to solve the issue (basic relay, percentage relay, multi slop). Each of them has its advantage and its limits.

In this paper, a Digital differential relay has been developed and simulated. The logic used to distinguish between the inrush current and the internal fault is based on the theory of harmonic analysis. The behavior of the presented relay has been simulated versus various situations (inrush current, internal fault and external fault). The obtained results show that the proposed algorithm provides a good discrimination and a fast action.

Keywords: Algorithm, Differential, DSP, Digital, power transformer, harmonic analysis.

1. INTRODUCTION

One of the most important and expansive element in power systems is the power transformer, which is used in different sizes, types, and connections. A power transformer functions as a node to connect two (02) different voltage levels. Therefore, the continuity of its operation is of vital importance in maintaining the reliability of power supply [1, 2]. However, transformers are expected to many internal and external stresses and the consequence of any failure can be very heavy in term of damage as well as in terms of operating losses [3]. So a performing and secure protection is needed.

Differential protection is widely used to protect large power transformer against internal faults. Its principle of operation is based on the fact that if the difference between the entering and the leaving currents in the protected zone exceed a predetermined value; the relay transmits a trip signal to the circuit breaker and isolates the faulted zone.

Based on this principle, the relay must operate when, and only when, an internal fault occurs. However, certain phenomena (such as inrush current, CT saturation levels,

nonlinearities...) in power transformer can create a differential current between its two terminals, even without internal fault, causing thus mal tripping.

When a transformer is energized, magnetizing inrush current that flows in one set of terminals may equal many times the transformer rating [4]. This is the most challenging problem in power transformer differential protection.

Over the years, many different methods of preventing differential relay operation on inrush have been utilized [5]:

- **Deactivate the relay:** since the magnetizing current has a damped nature, the simple way to avoid the mal tripping at the energizing moment was the deactivation of the relay until the death (disappearance) of the inrush current.
- **Decrease the acting speed:** Use slow-speed induction-type relays with long time and high current settings.

- **Power differential method:** This method is based on the idea that the average power drawn by a power transformer is almost zero on inrush, while during a fault the average power is significantly higher [5,6].
- **Rectifier relay :** This method takes advantage of the fact that magnetizing inrush current is in effect a half-frequency wave. Relays based on this method use rectifiers and have one element functioning on positive current and one on negative current. Both elements must operate in order to produce a trip. On inrush, the expectation is that one element only will operate, while on an internal fault, the waveform will be sinusoidal and both elements will operate. [5] [7]
- **Methods based on inrush current analysis:** Waveform recognition, wavelet transform, harmonic analysis...

In this paper, we propose an algorithm for digital differential relay based on the detection of the second harmonic component to discriminate between the false differential current at the energizing moment of power transformer and that causing by a real internal fault.

The first part of the paper is devoted to the description of the traditional differential relays, the DSP (Digital Signal Processing) based relay and the proposed algorithm. In the second part, simulations of the relay's behavior in several cases have been done and interpreted.

2. OPERATING PRINCIPLE OF TRADITIONAL DIFFERENTIAL RELAY

The basic scheme of the power transformer differential protection is shown in figure.1.

Differential relay compares the currents that enter with the currents that leave the protected zone. If the differential current (called also operating current I_{op}) is essentially zero, it is concluded that there is no fault in the protection zone. However, if operating current is not zero, the differential protection concludes that a fault exists in the zone and takes steps to isolate the zone from the rest of the system [8].

Fig.1 Typical Differential Relay Connection Diagram

The operating current in the differential relay is equal to:

$$I_{OP} = |I_1 - I_2| \quad (1)$$

If:

$I_{OP} = 0 \Rightarrow$ No internal fault.

$I_{OP} \neq 0 \Rightarrow$ An internal fault occurs.

Theoretically, the differential relay performs well as long as we consider that the behaviors of the CTs and the power transformer are ideals (no saturation of the magnetic circuit, no inrush current, no iron losses...).

In fact, the basic differential relay may operate incorrectly due to:

- Magnetizing inrush current
- Current transformer saturation
- Overexcitation conditions
- On-Load Tap-Changer (OLTC).

To do face against the weakness points of mal tripping causing by the phenomena cited above (previously) – except the problem of inrush current – the percentage restraint differential protective relay have been used for many years.

Percentage restrain relays employ a restraining current. The following are the most common ways to obtain the restraint current [9]:

$$I_{RT} = k \left| \vec{I_1} - \vec{I_2} \right|$$

$$I_{RT} = k \left(\left| \vec{I_1} \right| + \left| \vec{I_2} \right| \right)$$

$$I_{RT} = \text{Max} \left(\left| \vec{I_1} \right|, \left| \vec{I_2} \right| \right)$$

Where k is a compensation factor, generally taken as 0.5 or 1.

The differential relay generates a tripping signal if the operating current, I_{OP} , is greater than a percentage of the restraining current, I_{RT} :

$$I_{OP} > SLP \cdot I_{RT}$$

Figure.2 represents the operating characteristics of such relay. This characteristic consists of a line divides the coordinate plane in two parts. The upper part is the operating region while the lower part is the restraining region.

Fig.2 Characteristic of a percentage differential relay

3. DSP BASED RELAY

DSP based relay consists of the following main subsystems:

- Analog input subsystem,
- Analog and digital output subsystem,
- Analog to digital and digital to analog conversion subsystems,
- Processor.

The relay receives input currents via CTs from each phase of the power transformer. This analog signal is pre-processed using low pass filters to avoid aliasing effect. This later is passed through

an Analog to Digital Converter (ADC) because the processor can handle only numerical (logical) data. The digitized signal is processed in a Digital processor according to the algorithm implemented in its software. In the light of the processing results, a decision signals may be issued to the concerned organs (Circuit breaker, signalization, communication.....).

