Algorithm for Identification the Transformer Working Condition

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Abstract – **This paper presents an algorithm for detection of transformer's working regime, which allows avoiding the incorrect differential protection operation caused by the magnetizing inrush current during transformer's energization. The proposed algorithm is tested with simulations for a 20 MVA, 110/20 kV transformer.**

Keywords – **Power transformer, working regime identification, magnetizing inrush current.**

I. INTRODUCTION

Three main types of detection of internal faults in power transformers are known [6]. Two of them are based on measurement of currents, including increase of phase currents and increase of differential current. These faults are detected by dedicated equipment: overcurrent protection for phase currents and differential protection for differential current.

The differential protection is the fastest transformer protection as its goal is internal short circuit recognition, i.e. a switch-off signal should be issued to save expensive equipment. The major drawback of differential protection is the possibility for false operation caused by the magnetizing inrush current during transformer energization. The main concern in this type of protection is the recognition of transformer's work condition as the fault current's characteristics are very similar to magnetizing inrush current characteristics. Nevertheless, the harmonic component's content of the inrush current allows it's identifying.

The energization of transformer causes a transient process and magnetizing inrush current with the following characteristics [7] [8]:

- DC offset;
- Odd and even harmonics existence;
- Second-harmonic component increases with the decrease of the inrush current.

Two basic types of inrush current detection methods have been implemented based on these features [8] [9] [10] [11]:

Harmonic restrictors, that operate based on calculation of second to fundamental and fifth to fundamental harmonic ratios;

Waveform recognition; for instance recognizing the length of the time intervals during which the differential current is near zero.

This paper describes a generalized approach on power transformer's work condition identification based the two basic methods for inrush current detection. The goal is to achieve real-time work conditions identification algorithm that detects: normal work; no-load and internal short-circuit.

The principles of real-time current differential protection are used where the switching-off signal is the difference between the currents measured on both sides of the transformer.

II. SCOPES AND GOALS

At normal working condition the primary circuit currents and the rated secondary circuit currents have approximately equal magnitude and are shifted at an angle of approximately 180 degrees. There is a small differential current due to the magnetizing current, core losses and possible inaccuracy of measurements, whish should be accounted in the protection adjustment.

The energization of transformer at no-load causes a transient process whish is very similar to internal short circuit. Differential protection algorithms should detect this regime and avoid false relay operation. The most widely used techniques in this situation are based on the analysis of the second harmonic component, which presents in the inrush magnetizing current.

External short circuits could lead to an increase in the differential current also and thus could provoke false operation of the protection. To avoid this, a restraint current is applied with a value that defines the threshold of protection switching.

To assure correct protection behavior, the secondary transformer circuit is rated using equilibration coefficients, accounting the influence of magnetizing current and core losses.

III. ALGORITHM DESCRIPTION

A. Prerequisites

The object under consideration is two-winding power transformer 110 kV/20 kV, connection Y_0 /Y.

The input quantities are analogue – the phase currents in primary and secondary windings and the neutral current.

The algorithm is developed to analyze each phase separately.

All analysis are completed for three-phase symmetrical short circuit. Non-symmetrical short circuits are not considered.

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The differential protection is presented with its restraint characteristic (Fig.1). It has three sections – one horizontal and two sloped. The slopes of the restraint characteristic vary between 0.1÷0.5 for the second section and between 0.2÷0.7 for the third section depending on transformer's power. For this work the slopes are taken as follows:

0.1 for second section slope;

0.3 for third section slope.

The limits of the restraint characteristic are assumed as follows:

Horizontal section up to $0.5I_n$;

First slope section $(0.5\div2.5)I_n$;

Second slope section above $2.5I_n$.

The protection itself is not object of this study and is not considered also.

The quantum frequency of the input electrical signals is 1000 Hz, i.e. at each 1 ms a current's instantaneous value is taken.

Nominal and maximum currents are calculated for both power transformers' sides:

$$I_{n1}=\frac{S_n}{U_{n1}\sqrt{3}} \qquad I_{\max 1}=I_{n1}\sqrt{2}$$

$$I_{n2}=\frac{S_n}{U_{n2}\sqrt{3}} \qquad I_{\max 2}=I_{n2}\sqrt{2}$$

This calculus is done once and is based on transformer's parameters.

