Journal of Engineering Faculty, 1(2): 94-104, 2023

Journal of Engineering Faculty

| cumfad.cumhuriyet.edu.tr | Founded: 2023 Available online, ISSN Publisher: Sivas Cumhuriyet Üniversitesi

Design of Digital Differential Relay for Protection of Power Transformers Operating Under Highly Non-Linear Load

Hülya Doğan[1,a,*]

[1]*Department of Electrical and Electronics Engineering, Faculty of Engineering, Sivas Cumhuriyet University, 54104, Sivas, Turkey*
**Corresponding author*

Research Article

History

Received: 27/12/2023
Accepted: 29/12/2023

ABSTRACT

Electric Arc Furnaces (EAF) are the loads in the industry with highest rate of power consumption and they have a highly non-linear operating characteristic. In this study, Design of digital differential role model for protection of three-phase step-down power transformer supplying EAF and Matlab/Simulink simulation are presented. For this purpose, three-phase system model supplying power to EAF is modelled by means of Matlab/Simulink. In order to ensure sensitivity to role and distinguish the inrush currents from fault currents, inrush currents and current harmonics experimentally obtained from 100 MVA power transformer are measured. Thus, the difference between inrush and fault currents are specified and appropriate relay slope coefficients for designed dual-slope role characteristic are defined. When single-phase and multiphase faults in the obtained results of the simulation are examined in this study, it is revealed that the designed digital differential relay has an efficient operational performance in loads with highly non-linear and rapid changes characteristic such as EAF.

Keywords: Digital Differential Relay, Electric Arc Furnace (EAF), Non-Linear Load, Transformer Protection.

[a] hdogan@cumhuriyet.edu.tr

How to Cite: Doğan H (2023) Design of Digital Differential Relay for Protection of Power Transformers Operating Under Highly Non-Linear Load, Journal of Engineering Faculty, 1(2): 94-104

Introduction

Power transformers are one of most important equipment used in electric power systems [1]. The faults occur in power transformers are generally internal faults or originating from transformer connections [2]. Repair periods of power transformer faults are often long and their costs are high. Therefore, ensuring protection and reliability of power transformers is rather important.

Differential protection, which evaluates the differential current in terminals of power transformers and predicts potential faults is commonly used. However, differential circuit relays are affected by many factors such as saturation of transformer, tap-changing, over excitation and inrush currents [3]. Therefore, it is necessary to distinguish between inrush current and fault current. In order to make this distinction, various methods based on processing of current harmonics have been used [4-6]. In addition, numerous studies have been conducted to determine the distinction between harmonic limitation method, inrush current and fault current [7-11]. However, these methods are insufficient to determine the distinction between inrush and fault currents when the transformer is energized. In order to overcome this insufficiency, magnetic flux and tension suppression methods [12-14] and induction based methods have been developed [15-17]. However, as these approaches are dependent on the parameters of transformers, they are difficult to implement in practice. Some researchers have argued that voltage signals can be used to ensure the reliability of differential protection [18] and difference power can be utilized to define inrush current [19]. In addition to these studies, some researchers have revealed that signal-processing methods based on artificial intelligence [20-25], fuzzy logic [26-32] and wavelet transform [33-39] can be used for differential protection of transformers. However, these methods fall short in practice as the complexity of processes limit their application to the role and they cause noise distribution [40].

Electric arc furnaces (EAF) are the non-linear loads with the highest power in the industry. Particularly, when there is a short circuit during the process of charging and melting by EAF, waveform of current and voltage change rapidly. This causes frequent increases in inrush current and harmonic currents [41].

In this study, three-phase electric system model of the system supplying 60 MVA EAF plant is modelled by using Matlab/Simulink. A differential protection relay is prepared for the 380/34,5 kV step-down transformer station having 100 MVA Yn/Yn connection structure to perform protection under heavy non-linear load. Digital Differential Role (DDR) is defined as dual-slope. An algorithm is developed by using the threshold values of inrush and harmonic currents experimentally measured with power analyzer during charging and melting processes of EAF and stability of the relay is increased with elimination of numerical zero-component and adaptation of vector group [42-43]. When faults of a single phase and multiphase in the results of simulation are examined, it is observed that the designed DDR has an effective operational performance in highly non-linear and rapidly changing loads such as EAF and this finding is presented in the study.

