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Using Digital Relays for Improved Power Transformer Differential Protection

D. C. Idoniboyeobu[1*] and D. M. A. Bob[1]

[1]*Department of Electrical Engineering, Rivers State University of Science and Technology Nkpolu, Port-Harcourt, Nigeria.*

Authors' contributions

This work was carried out in collaboration between both authors. Author DCI designed the study. Author DMAB performed the statistical analysis and wrote the protocol. Author DCI wrote the first draft of the manuscript and managed literature searches. Authors DCI and DMAB managed the analyses of the study and literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

Power transformers form a vital component of the electrical power system; hence the protection of this equipment is a matter of priority towards ensuring a stable power supply. The unplanned outages of a power transformer could cost utility millions of dollars. It is therefore of great importance to minimize the frequency and duration of unwanted outages due to power transformer faults. This work focuses on improved methods of power transformer differential protection using weighted least square scheme. This scheme ensures security for external faults, inrush currents, over excitation conditions and provides dependability for internal faults.

Keywords: Differential protection; Inrush current; percentage restraint; harmonic; harmonic component; fault current.

**Corresponding author: E-mail: dikioidoniboye@yahoo.com;*

1. INTRODUCTION

The continuity of the power transformer operation is of vital importance in maintaining the reliability of the power system. Since there is no known method of stopping electrical faults, protection of very sensitive equipment like the power transformer against faults require high speed, and reliable protective relays. For this purpose, protection schemes adopting the use of digital relays become a matter of priority [1,2,3,4,5,6,7,8,9].

Protection scheme required for the protection of power system components against abnormal conditions such as faults essentially consist of protective relaying and circuit breaker [10,11]. The protective relay functions as a sensing device [12,13,14,15]. It senses the fault, and then determines its location and finally, sends tripping command to the circuit breaker. The circuit breaker on receipt of the command disconnects the faulty section. The usefulness of reliable efficient fast-operating digital relays cannot be overempersised.

The approach of the use of Digital relays [12,6,16,17] in the protection of power transformers ensures security for inrush and over excitation conditions in a power transformer which produce false differential currents that could cause relay mal-operation. In the area of digital protection of power transformer, two different approaches have been used to distinguish between the internal fault currents and the magnetizing inrush current. The first approach considers the use of digital filters for separating fundamental and second harmonic component from the differential wave form. The second approach to distinguish the inrush current from internal fault current is by correlating the differential current waveform with a pair of orthogonal waveforms like sine, cosine and odd-even square waves of one cycle duration. In this work, the least square filtering approach for transformer differential protection using digital simulation for variety of inrush and fault current data is being used.

2. MATHEMATICAL BACKGROUND

In the wave-form modeling, the differential fault current and inrush current wave forms of a power transformer are assumed to comprise of a decaying dc component plus fundamental and selected higher harmonics. The model coefficients are estimated by using weighted least square filtering technique [18,19]. Using pre-fault and post fault differential current samples. A general model of the inrush or fault [18] current waveforms of a power transformer is given by

$$X\ (t) = \Sigma_{m=1}\ Y_m \mathrm{Sin}\ (m\omega t + \theta_m) + Y_O\ e^{-t/}\tau \quad (1)$$

Where

$X(t)$ = instantaneous differential current sample at time t.
Y_m = peak component of the m^{th} harmonic differential current.
Y_O = dc component.
τ = decay time constant of the dc component.
$\omega = 2\pi ft$, where f is the frequency of the waveform.

Equation 1 can be expanded in the form while recalling from our Trigonometical identities as
Sin (A+B) = SinACosB + CosASinB
Sin (A-B) = SinACosB –CosASinB

Then we write in the form

$$X\ (t) = \Sigma_{m=1}\ Y_{ms}\mathrm{Sin}\ m\omega t + Y_{mc}\mathrm{Cos}\ m\omega t + Y_O + Y_0^{'}\ (t) + Y_0''(\ t^2\ ) \quad (2)$$

Where Y_{ms} is the magnitude of the sine component and Y_{mc} is the magnitude of the cosine component.

