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Waveform feature monitoring scheme for transformer differential protection

Bahador FANI[†1], Mohamad Esmail HAMEDANI GOLSHAN[1], Hosein ASKARIAN ABYANEH[2]

([1]*Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran*)

([2]*Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran*)

[†]E-mail: fani@ec.iut.ac.ir

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Abstract: We propose a new scheme for transformer differential protection. This scheme uses different characteristics of the differential currents waveforms (DCWs) under internal fault and magnetizing inrush current conditions. The scheme is based on choosing an appropriate feature of the waveform and monitoring it during the post-disturbance instants. For this purpose, the signal feature is quantified by a discrimination function (DF). Discrimination between internal faults and magnetizing inrush currents is carried out by tracking the signs of three decision-making functions (DMFs) computed from the DFs for three phases. We also present a new algorithm related to the general scheme. The algorithm is based on monitoring the second derivative sign of DCW. The results show that all types of internal faults, even those accompanied by the magnetizing inrush, can be correctly identified from the inrush conditions about half a cycle after the occurrence of a disturbance. Another advantage of the proposed method is that the fault detection algorithm does not depend on the selection of thresholds. Furthermore, the proposed algorithm does not require burdensome computations.

Key words: Transformer differential protection, Differential current waveform, Inrush current, Fault current, Waveform feature, Waveform processing

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1 Introduction

The power transformer is one of the most important components in a power system. It possesses certain special features, which make complete protection difficult. Differential protection is commonly used as the primary protection of the power transformers. While it should operate rapidly when internal faults occur, differential protection should be blocked under non-fault conditions such as inrush current. The security and speed requirements of transformer differential relays appear to be crucial in the matured power systems, including modern power transformers. These systems require small fault clearing time to avoid equipment damages and stability problems due to high level short circuit currents. In addition, in some possible conditions, the conventional algorithms such as those based on the principle of the second harmonic restraint may operate wrongly for inrush current or clear faults with unacceptable delays. In recent years, the possibility of implementing more complicated and efficient algorithms has been provided in the digital relays. Therefore, researchers have been motivated to develop more secure differential protection algorithms with an emphasis on improvements in operation speed and reliability for different kinds of transformer internal faults.

One class of the transformer differential protection algorithms is based on the equivalent circuit of the transformer such as transformer model based modal analysis (Sidhu and Sachdev, 1992), the leakage inductance based technique (Ge *et al.*, 2005), and the induced voltage based method (Kang *et al.*, 2007).

Some transformer differential protection algorithms are based on processing the harmonic content of the differential currents. The conventional approach uses the principle of the second harmonic restraint (Guzman *et al.*, 2001). The main drawback of the method is that the possible harmonic in the internal fault current can cause differential relay either not to operate or to operate with a long delay. In addition, any internal fault with energizing cannot be cleared quickly until the inrush current fades out, and thus the differential relay is unblocked. To improve the performance of the second harmonic based algorithms, some novel techniques such as voltage restraint (Liu *et al.*, 1992), complex second harmonic restraint (Kulidjian *et al.*, 2001), dynamic digital filter (Al-Othman and El-Naggar, 2009), and harmonic characteristics based schemes (Hamedani Golshan *et al.*, 2004; Hamedani Golshan and Samet, 2006) have been proposed.

In some algorithms, faults conditions are recognized by distortion characteristics of the differential current waveform. The operation criterion in the conventional method is the duration in which differential current remains near zero (Giuliante and Clough, 1991). Asymmetry of inrush current is decreased by the saturation of current transformers when dead angles disappear. As a result, some improved methods such as short-time correlation (Zhang *et al.*, 2002), correlation analysis of waveform (Lin *et al.*, 2002; Bi *et al.*, 2007), morphological scheme (Lu *et al.*, 2009), and method based on error estimation (He *et al.*, 2006) have been proposed to obtain better identification results.

Other algorithms have taken advantage of wavelet transform (WT) (Ozgonenel, 2006; Samantaray *et al.*, 2007), artificial neural network (ANN) (Tripathy *et al.*, 2008), the fuzzy inference system (FIS) (Shin *et al.*, 2003), the transmission line method (TLM) (Ozgonenel *et al.*, 2007; 2008), hidden Markov models (HMM) (Ma and Shi, 2000), and principal component analysis (PCA) (Kilic *et al.*, 2009).