All quantities for the secondary winding have been transferred to the primary and the equilibration by module and phase angle is made. Modulus equilibration is rated on primary nominal current and angle equilibration is rated on transformer's primary winding. Protection ignores zero-ordered currents. Rating is mandatory as transformers (power and current) coupling should be taken in consideration.

The values of equilibration coefficients are defined once using as input: the nominal power, nominal linear voltages, windings coupling and primary nominal currents of current transformers.

The modulus of equilibration coefficients are equal to:

$$I_{nm.m.}\frac{I_{\text{вх}}}{I_n}\sqrt{3}\frac{U_\Lambda}{S_n},$$

where $I_{\text{пт.т.}}$ – nominal current of the current transformer;

U_Λ – nominal voltage of the current transformer;

I_n – nominal current of the power transformer.

Angle equilibration coefficients are calculated depending windings coupling and zero-ordered currents.

B. Digital Filter

The digital filter is used to settle the fundamental and the second harmonic components of the calculated differential current. It is based on the presumption that inrush current could be described as sum containing exponential component and high-frequency harmonics:

$$i_{dif}=I_0e^{\alpha t}+\sum_{k=1}^{5}I_k\sin(k\omega t+\varphi_k),$$

$$i_{dif}=I_0e^{\alpha t}+\sum_{k=1}^{5}I_k\cos(\varphi_k)\sin(k\omega t)+ \\ +\sum_{k=1}^{5}I_k\sin(\varphi_k)\cos(k\omega t) \qquad (1)$$

Here k is the consecutive high harmonic.

It is assumed that the inrush current could be reproduced in an adequate manner if it's shaped with harmonics up to 5th including. The similarity of the differential current waveform with that of the inrush magnetizing current (with minimum RMS error) is a criterion to recognize the no-load energization. In the procedure of error minimization the digital filter coefficients are also RMS calculated.

TABLE I
DIGITAL FILTER COEFFICIENTS, SINUSOID AND CO SINUSOID CONSTITUTIONALS FOR THE FUNDAMENTAL AND THE SECOND HARMONIC

Num ber	***Sin correction funda mental (sin50)***	***Sin correction second harmonic (sin100)***	***Cosin correction funda mental (cos50)***	***Cosin correction second harmonic (cos100)***
1	0.064516	0.064516	0.301832	0.147130
2	0.074738	0.060534	0.009637	0.039017
3	0.084127	0.034127	0.098432	0.114435
4	0.065109	0.024570	0.075844	0.092640
5	0.027675	0.084127	0.075520	0.049231
6	0.003225	0.103225	0.110598	0.005166
7	0.027675	0.077675	0.105704	0.053612
8	0.057134	0.029258	0.068718	0.101044
9	0.087127	0.027675	0.053997	0.097436
10	0.095616	0.080390	0.043603	0.052587
11	0.096774	0.103225	0	0

The filter works with a full data image, i.e. the maximum delay is one period of fundamental frequency – 20 ms. Actually, values attend their real ratios after 12th ms and the real filter delay varies between 12 and 15 ms. Multiplication is among the longest processor tasks and the algorithm should work in real time so multiplications number should be reduced. To achieve this goal the algorithm joins the instantaneous values of the differential current. During this join the couples can possess different signs.

TABLE II
SIGNS OF COUPLES ON JOINING

Couple / orthogonal component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***
sin50	+ +	+ +	+ +	+ +	+ +	- -	- -	- -	- -	- -	-
sin100	+ +	+ +	+ +	- -	- -	- -	- -	- -	+ +	+ +	+
cos50	- +	- +	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -	0
cos100	- +	+ -	+ -	+ -	+ -	+ -	- +	- +	- +	- +	0

C. Restraint characteristic

A dual slope restraint characteristic is used to avoid differential protection false operation at external short circuits. The restraint operation is function of the restraint current and operational (differential) current.

The restraint current is obtained as average sum of the biggest instantaneous values of primary and secondary windings currents. The restraint characteristic is a seesaw line composed of three sections: horizontal; first slope with tgα_1 ; second slope with tgα_2 – fig. 1.