If X_m (t) represents the measured instantaneous sample of the differential current at time t, and error e(t) is obtained as;

$$e\ (t) = X_m\ (t) - X(t) \quad (3)$$

Now if n samples are taken, a weighed least square error vector can be formed as;

$$e = \{\ X_m\ (t) - X\ (t)\}^T\ Q\ \{\ X_m\ (t) - X(t)\ \} \quad (4)$$

Where Q is a weighting matrix and the value of X (t) will be given by;

$$\begin{bmatrix} X(t_1) \\ \vdots \\ X(t_3) \\ X(t_4) \\ \\ \\ \vdots \\ X(t_n) \end{bmatrix} = \begin{bmatrix} Sin\omega t_1 Cos\omega t_1 & \cdots & Sin2\omega t_1 Cos2\omega t_1 & t^2 \; t_1 1 & & & \cdots & \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ Sin\omega t_3 Cos\omega t_3 & \cdots & Sin2\omega t_3 Cos2\omega t_3 & t_3^2 t_3 1 & & & \cdots & \\ Sin\omega t_4 Cos\omega t_4 & \cdots & Sin2\omega t_4 Cos2\omega t_4 & t_4^2 t_4 1 & & & \cdots & \\ & \cdots & & & & & \cdots & \\ & \cdots & & & & & \cdots & \\ \vdots & \ddots & \vdots & \vdots & \vdots & \cdots & \ddots & \vdots \\ Sin\omega t_n Cos\omega t_n & \cdots & Sin2\omega t_n Cos2\omega t_n & t_n^2 t_n 1 & & & \vdots & \end{bmatrix} \begin{bmatrix} Y_{1s} \\ \vdots \\ Y_{3s} \\ Y_{4s} \\ \\ \\ \vdots \\ Y_{ns} \end{bmatrix} \tag{5}$$

And p = order of the model.

In many applications of matrices to technological problems involving oscillations, vibrations, etc, equations of the form

$$\mathbf{A}x = \boldsymbol{\Lambda}x$$

Where A is a square matrix, x is a column matrix and $\boldsymbol{\Lambda}$ is a scalar quantity.

If n > p, equation 2 may be solved in the least square sense as

$$[Q]\,[A]\,[Y] = [Q]\,[X(t)] \tag{6}$$

[W]=Normalized weighting matrix
[Q]=Weighting matrix (Scalar)
[Y]=Matrix of peak component of differential current dc component
[A]=linear transformation of a skew matrix

Where q i j are elements of the weighting matrix [Q], the weighting matrix [Q] can be chosen to improve the fit at sample points likely to be subjected to less random measurement noise. The coupling terms q_{ij} ($i \neq j$) determine the weight given to minimize the i_{th} and j_{th} combined, error. If additional harmonic distortion not accounted for in the model is suspected, then sample points spaced at ½ harmonic period may be coupled to reduce the systematic error introduced.

If the rank of [A] is p and $[Q^T]\,[Q]$ is symmetric and positive definite, the weighted least square solution of equation 5 is determined from the weighted normal equations. If we multiply both sides of equation 6 by $[A^T]\,[Q^T]$, we have;

$$[A^T]\,[Q^T]\,[Q]\,[A]\,[Y] = [Q]\,[X(t)]\,[A^T]\,[Q^T]$$

Which gives

$$[A^T]\,[Q^T][A]\,[Y] = [A^T]\,[Q^T]\,[X(t)] \tag{7}$$

From equation 6 we can simplify to get:

$$[Y] = [A]^{-1}\,[X(t)] \tag{8}$$

Since $A^{-1} = W$

And $[A]^{-1}\,[A] = [I]$ unity matrix

$$[Y] = [W]\,[X(t)] \tag{9}$$

Substituting equation 8 into equation 6 we have

$$[Q]\,[A]\,[W]\,[X(t)] = [Q]\,[X(t)] \tag{10}$$

Simplifying further, we have

$$[Q]\,[A]\,[W] = [Q] \tag{11}$$

Multiplying both sides of equation 11 by the components $[A^T]\,[Q^T]$ we have

$$[A^T]\,[Q^T]\,[Q]\,[A]\,[W] = [A^T]\,[Q^T]\,[Q] \tag{12}$$

Where the normalized weighting matrix [W] is;

$$[W] = \{[A^T]\,[Q^T]\,[Q]\,[A]\}^{-1}\,[A^T]\,[Q^T]\,[Q] \tag{13}$$

And T = transpose of quantity.