Some of the conventional methods require the equivalent circuit parameters as well as iron-core constructions and winding connections of the transformer. Some of these algorithms, such as algorithms based on the dead time angle detection, have more than one cycle inherent delay. Some of these algorithms need the voltage signals other than the current signals. Almost all of them depend on the selection of thresholds. Some of them are not able to detect the faults accompanied by the magnetizing inrush.

In this paper, the general scheme for a group of transformer differential protection algorithms is presented. These algorithms are based on monitoring a special feature of the differential currents waveform (DCW) as input signals to the algorithms. Then a new algorithm related to the general scheme is introduced, and its main components are explained. These elements include behavior observation of the DCW under fault and inrush current conditions, choosing the second derivative sign as the feature of these signals for discrimination between fault and inrush currents, defining a discrimination function (DF) for quantifying the signal feature, tracking the signs of three-phase decision-making functions (DMFs) computed from the discrimination function, and carrying out a suitable logic for the detection of faults. The advantages of the proposed method in comparison to the conventional methods are reliability, sensitivity, and simplicity for implementation. None of the conventional methods combine all these features.

2 Basic theory of the waveform feature monitoring scheme

A group of the transformer differential protection algorithms belong to a general scheme based on monitoring a special feature of the DCW. The scheme originates from the different characteristics of the differential currents or some quantities extracted from them under internal faults and inrush current conditions after occurrence of in-zone disturbances. Based on this idea, the corresponding algorithms process the DCWs for distinguishing internal faults from inrush current conditions after detection of in-zone disturbances. In the first step, the differential currents, or some quantities related to them such as the normalized second harmonic of the differential currents (the original signals) are considered the signals with different behaviors during a time after fault or switching inception. Then for modeling the behaviors, a feature of the original signals such as the time variations or the rate of the time variations of the signals (signal feature) is chosen. In the next step, to quantify the chosen feature, a DF is defined and computed for three phases by using the samples of the original signals. As time passes from the instant of disturbance inception, the behavior of the original signals and corresponding DFs may change. Therefore, to remove the effects resulting from the varying behavior of the DFs, a DMF is defined and calculated for three phases in the fourth step. Finally, in the last step, the signs of the tracked three-phase DMFs are used to distinguish between inrush and fault currents.

3 A new algorithm based on monitoring the second derivative sign of differential currents waveform

Two algorithms based on the above general scheme have been introduced in Hamedani Golshan *et al.* (2004) and Hamedani Golshan and Samet (2006). These algorithms are based on employing the normalized second harmonic as the original signals. Some disadvantages of these algorithms are as follows:

1. Extraction of the fundamental component and second harmonic of the differential currents increases the required computations.

2. Some algorithms' parameters depend on the filter used for extracting the frequency components. These parameters are determined by trial and error.

3. In the case of energizing a faulted transformer, the algorithms fail to detect fault in a reasonable time.

The above-mentioned algorithms apply the first- or second-difference function to convert the difference between inrush and internal fault currents into a quantitative description. Also, the algorithm proposed in Kang *et al.* (2004) is based on the third-difference function of the differential current. This algorithm requires thresholds selection.

In this study, a new algorithm based on the general scheme is introduced to avoid the above-mentioned drawbacks. The first and second disadvantages are avoided since it uses the DCW directly as the original signals. In addition, it can detect internal faults in a reasonable time in all cases without using the cross-blocking principle. The algorithm includes the following elements:

1. Observations: Fig. 1 shows typical DCWs for magnetizing inrush and fault conditions immediately after the disturbance inception. Since the magnetizing inrush current corresponds to the transformer core saturation, the DCW due to inrush has a conical shape (non-sinusoidal); in other words, it begins with a low slope and then its slope is raised. But the DCW due to fault is very similar to the normal sinusoid; in other words, it begins with a higher slope and then its slope decreases. These characteristics originate from the difference in the nature of fault and inrush currents and are consistent for different transformer and power system parameters (Guzman *et al.*, 2001). Thus, the internal fault conditions can be distinguished from inrush currents by exploiting different characteristics of fault and inrush currents waveforms. Therefore, DCW can be considered the original signals.

2. Signal feature: Based on the above-stated principles, it is expected that the concavity of DCW during a short time after disturbance inception is a suitable criterion for discriminating between fault and inrush currents.