Principle of Digital Differential Relay

Basic connection diagram of DDR is presented in Figure 1. When conversion ratios of current transformers are taken into consideration, the value read from secondary ends of current transformers is expressed by the equation (1).

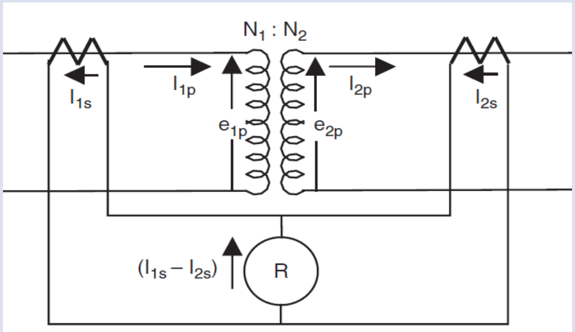

Figure 1. Connection diagram of differential relay for one phase

$$N_1.n_1.I_{1S} = N_2.n_2.I_{2S} \tag{1}$$

In this statement, it will be $I_{1S} = I_{2S}$ in case of a fault. However, in the event of a fault in the system, this value will be considerably higher than zero. In this case, the expression of differential current is defined by expression (2).

$$I_d = |I_{1S} - I_{2S}| \tag{2}$$

In order for differential relay to operate, there should be a current on current transformer winding higher than the specified current value. This current value is accepted as the average of the currents at the primary and secondary ends of the transformer. This current is called the limiting current. Mathematical expression of limiting current is as in equation (3).

$$i_r = \frac{|I_{1S} + I_{2S}|}{2} \tag{3}$$

Basic double slope characteristic curve of DDR is shown in Figure 2 [42]. In order for the relay to operate steadily in dual-slope relay characteristic, the conditions specified in expression (4) should be satisfied.

$$\begin{aligned} I_{base} < i_{s2} \quad & if \quad I_{op} > k_1.I_{base} + I_{s1} \\ I_{base} \geq i_{s2} \quad & if \quad I_{op} > (k_2.I_{base} + (k_1 - k_2).i_{s2} + i_{s1} \end{aligned} \tag{4}$$

The coefficients defined as k1 and k2 represent the characteristic of DDR and they are selected specifically for each relay. Due to the existence of high and variable current in the operating processes of EAFs, it is rather important to determine k1 value in particular. This value may be small for loads without non-linear and high currents. However, a minimum current of 5 kA is required to generate electric arc in EAFs. Therefore limiting of the base current is also high.

This should be taken into consideration when determining the limiting current in EAFs. Taking a low value for k1 will cause DDR to send a mal-operation signal to breakers during the process of energizing the EAF and melting.

It is necessary for DDR to operate in a highly sensitive manner and minimize the failure rates. Elimination of component zero and adaptation of vector group may decrease the failure rate [43-44]. Thus, these techniques are used to distinguish internal and external faults occur in the protection zone of relay.

A. Adaptation of the Vector Groups to Reduce the Error of Digital Differential Relay

In order to reduce the failure rate of DDR, it is necessary to adjust the vector group adaptation of transformer. The conversion matrix presented in equation (5) is used to adjust the vector group. In this expression, k values show the phase shift coefficients of transformers depending on the connection group of transformer.

$$A = \frac{2}{3}.\begin{bmatrix} \cos(k.30)^0 & \cos((k+4).30)^0 & \cos((k-4).30)^0 \\ \cos((k-4).30)^0 & \cos(k.30)^0 & \cos((k+4).30)^0 \\ \cos((k+4).30)^0 & \cos((k-4).30)^0 & \cos(k.30)^0 \end{bmatrix} \quad (5)$$

The vector group in transformers depends entirely on the application purpose of transformer. In arc furnaces, on the other hand, the step-down transformers supplying the furnace transformer generally use the YnYn0 type of vector group connection, and step-down transformers used in this study have this vector connection group. In this case, when it is accepted that k=0, expression (5) can be shown with conversion matrix T in equation (6) and this formula is used in adaptation of the vector group.

$$T = \frac{1}{3}.\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \quad (6)$$

The basic block structure used for elimination of component zero and vector adaptation of a three-phase system is shown in Figure 3.