The computational overhead of equation 7 may be reduced by noting that the choice of t in equation 8 is arbitrary. Without loss of generality, a value of t may be arbitrarily chosen such that [A] is a linear transformation of a skew symmetric matrix.

Substituting Y in equation 5, we get an error vector e of the form $e = X_m(t) - X(t)$ and the root mean square error (RMSE) is obtained as

$$\mathrm{RMSE} = \sqrt{\frac{[X_m(t) - X(t)]^{I}\, Q\, [X_m(t) - X(t)]}{N}} \qquad (14)$$

Where N = number of samples (data window) used for performing computation.

By adding more harmonics to the model, by increasing the data window, a comparison of the RMSE gives an idea of the correct model to be chosen and also the data window required for computing weighting factors.

3. METHODOLOGY

In case of power transformer, the magnetizing inrush currents need to be modeled up to the 5th harmonic, thus a sampling rate of 600Hz is adequate for detection of all significant frequency components. It is general practice to sample at rate of 2.5 times the highest power frequency component present to overcome such problems as finite roll-off time filters and spurious high frequency noise components. The most realistic approach is governed by the availability of computation time between one sample and the next and the delay causes by the filters. Based on these considerations, a sample rate of 720Hz (12 samples per cycle) is chosen as the sampling rate. The differential inrush current contains significant 2nd harmonic component and also some amount of 3rd harmonic components. The dc component is present in case of periodic inrush current, but is practically absent in case of periodic inrush current. In certain cases of Current Transformer (CT) saturation and over excitation of transformers significant amounts of 5th harmonic currents are found. Thus in general, the power transformer fault or inrush current model is of the form:

$$X(t) = Y_O + Y'_O + Y''_O t^2 + Y_{m1}\sin\omega t + Y'_{m1}\cos\omega t + Y_{m2}\sin 2\omega t + Y'_{m2}\cos 2\omega t + Y_{m3}\sin 3\omega t + Y'_{m3}\cos 3\omega t + Y_{m5}\sin 5\omega t + Y'_{m5}\cos 5\omega t + \qquad (15)$$

However, the correctness of the model depends on the type of transformer and the operating conditions mentioned earlier. It may be desirable to consider only up to 2nd harmonic and fit the model with measured data and compute RMSE for the model. Then the model order is increased by adding more harmonic and comparing the RMSE. The lowest RMSE gives the correct model for the fitted data. For transformer protection, the weights are computed as shown in equation 6 and are used to compute the peak values of fundamental and 2nd harmonic components using the change of differential current data from sample to sample.

4. RESULTS

The wave-forms of the internal fault and inrush currents are generated by EMTP software, as shown in Figs. 1 and 2.

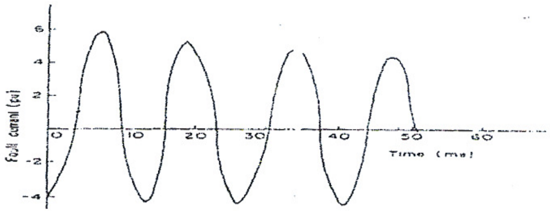

Fig. 1. Internal fault current waveform

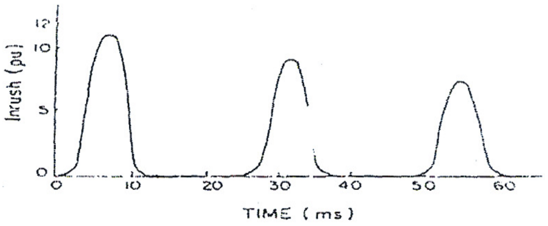

Fig. 2. Magnetizing inrush waveform

5. DISCUSSION OF RESULTS

5.1 Comment on Fig. 3

Fig. 3 shows the performance of the least square filter for inrush current waveforms for two different conditions (i) when the waveform is modeled up to 2nd harmonic and (ii) when it is modeled up to 3_{rd} harmonic. Between 0-0.6ms there is an overlap of the restraining current and the operating current hence there is the likelihood of relay mal operation as the relay is expected to restrain operation. Using the 2nd harmonic model, the chance of mal operation of the relay is evidenced as shown in Fig.3 the 3_{rd} harmonic model, however yields sufficient restraint for inrush current waveforms.