3. Discrimination function: The concavity of a signal can be determined by the sign of the second derivative of the signal. If the second derivative sign of a positive signal is positive, then the concavity of its curve is upward; otherwise, the concavity curve is downward. Therefore, the sign of the second derivative function of the positive differential currents is positive for the case of inrush current and negative for the fault current during a short time after disturbance inception. The second derivative function (SDF) of the differential currents can be calculated when the signals are processed digitally using time samples of the waveforms as

$$\mathrm{SDF}(n) = i_{\mathrm{d}}(n) - 2i_{\mathrm{d}}(n-1) + i_{\mathrm{d}}(n-2), \quad (1)$$

where $i_{\mathrm{d}}(n)$ denotes the nth sample of the differential current. The differential currents can be positive or negative after the disturbance inception depending on switching or fault instant. Therefore, because the sign of the second derivative function should always be positive for inrush current and negative for the fault current regardless of the sign of the differential currents, we define the DF using the sign function as

$$\mathrm{DF}(n) = \left(i_{\mathrm{d}}(n) - 2i_{\mathrm{d}}(n-1) + i_{\mathrm{d}}(n-2)\right)\mathrm{sign}\left(i_{\mathrm{d}}(n)\right). \quad (2)$$

The waveforms of DFs for a typical DCW are shown in Fig. 1. A practical point is related to the error in the second derivative function introduced by possible noise in the differential currents. Although fault or inrush currents do not usually contain high frequency components, some noises may be introduced by measurement processes. Such errors can be reduced using moving averages of sampled data. The moving average of order N of a set of numbers Y_1, Y_2, Y_3, … are defined as $(Y_1+Y_2+\ldots+Y_N)/N$, $(Y_2+Y_3+\ldots+Y_{N+1})/N$, … (Spiegel and Stephens, 2008). To avoid large delays caused by the process of moving averages, the moving averages of order three is used here. Thus, for computing the second derivate function, the averaged values of differential currents are used in Eq. (2) instead of the sampled values.

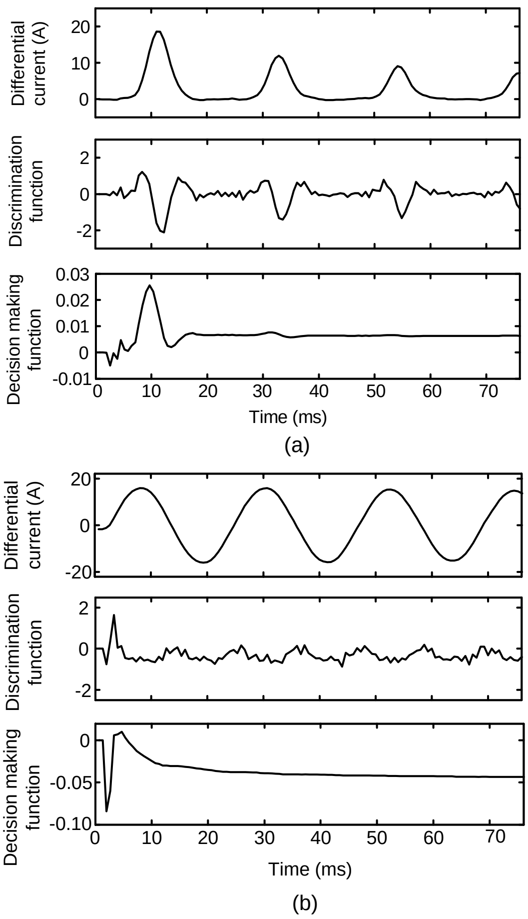

Fig. 1 Different behaviors of fault and inrush currents
(a) Typical inrush current (top) and its discrimination function (middle) and decision making function (bottom); (b) Typical fault current (top) and its discrimination function (middle) and decision making function (bottom)

4. Decision making functions: As time passes from the disturbance instant, the sign of the DFs can reverse due to the variation of the behavior of the inrush or fault current waveforms. Therefore, we define DMFs as the weighted sum of the discrimination functions values from disturbance instant up to the present time:

$$\mathrm{DMF}(n)=\sum_{h=1}^{n}\frac{\mathrm{DF}(h)}{h^2}. \tag{3}$$

In each sample n, DMF(n) is a function of the area under curve DF(n). The DMF has been defined such that the internal fault conditions can be recognized from inrush current conditions by determining only the sign of DMF. As time increases from the instant of disturbance, the behavior of function DMF reverses. The term h^2 in the denominator of the DMF is a weighting factor that increases with time. This term has been included to eliminate the effect due to the reversing behavior of DMF as time increases. From Fig. 1, DMF corresponding to inrush (fault) current becomes positive (negative) after a short time from disturbance inception. Thus, the operation of the differential relay can be based only on the sign of DMFs.