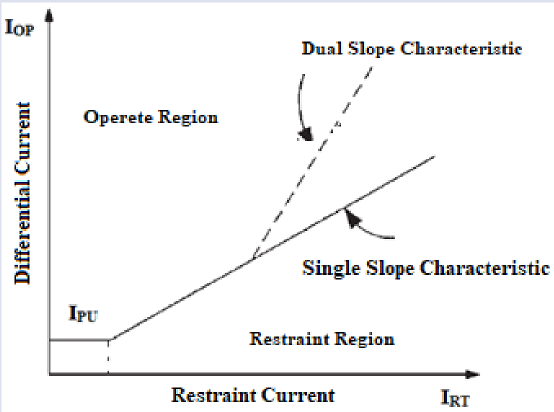

Figure 2. Basic characteristic curve of differential relay

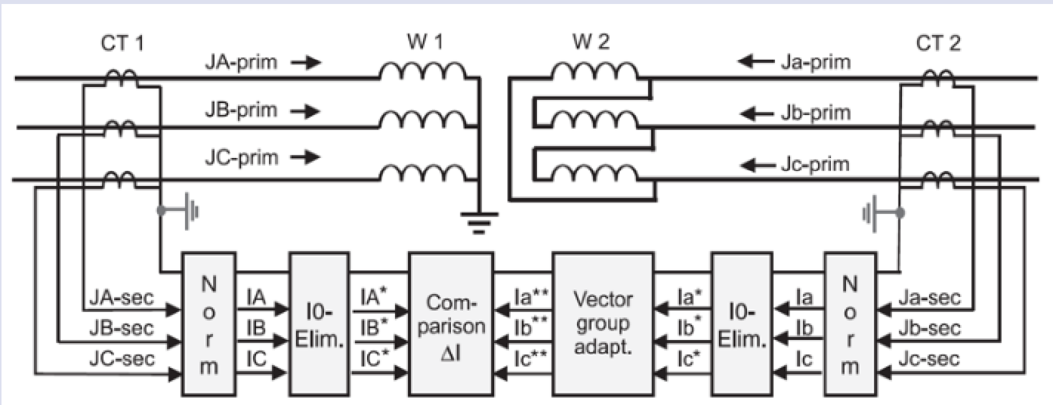

Figure 3. Basic block structure for elimination of component zero and vector group adaptation of a three-phase system [44].

B. Zero-Sequence Elimination to Reduce the Error of Digital Differential Relay

Symmetrical components of a three-phase system are generally defined with expression (7). In order for the relay not to send a mal-operation signal, it is necessary to eliminate the value of component zero in this expression.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_{a,0} \\ V_{b,0} \\ V_{c,0} \end{bmatrix} + \begin{bmatrix} V_{a,1} \\ V_{b,1} \\ V_{c,1} \end{bmatrix} + \begin{bmatrix} V_{a,2} \\ V_{b,2} \\ V_{c,2} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} . \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}$$
(7)

Depending on the phase currents, zero component expression is defined by the equation (8).

$$I_0 = \frac{1}{3}.(I_a + I_b + I_c) \tag{8}$$

In case zero component is eliminated based on vector adaptation, eliminated phases are expressed with equation (9).

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \frac{1}{3} . \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} . \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{9}$$

C. Defining of Algorithm for Digital Differential Relay

Flow chart of the protection algorithm designed for DDR is shown in Figure 4. This algorithm will send a trip signal to breaker in case of an error in the protection zone defined for transformer and the breakers will be opened. Fast Fourier Transform (FFT) is used in calculation of harmonic values to accelerate the opening time of breaker. A power analyzer is connected to the 100 MVA step-down transformer to distinguish the inrush and fault currents are recorded. Based on these experimental measurements, appropriate slope coefficients (k1 and k2) and F1 and F2 constant are determined in the algorithm.