5.2 Comment on Fig. 4

Fig. 4 shows the inrush performance of the 5th harmonic model. It is found that the restraining current (graph A), do not at any time overlap or intersect with the operating current (graph B). This is an indication that the restraint is sufficiently large and there is no chance of relay mal operation.

5.3 Comment on Fig. 5

Fig. 5 shows the performance of the least square filter for internal faults on the power transformer.

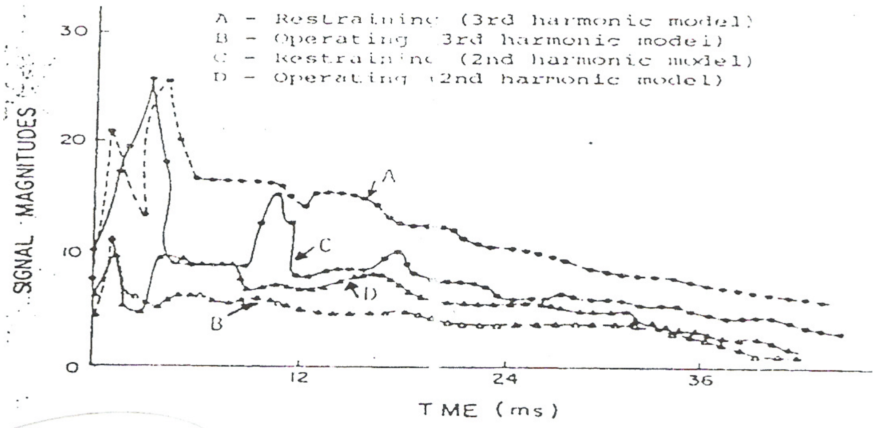

Fig. 3. Inrush performance of 2nd and 3rd harmonic models

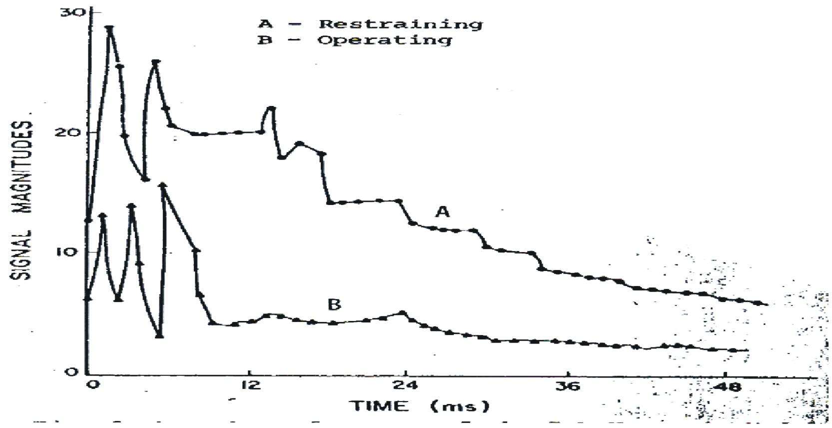

Fig. 4. Performance of 5th harmonic model

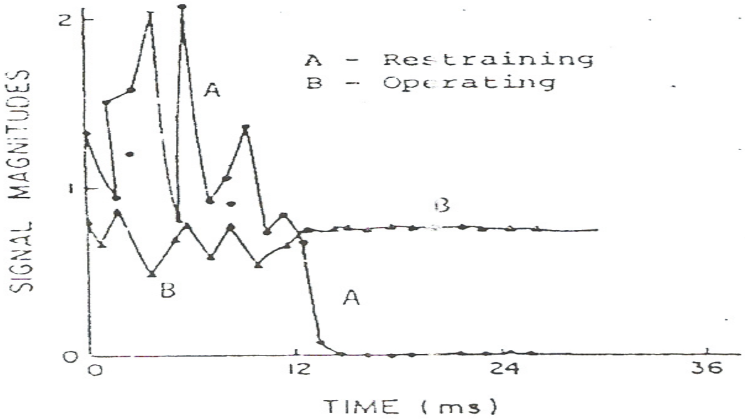

Fig. 5. Internal fault current performance of 2nd and 3rd harmonic model

It also shows a tendency of the relay mal operation at some time between 0 - 0.14ms. For all the three models, the time taken to respond to an internal fault is of the order of 11-12 samples, ie one cycle based on 720Hz sampling rate. The performance of the 5_{th} harmonic filter is found to be more stable in comparison to either 2_{nd} or 3_{rd} harmonic filters for internal fault conditions.