4 Experimental results

The proposed algorithm is tested on a three-phase, three-winding 5-kV·A, 400/230/20 V, 50-Hz laboratory prototype power transformer. The experimental setup for collecting different types of investigated differential currents is shown in Fig. 2. To verify the performance of the proposed algorithm, numerous tests have been carried out on this physical dynamic model. The conditions investigated include energizations, faults, and energizations with faults for the transformer under no-load or on-load conditions. Figs. 3–5 show some examples of the experimental test results. In the following analysis, the solid, dashed, and dotted lines denote phases A, B, and C, respectively. The experimental data are analyzed offline, after the DCWs are recorded at the 1.2-kHz sampling frequency.

Consider a case of energization at the high voltage side of the no-load transformer. Fig. 3 shows

DCWs, moving averages of DCWs, DFs, and DMFs for this case. As shown in Fig. 3a, DCWs corresponding to phases A and C are the asymmetric waveform, and DCW corresponding to phase B is symmetric waveform. It is observed from Fig. 3d that DMFs corresponding to the inrush currents are positive.

Table 1 gives the results of applying the proposed algorithm to some test cases. These cases are different in view of the residual flux in transformer core (high or low), the inception angle of voltage source at phase A, and transformer loading. As can be observed, the values of DMFs are positive for all cases.

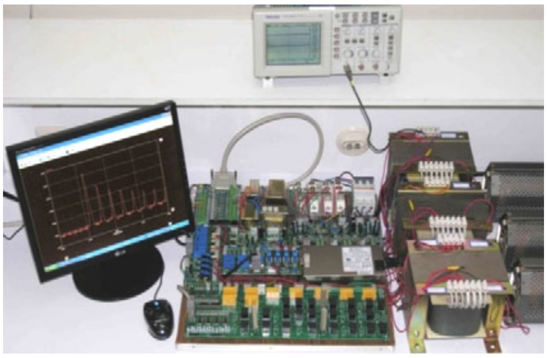

Fig. 2 Experimental setup for differential current data collections

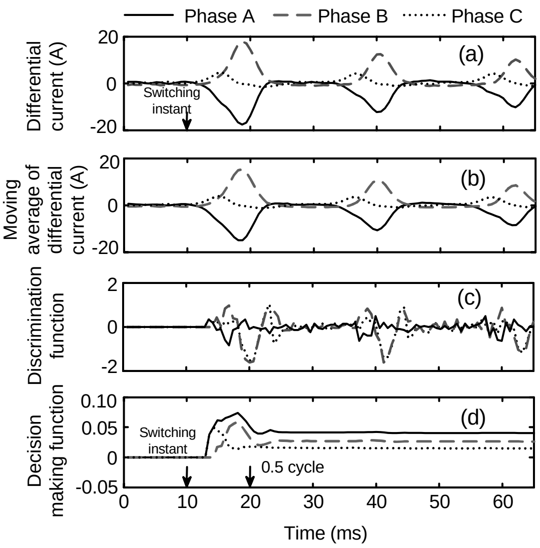

Fig. 3 Energization at the high voltage side
(a) Differential current; (b) Moving average of differential current; (c) Discrimination function; (d) Decision making function

Also, consider a case of internal AB fault (phase A to phase B) at the secondary winding side of the loaded transformer. The DCWs, moving averages of DCWs, DFs, and DMFs are shown in Fig. 4. DMFs corresponding currents are negative. In addition, in Table 2 the calculated DMF for some different fault cases including low current turn-to-turn and turn-to-ground faults under no-load and load conditions of transformers are presented. For all the cases, the proposed algorithm detects the fault conditions after 10 ms.