Measurement of Inrush and Harmonic Currents in 100 MVA Step-Down Power Transformer

HIOKI 3197 and Chauvin Arnoux (CA) 8332B power quality analyzers are connected to 100 MVA step-down transformer supplying the 60 MVA EAF furnace in Sivas Iron and Steel Plants Inc. (SIDEMIR) and experimental measurements are taken according to IEC 61000-4-7 and IEC 61000-4-30 standards.

Changes of harmonic values and inrush currents generated in charge, drill, melting and refined phases of EAF are recorded. Inrush current sample of three phases measured with HIOKI 3197 power quality analyzer from 100 MVA step-down transformer supplying EAF and 2nd harmonic changes of phase B measured with CA 8332B power quality analyzer are shown in Figure 5 and Figure 6 respectively. By using these experimentally obtained values, distinction between the fault and inrush currents are determined in the algorithm presented in Figure 4 and appropriate slope coefficients (k1 and k2), and F1 , F 2 values for stable operation of the relay are experimentally determined. In addition, non-linear V-I characteristic of EAF is experimentally defined by using the measured current and voltage waveforms [45].

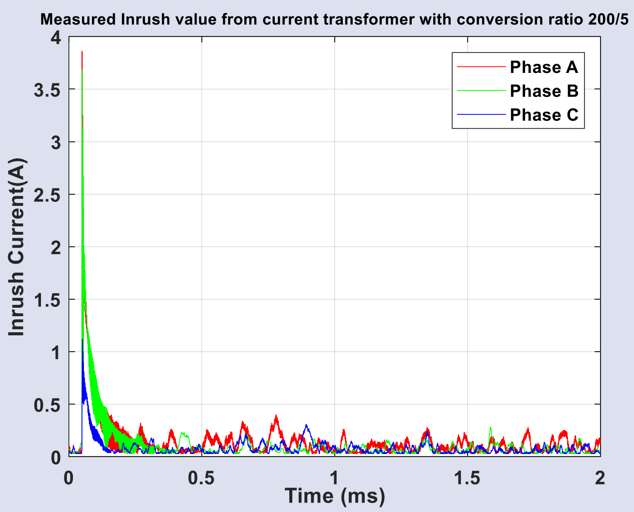

Figure 5. Inrush current waveform measured from 100 MVA step-down transformer supplying EAF with HIOKI 3197 power quality analyzer.