For real-time implementation of digital protection of a three phase power transformer a sampling rate of 720Hz based on a 60Hz waveform is chosen. This gives a computing time of 1.389ms between consecutive data samples. The model co-efficient are computed off-line and are stored as scaled integers in the computer memory. The total number of multiplication for the above algorithm shall be 18 for three phases and shall require 630μs execution time. The total time including data acquisition and other program execution shall be 630μs. thus the real time restriction of 1.389 milli second is adequate for completing the execution of the least square algorithm on a microprocessor with an execution time of 16 – 35μs.

6. CONCLUSION

The least square filtering algorithm for the harmonic restraint differential protection of power transformers is presented in this work. The study showed an improved method of power transformer differential protection using weighted least square scheme. This approach assumes that the fault current waveform contains a decaying DC component, a fundamental component and substantial amounts of 2^{nd}, 3^{rd} and 5^{th} harmonic components, the later mostly during saturation and over-excitation conditions. Wave shape recognition technique is another alternative for discriminating internal fault from inrush conditions. Unfortunately, this technique fails to identify transformer over excitation conditions. The least square approach is thus better for these applications. The technique can be programmed in real-time for implementation with a microprocessor. An RMSE criterion has been established to identify the correct model to fit in a set of sampled data of the differential current waveforms. For fast decaying inrush current waveforms, the algorithm yields excellent restraint; whereas, with slow decaying waveforms, the restraint seems to be smaller. However, choosing a proper model of the waveform, sufficient restraint can be generated against the inrush current. The performance of the filter for internal fault currents is of the order of 1 cycle based on 60Hz waveforms. This time could be further reduced by choosing a higher sampling rate, i.e. 16 samples per cycle. However, for microprocessor application a higher sampling rate is undesirable, as it results in the availability of less time for on-line computation.

7. RECOMMENDATION

7.1 Common Harmonic Restraint/Blocking

The evaluation of existing harmonic restraint/blocking methods makes it clear that independent restraint/blocking methods may fail to ensure security for some real-life inrush conditions. Common harmonic restraint blocking could provide solutions, but the behaviour of these methods for internal faults combined with inrush currents requires further study. Combining restraint and blocking into an independent restraint blocking methods provide a new approach to transformer differential protection. Even harmonics of the differential current provide restraint, while both the fifth harmonic and d.c. component block relay operation.

7.2 Use of Optical Current Transformers

The optical current transformers have many essential advantages over the classical current transformers. The lack of saturation effect, which will help avoiding many problems with differential relaying, is the primary benefit apart from excellent electric isolation and absence of any flammable materials such as oil. Present-day optical current transformers are of two types: a bulk optical current transformer which uses a ring-like glass sensor and an optical fiber current transformer which uses an optical fiber as a senior. The later kind displaying higher accuracy is of a particular interest.

The Rogowski's coil, a current measuring device that produces a low power output but offers many advantages over the classical current transformers, is another option for improving the operating conditions for power transformer protection [14,20].

The integrated measuring unit for both voltage and current is a good example. The operating principle of it is based on Poynting's theorem which defines the electromagnetic energy in terms of the electric and magnetic field intensities at a point in space. The current is measured by sensing the tangential component of the magnetic field. The voltage is measured by sensing the radial component of the electric field in a well defined region around the high voltage conductor.

However, it is anticipated that in the near future more measurements will be available to power transformer relays owing to both substation integration and novel sensors installed on power transformers. All these will change the practice for power transformer protection.

7.3 Application of the BE1-700 Digital Protection Relay

The BE1-700 digital protective relay is a product of Baseler Electric, Highland, Illinois USA. It is a multifunction device with features and capabilities that enhances faster, more secure and dependable protection of the modern power transformers [10].

In this project, the application of the BE1-700 digital protective relay is being considered as suitable for the protection of power transformers. It is noteworthy that the availability of electric power is a key factor for the economic and industrial development of any Nation.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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