Table 1 The calculated DMF under inrush current tests

Residual flux	Inception angle	Phase	Calculated DMF	
			No load	On load
Low	0°	A	0.037	0.025
		B	0.037	0.027
		C	0.055	0.039
	36°	A	0.053	0.042
		B	0.045	0.058
		C	0.073	0.062
High	72°	A	0.034	0.039
		B	0.043	0.036
		C	0.052	0.048
	144°	A	0.063	0.044
		B	0.057	0.046
		C	0.073	0.044

DMF: decision making function

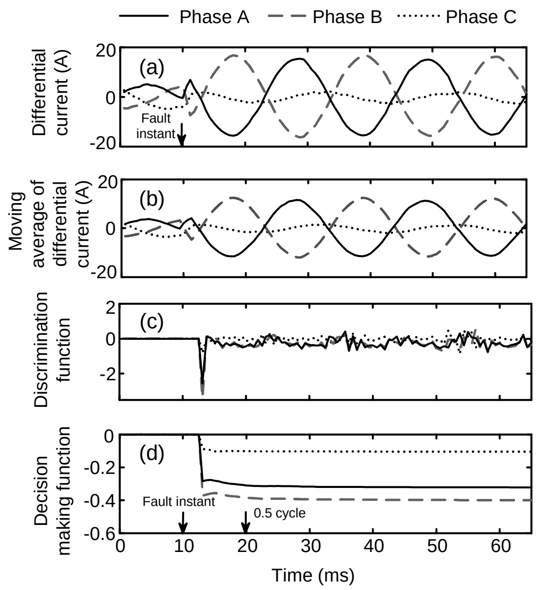

Fig. 4 An internal phase A to phase B fault
(a) Differential current; (b) Moving average of differential current; (c) Discrimination function; (d) Decision making function

Table 2 The calculated DMF under fault current tests

Inception angle	Phase	Calculated DMF			
		No load		On load	
		10% TTF	25% TGF	10% TTF	25% TGF
0°	A	−0.45	−0.42	−0.38	−0.36
	B	−0.13	−0.18	−0.16	−0.12
	C	−0.54	−0.22	−0.53	−0.27
36°	A	−0.43	−0.51	−0.51	−0.25
	B	−0.19	−0.12	−0.14	−0.12
	C	−0.31	−0.66	−0.36	−0.53
72°	A	−0.44	−0.52	−0.31	−0.51
	B	−0.18	−0.15	−0.18	−0.14
	C	−0.35	−0.27	−0.65	−0.39
144°	A	−0.52	−0.37	−0.47	−0.33
	B	−0.17	−0.17	−0.12	−0.18
	C	−0.51	−0.29	−0.51	−0.36

DMF: decision making function. TTF: turn-to-turn fault; TGF: turn-to-ground fault

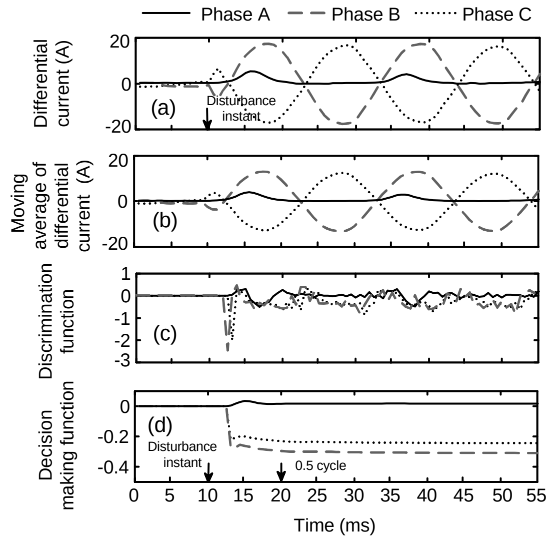

Fig. 5 Energization with a phase C to ground (CG) internal fault

(a) Differential current; (b) Moving average of differential current; (c) Discrimination function; (d) Decision making function

A case of energization with an internal CG (phase C to ground) fault is also investigated (Fig. 5), showing DCWs, moving averages of DCWs, DFs, and DMFs for this case. As shown, two-phase currents include simultaneous fault and inrush currents, and one-phase current includes only the inrush current. The DMFs corresponding to two faulted phases currents are negative but the DMF corresponding to other phase is positive (Fig. 5).

A total of 120 cases are tested: 40 cases of magnetizing inrush conditions, 40 cases of faulty conditions, and 40 cases for simultaneous internal fault and inrush conditions. The offline test results show that the proposed algorithm is accurate for building a reliable differential protection scheme for three-phase power transformers. In addition, in all cases of tested faults, the fault is identified in about half a cycle after the occurrence of a disturbance.