Figure.3 represents the general aspect of a DSP based Relay.

Fig.3: Block diagram of typical DSP based relay

4. THE PROPOSED ALGORITHM

The proposed algorithm is relied on the fact that the magnetizing inrush currents are characterized by having high second harmonic content [10]. While this character is not notified in the case of internal or external faults.

Research studies have found that the second harmonic component compared with the fundamental, in the case of inrush current, is somewhere between 30 % and 70 % [10-12].

To achieve the harmonic analysis of the differential current, the FFT (Fast Fourier Transform) has been used. FFT is a powerful mathematical tool that helps to extract the fundamental and higher harmonic components from the differential signal:

$$i(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (C_k \cos(k\omega t) + S_k \sin(k\omega t))$$

a_0 : is the DC component.

C_k : Fourier cosine coefficient.

S_k : Fourier sine coefficient.

The discrete forms of the cosine and sine coefficients can be expressed as follow:

$$C_k = \frac{2}{N} \sum_{n=1}^{N-1} X(n) \cos\left(\frac{2k\omega t}{N}\right)$$

$$S_k = \frac{2}{N} \sum_{n=1}^{N-1} X(n) \sin\left(\frac{2k\omega t}{N}\right)$$

$X(n)$: is the current $i(t)$ in its discrete form.

The Fourier harmonic coefficients are given by:

$$F_k = \sqrt{S_k^2 + C_k^2}$$

F_k : is the k^{th} harmonic coefficient for $k=1,2,\dots,N$.

The flow chart of the developed algorithm is shown in figure.4.

Fig.4: Flow chart of the proposed algorithm.

First, the relay loads the setting parameters and reads data from CTs, then it calculate the difference of current, I_D , between the primary and the secondary sides of the power transformer. If the differential current is less than the threshold; the situation is classed as a normal operating mode. Otherwise, two cases are possible: an internal fault or a magnetizing inrush current.

To discriminate between these phenomena, the relay must make a second test based on harmonic analysis (fact that the magnetizing inrush current is specified by high harmonic components content that have not significant presence in fault currents. So it proceeds to the harmonic analysis and compare the second harmonic with the fundamental. If the test is satisfied (2^{nd} Harmonic is greater than 30 % of the fundamental) this means that the remarked differential current is due to the energizing inrush current, and consequently the relay must not release the tripping signal.

If the second condition is not satisfied, the relay recognizes an internal fault and releases a trip signal to isolate the transformer.

5. SIMULATIONS AND RESULTS

The proposed algorithm has been implemented using Matlab/Simulink packages. As the software MatLab and Simulink presently do not have a toolbox which helps us in simulating power system protective devices, we have built a model for the differential relay according to the logic discussed in the above cited algorithm.

The simulations presented in this paper is performed on a step-down three-phase power transformer 250 MVA rated power; the primary and the secondary line to line voltages were 230kV \ 63 kV respectively.

To prove the effectiveness of (the proposed algorithm) developed relay, we have simulated the behavior of the relay versus three essential cases:

- Behavior of the relay versus the magnetizing inrush current.
- Behavior of the relay versus an internal fault.
- Behavior of the relay versus an external fault.

A. *The first case:* magnetizing inrush current

The magnetizing inrush current occurs each time when the transformer is energized. Figure 5 represents the result of simulation of the primary current (phase A).

Fig.5: Inrush current resulted following the energizing of the transformer.

Since the inrush current appears mainly in the primary side of the transformer, the currents caught by the CTs at the transformer terminals are greatly different. Consequently, the relay detects a differential current (see figure.6).

This inrush current usually causes mal operation of traditional differential relays. Furthermore, the disconnection of the transformer during the inrush phenomenon may be very dangerous (a considerable overvoltage can be generated and leads to micro-dielectric breakdown of the transformer insulation).

That is why in our algorithm, after the detection of the differential current, a second condition (based on harmonic analysis) is added for best discrimination between the differential current caused by the inrush situation and that caused by internal fault.

Figure.6 shows that the second harmonic is greater than 30% of the fundamental. Hence, this blocks the relay to generate the trip signal (fig.6).

Fig.6: Simulation results in the case of magnetizing inrush current.

B. The second case: Internal fault

At $t = 4\text{s}$, an internal fault, between phase A and the ground, is created at the secondary side of the transformer. The simulation results (figure.7) show that the relay detects an important differential current. At this point, two cases are possible: inrush current or internal fault. Therefore, the relay must proceed to harmonic analysis to decide whether a tripping signal is needed or not. As the second harmonic is significantly less than 30% of the fundamental, the first case is eliminated and a decision to trip is carried out.

It should be noted also that the acting time of the relay is just 21 milliseconds which is considerably lower than the maximum acceptable time (100 msec) specified by IEEE standard for transformer protection, Thing which proves the fast character of the proposed algorithm.

Fig.7: Simulation results in the case of Internal fault.

C. *The third case:* External fault

In this case, an external fault, between phase A and the ground, is simulated at the secondary side of the transformer.

The results of simulation are shown in figure.8.

No differential current is detected, no matter for the relay because the fault is occurred outside the responsibility area of the differential relay.

Fig.8: Simulation results in the case of external fault.

6. CONCLUSIONS

In this paper, a DSP based differential relay for large power transformer has been implemented and simulated. The proposed algorithm is based on the theory of harmonic analysis to discriminate between the internal fault and the inrush current created during the switching of the power transformer.

As Matlab \ Simulink lacks a toolbox that helps us in simulating protective devices; we have developed our own Relay's model. The simulation results of the proposed differential relay gave very satisfactory results in term of discrimination as well as in term of rapidity (operating time).

The success of such algorithm for digital relays allows reducing the complexity of traditional relays with more accurate results, higher reliability and less cost.

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