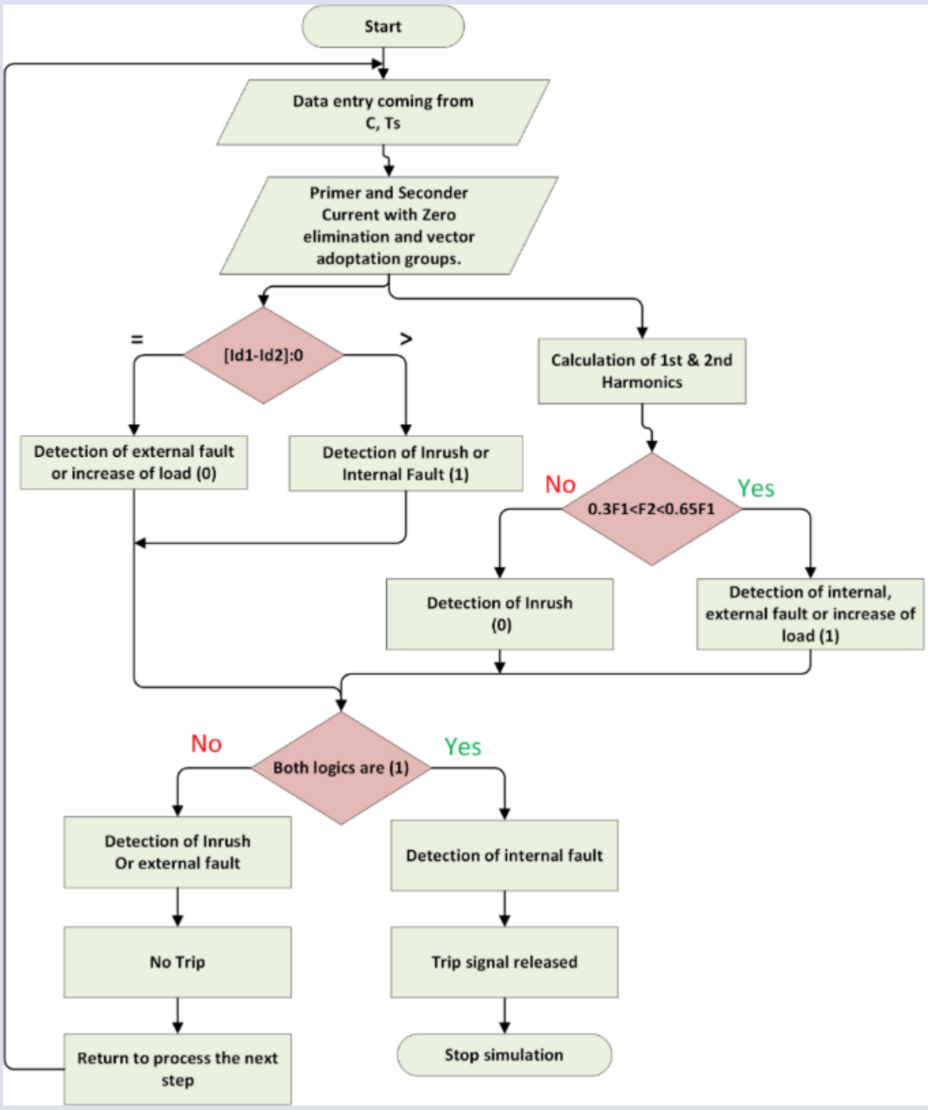

Figure 4. Digital Differential Relay Protection Algorithm..

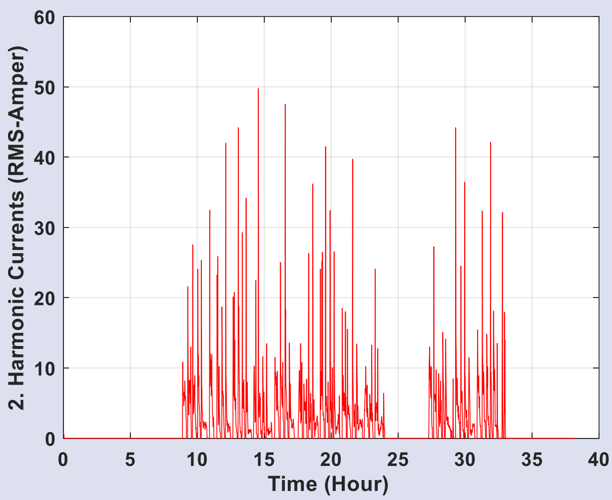

Figure 6. RMS variation of 2nd harmonic current of phase B at primer side measured from 100 MVA step-down transformer supplying EAF with CA 8332B power quality analyzer.

Modelling of Three Phases Electrical System of EAF and DDR, Simulation Results

In modelling the electric system supplying EAF, the single-line diagram presented in [45] is used. The system supplies a 60 MVA EAF. The system includes a 36 MVar compensation and uses Static Var Compensation (SVC). The SVC system is designed to automatically adjust the firing angles of thyristor depending on reactive power compensation as shown in [46]. An 18 MVar 150 Hz single-tuned filter parallel to SVC system is used. 15.3 MVar 100 Hz C-Type High Pass filter, 10 MVar 150 Hz C-Type High Pass filter and 4.7 MVar 200 Hz single-tuned filter existing in the system are modelled for harmonic elimination [41]. Transformer parameters for EAF transformer, SVC transformer and step-down transformer are presented in appendices section. In order to test digital differential protection by using these data, three-phase system model of the electrical system is created with Matlab/Simulink as shown in Figure 7. In this model, V-I arc model tested with real experimental measurements given in [47] is used for the characteristic of electric arc.