Section limits defined by the restraint current are follows:

Horizontal, defined by restraint current with magnitude up to 0.5In;

First slope inclined on tgα_1 and limits defined by restraint current with magnitude from 0.5 to 2.5In;

Second slope inclined on tgα_1 and limits defined by restraint current with magnitude from 0.5 to 2.5In;.

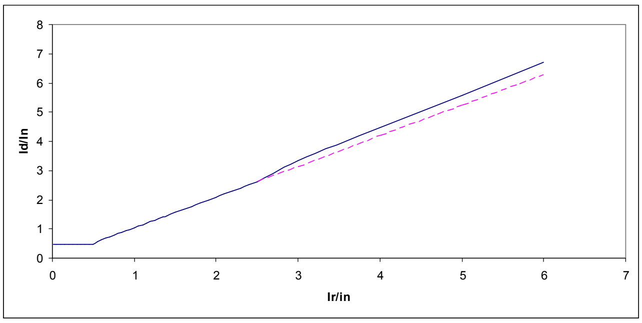


Figure 1
Dual slope restraint characteristic

The current instantaneous value of the base restrain current is composed of the sum of all phase instantaneous values multiplied by constant 50*10^{-3} (industrial frequency divided on quantum frequency). Thus an average is calculated for the entire modulation period.

The value obtained is compared with current limits of the restraint characteristic so its position is identified. According to the position in the characteristic the value of the operative restrain current is calculated.

D. Operation

The operational current is calculated as an average value of the fundamental obtained via digital filtration. This value is compared with the restraint current's instantaneous value and in when it is bigger or equal the protection is put on operation. The harmonic blocking checks for second harmonic component in the differential current and depending on the result no-load energization regime is recognized or internal fault. The restraint mechanism forbids transformer's switch-off when the ratio second harmonic / fundamental is bigger than a constant with a value between 0.01 and 0.4. In most cases this constant is taken 0.2 [5].

IV. ALGORITHM'S TEST

A. Transformer parameters

The algorithm is simulated with a 20 MVA rated power transformer, 110 kV / 20 kV, Y$_0$/Y. Coupling of CTs is considered when digital filter coefficients are calculated.

All nominal and maximum currents are calculated after transformers data introduction.

The ratio second harmonic / fundamental after which the protection is set in operation is 17%.

B. Work conditions detection

Energization at no-load

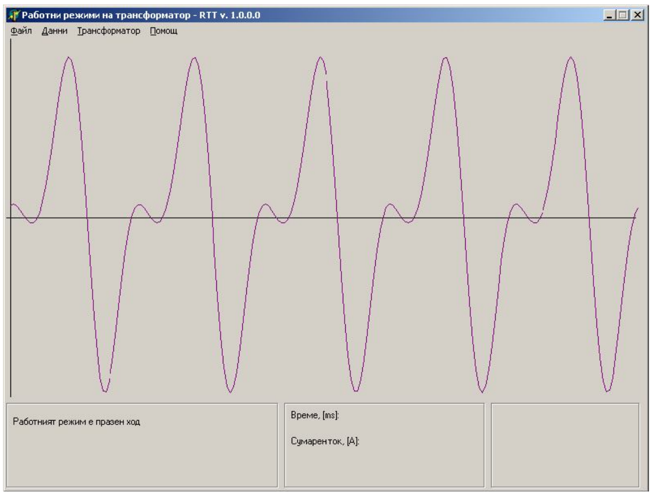
A practically observed and confirmed inrush current's curve is used [2][3][4]. Its high harmonic constitution is listed in the table bellow, no a-periodic offset.

TABLE 3
PERCENTAGE OF HIGH HARMONICS RATIONED TO FUNDAMENTAL ON INPUT CURRENT FORMING FOR NO-LOAD ENERGIZATION

Harmonic	Modulus %	Phase °
1	100	-145
2	78	76
3	10	-45

The curve of phase current is shown in figure 2. The working condition expected is no-load energization, as the second harmonic/fundamental ratio is 78% and protection's operational limit is 17%.

The model of currents chosen supposes recognition of an internal short circuit as the differential current increases, but the harmonic restraint correctly calculates the presence of a high value of second harmonic component and forbids protection set-on.