For comparison, the performance of some conventional algorithms is also investigated by applying different types of differential currents obtained from the laboratory prototype power transformer (Fig. 2). When the dwell-time approach is implemented, a low-current threshold is necessary for identifying the dead angles for DCW. Assume the low-current threshold is set to 0.8% of the maximum of the absolute value in one cycle. The non-current range dead angle of the dwell-time approach is δ_{dw}, which is denoted by the angle corresponding to non-current in one cycle (360°) (Lin *et al.*, 2002). Under extreme inrush current tests, the dwell-time approach of δ_{dw}=60° may malfunction even using the cross-blocking principle due to the deforming currents waveforms caused by the current transformers saturation.

If the ratio of the second harmonic to the fundamental component is less than the restraint index, the second harmonic restraint will open the differential protection; otherwise, the protection should be blocked. The second harmonic based scheme with a 15% restraint index may malfunction even using the cross-blocking principle under some inrush current conditions. Furthermore, non-operation time for this scheme can reach about 50 ms for some switching cases on a faulted transformer.

The malfunction problem of the dwell-time approach under extreme inrush current conditions is solved by applying the short-time correlation transform to eliminate the CT saturation effect and identifying the dead angle (Zhang *et al.*, 2002). However, it still presents some negative aspects of the dwell-time approach and operates with an inherent delay of about 1.5 cycles for some fault conditions. The high security for differential protection is also obtained by applying an improved correlation algorithm (Lin *et al.*, 2002). In this scheme, fault currents can be distinguished from the inrush current if the improved waveform correlation coefficient between the first and second half cycles of the differential current of each phase is over a threshold. The need for choosing thresholds and operation with inherent delays for fault conditions are disadvantages of this scheme. Thus, compared with other algorithms, the proposed algorithm has the following main advantages:

1. The operating speed is very high. The operating time is generally less than 10 ms.

2. The fault detection algorithm does not depend on the selection of thresholds.

3. This algorithm does not require burdensome computation.

5 Conclusions

A new algorithm for the waveform feature monitoring scheme is proposed to discriminate between internal fault and magnetizing inrush current in a power transformer. The proposed algorithm is based on the signs of three-phase tracked decision-making functions obtained from the second derivative of differential currents after the disturbance occurrence. Experimental results show that this algorithm has high security. In addition, the sensitivity of the algorithm is higher than that of the other algorithms relevant to the scheme; therefore, it can rapidly detect different kinds of transformer internal faults without using any cross-blocking principle, even when the fault currents are seriously distorted by harmonics or when the fault current occurs simultaneously with the inrush current. The algorithm does not require choosing any coefficient or threshold and requires little computation.

References

Al-Othman, A.K., El-Naggar, K.M., 2009. A new digital dynamic algorithm for detection of magnetizing inrush current in transformers. *Electr. Power Compon. Syst.*, **37**(4):355-372. [doi:10.1080/15325000802548699]

Bi, D.Q., Zhang, X.A., Yang, H.H., Yu, G.W., Wang, X.H., Wang, W.J., 2007. Correlation analysis of waveforms in nonsaturation zone-based method to identify the magnetizing inrush in transformer. *IEEE Trans. Power Del.*, **22**(3):1380-1385. [doi:10.1109/TPWRD.2007.900147]

Ge, B.M., de Almeida, A.T., Zheng, Q.L., Wang, X.H., 2005. An equivalent instantaneous inductance-based technique for discrimination between inrush current and internal faults in power transformers. *IEEE Trans. Power Del.*, **20**(4):2473-2482. [doi:10.1109/TPWRD.2005.855443]

Giuliante, A., Clough, G., 1991. Advances in the Design of Differential Protection for Power Transformers. Proc. Georgia Technical Protective Relaying Conf., p.1-12.

Guzman, A., Zocholl, S., Benmouryal, G., Altuve, H.J., 2001. A current-based solution for transformer differential protection-part I: problem statement. *IEEE Trans. Power Del.*, **16**(4):485-491. [doi:10.1109/61.956726]

Hamedani Golshan, M.E., Samet, H., 2006. A new differential protection algorithm base on rising rate variation of second harmonic current. *Iran. J. Sci. Technol. Trans. B Eng.*, **30**:643-654.