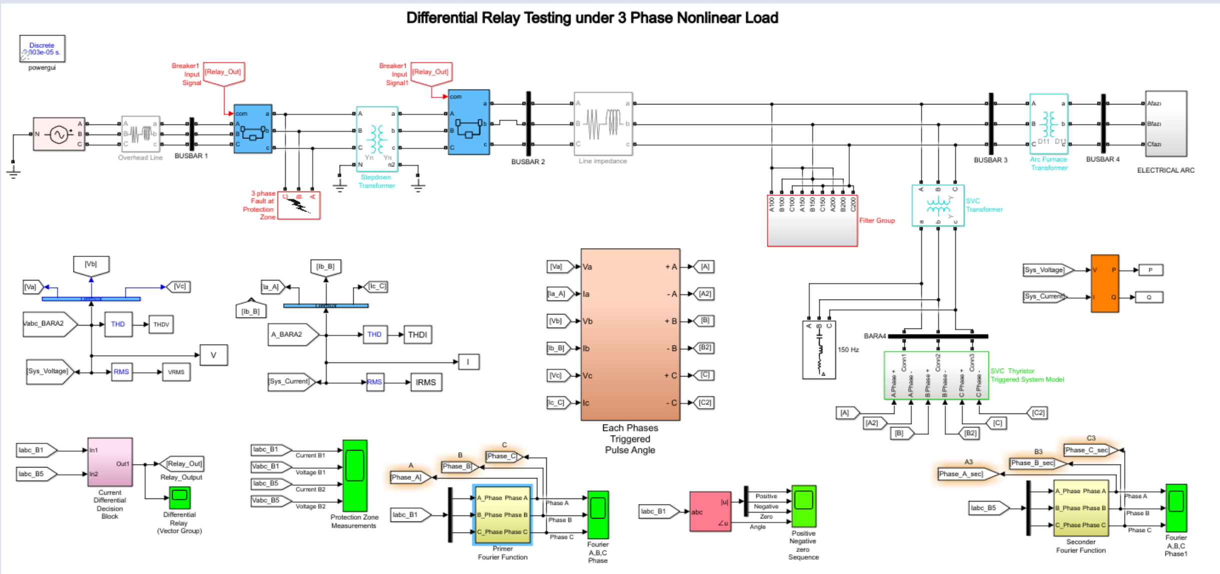

Figure 7. 3 phase system model of the electric system supplying EAF with differential protection.

To design the dual-slope differential relay, the algorithm structure given in Figure 4 is designed as matlab function block. By using the inrush and 2nd harmonic values obtained from experimental measurements, stable operation of differential relay is ensured and mal-operation trip signals are prevented. As seen from the experimental measurements, 2nd harmonic value reaches up to 50 A at the beginning of charging and melting processes of EAF. The reasons why this value is high in these processes are the instabilities at the beginning of melting process and short circuits caused by the contact of electrodes with metal. However, such circumstances don't cause any fault in the system and they occur due to the operation of the furnace. In case, there is a fault in the system, however, this value will be above 50 A and this should be supported with variance in inrush currents. Slope coefficients of the digital differential relay designed in the study are designed by taking the dynamic operating regimes in three operating processes of EAF. In order to distinguish between the fault and inrush currents from each other, threshold values are determined based on inrush and harmonic currents obtained from experimental measurements. Sensitivity of digital differential relay is increased with vector component adaptation and elimination of zero and erroneous output signals are prevented, and stability of the relay is increased. The relay will create a trip signal when a fault occurs within the transformer protection zone and open the breakers. It will continue to operate normally outside the protection zone.

Test results regarding the occurrence of a three-phase fault in the 1st second within the protection zone of the tested DDR are shown in Figure 10-12 respectively. The relay doesn't trip outside the protection zone. The presented digital differential role is designed in the manner to detect different types of electrical faults intuitively. Opening times obtained in different types of faults are shown in Table 1.