Работният режим е празен ход

Време, [ms]:

Сумарен ток, [A]:

Figure 2
Input current and no-load energization regime detected of the power transformer.

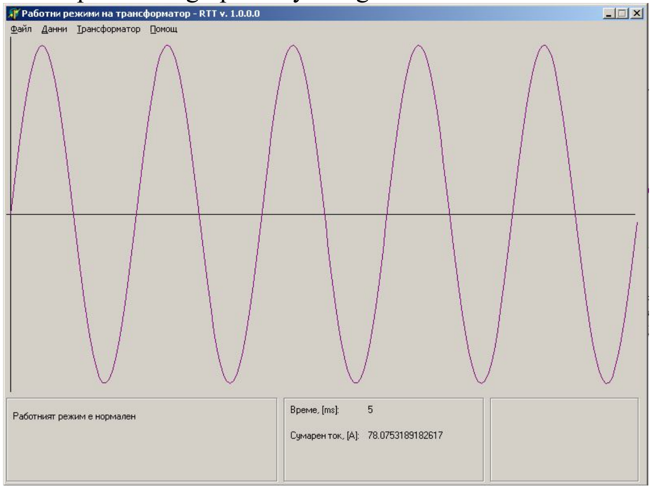
Normal working condition

The curve is a sinusoid based on the following prerequisites:

TABLE 4
PERCENTAGE OF HIGH HARMONICS RATIONED TO FUNDAMENTAL ON INPUT CURRENT FORMING FOR NORMAL WORKING CONDITIONS

Harmonic	**Modulus %**	**Phase °**
1	100	180
2	0	0
3	0	0

It is presented graphically in figure 3.



Работният режим е нормален

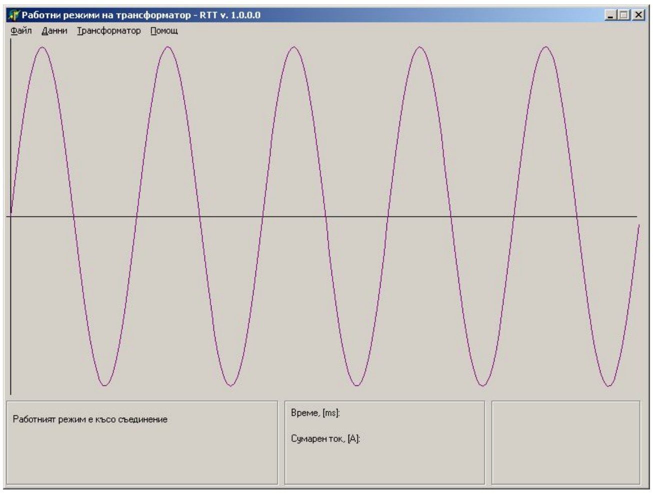
Време, [ms]: 5

Сумарен ток, [A]: 78.0753189182617

Figure 3
Input current and detected normal working condition of power transformer

The working condition expected is normal as no high harmonics in phase currents are presented in the model chosen and it evolves by $i_t = I_{\max} \sin(\omega t + \varphi)$. No differential current will appear and the restraint current will always be superior. Thus, the protection will never be set on operation.

Internal short circuit



Работният режим е късо съединение

Време, [ms]:

Сумарен ток, [A]:

Figure 4
Input current and detected working condition on internal short circuit of power transformer

A symmetrical internal short circuit with one winding power supply and current peak of $8I_n$ is simulated. This is abnormal working condition defined by input current 8 times bigger than the nominal but with the same distribution law as on normal working conditions on transformer's primary winding. No current appears in the secondary winding.

To obtain this we need to make the secondary winding linear voltage equal to zero.

The instantaneous values of the differential current are quite bigger than the restraint current's and the ratio second harmonic/fundamental is lower than the constant chosen 17% (fig.4). The algorithm recognizes the internal short circuit.

V. CONCLUSION

An algorithm for power transformer working conditions detection and a program for its practical application is developed. The program is dedicated to avoid incorrect set-offs due to differential protection false operation when energizing the transformer at no-load. The algorithm is based on measurement of currents in both transformer windings and real-time data treatment.

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