Hamedani Golshan, M.E., Saghaian-nejad, M., Saha, A., Samet, H., 2004. A new method for recognizing internal faults from inrush current conditions in digital differential protection of power transformers. *Electr. Power Syst. Res.*, **71**(1):61-71. [doi:10.1016/j.epsr.2003.11.015]

He, B., Zhang, X., Bo, Z.Q., 2006. A new method to identify inrush current based on error estimation. *IEEE Trans. Power Del.*, **21**(3):1163-1168. [doi:10.1109/TPWRD.2005.861337]

Kang, Y.C., Won, S.H., Kang, S.H., Crossley, P.A., 2004. A Transformer Differential Relay with a Core Saturation Detection Algorithm. 8th IEE Int. Conf. on Developments in Power System Protection, p.368-371.

Kang, Y.C., Lee, B.E., Kang, S.H., 2007. Transformer protection relay based on the induced voltages. *Int. J. Electr. Power Energy Syst.*, **29**(4):281-289. [doi:10.1016/j.ijepes.2006.08.001]

Kilic, E., Ozgonenel, O., Usta, O., Thomas, D., 2009. PCA based protection algorithm for transformer internal faults. *Turk. J. Electr. Eng. Comput. Sci.*, **17**(2):125-149.

Kulidjian, A., Kasztenny, B., Campbell, B., 2001. New Magnetizing Inrush Restraining Algorithm for Power Transformer Protection. IEE Int. Conf. on Developments in Power System Protection, p.181-184.

Lin, X., Liu, P., Malik, O.P., 2002. Studies for identification of the inrush based on improved correlation algorithm. *IEEE Trans. Power Del.*, **17**(4):901-906. [doi:10.1109/TPWRD.2002.803730]

Liu, P., Malik, O.P., Chen, D., Hope, G.S., Guo, Y., 1992. Improved operation of differential protection of power transformers for internal faults. *IEEE Trans. Power Del.*, **7**(4):1912-1918. [doi:10.1109/61.156994]

Lu, Z., Tang, W.H., Ji, T.Y., Wu, Q.H., 2009. A morphological scheme for inrush identification in transformer protection. *IEEE Trans. Power Del.*, **24**(2):560-568. [doi:10.1109/TPWRD.2008.2002982]

Ma, X., Shi, J., 2000. A new method for discrimination between fault and magnetizing inrush current using HMM. *Electr. Power Syst. Res.*, **56**(1):43-49. [doi:10.1016/S0378-7796(00)00099-7]

Ozgonenel, O., 2006. Wavelet based ANN approach for transformer protection. *Int. J. Comput. Intell.*, **2**(3):161-168.

Ozgonenel, O., Thomas, D.W.P., Christopoulos, C., 2007. TLM modeling of transformer with internal short circuit faults. *Int. J. Comput. Math. Electr. Electron. Eng.*, **26**(5):1304-1323. [doi:10.1108/03321640710823037]

Ozgonenel, O., Kilic, E., Khan, A., Rahman, M.A., 2008. A new method for fault detection and identification of incipient faults in power transformers. *Electr. Power Compon. Syst.*, **36**(11):1226-1244. [doi:10.1080/15325000802084737]

Samantaray, S.R., Panigrahi, B.K., Dash, P.K., Panda, G., 2007. Power transformer protection using S-transform with complex window and pattern recognition approach. *IET Gener. Transm. Distr.*, **1**(2):278-286. [doi:10.1049/iet-gtd:20060206]

Shin, M.C., Park, C.W., Kim, J.H., 2003. Fuzzy logic-based for large power transformer protection. *IEEE Trans. Power Del.*, **18**(3):718-724. [doi:10.1109/TPWRD.2003.813598]

Sidhu, T.S., Sachdev, M.S., 1992. On line identification of magnetizing inrush and internal faults in three phase transformers. *IEEE Trans. Power Del.*, **7**(4):1885-1890. [doi:10.1109/61.156991]

Spiegel, M.R., Stephens, L.J., 2008. Theory and Problems of Statistics (4th Ed.). Schaum Publishing Co., New York.

Tripathy, M., Maheshwari, R.P., Verma, H.K., 2008. Radial basis probabilistic neural network for differential protection of power transformer. *IET Gener. Transm. Distr.*, **2**(1):43-52. [doi:10.1049/iet-gtd:20070037]

Zhang, H., Wen, J.F., Malik, O.P., 2002. Discrimination between fault and magnetizing inrush current in transformers using short-time correlation transform. *Int. J. Electr. Power Energy Syst.*, **24**(7):557-562. [doi:10.1016/S0142-0615(01)00065-5]