Table 1. Opening time of DDR in different fault conditions

Fault Types				Opening time of relay (ms)
Phase A	Phase A	Phase A	**Ground**	
+	**-**	**-**	**+**	**3.92**
-	**+**	**-**	**+**	**3.23**
-	**-**	**+**	**+**	**6.47**
+	+	-	+	3.14
+	-	+	+	3.04
-	+	+	+	6.76
+	+	+	+	2.94
+	+	-	-	3.03
+	-	+	-	6.37
-	+	+	-	6.58
+	+	+	-	3.05

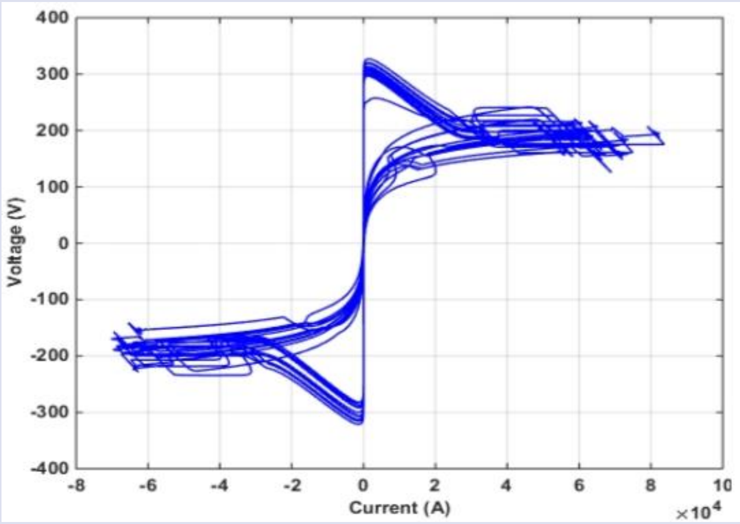

Figure 8. Dynamic V-I characteristic of electrical arc as result of simulation

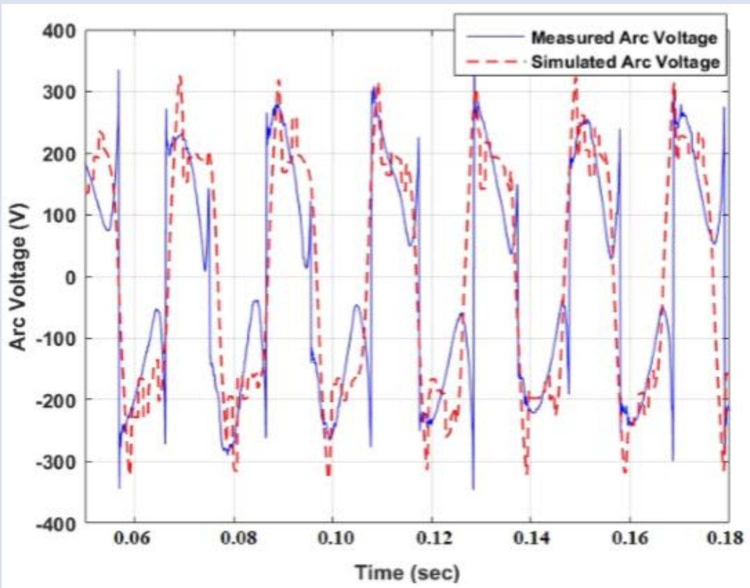

Figure 9. Comparison of the arc voltage variation with real time measurement and simulation results

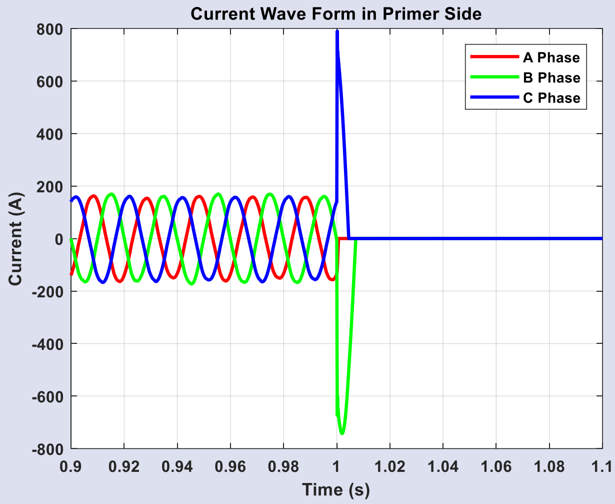

Figure 10. Current waveform in primer side under three-phase fault

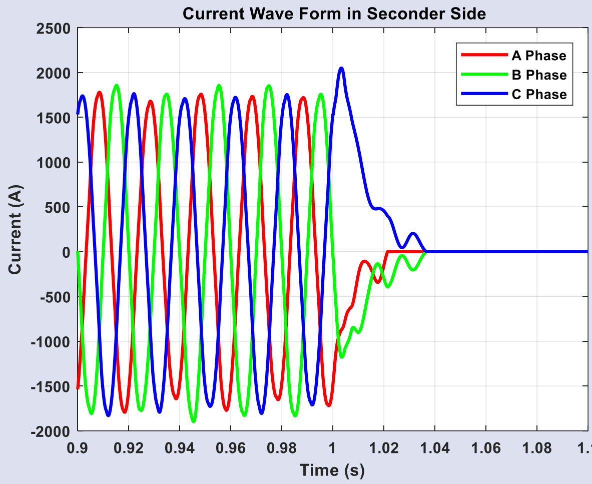

Figure 11. Current waveform in seconder side under three-phase fault

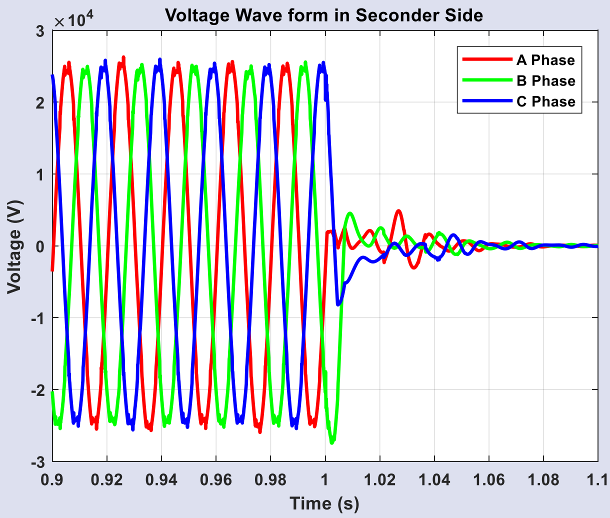

Figure 12. Current waveform in primer side under three-phase fault

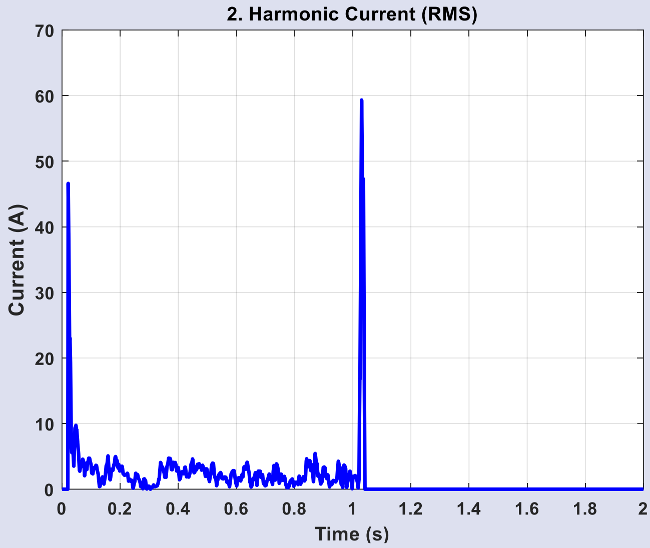

Figure 13. 2th harmonic RMS changes in secondary side under three-phase fault

Conclusion

DDR design for 100 MVA power transformer supplying EAF is presented and operation of DDR under highly non-linear load is tested in this study. For this purpose, 3-phase model of the electrical system is modeled with Matlab/Simulink. The experimental results showed that k1 and k2 should be 0.4 and 0.6 respectively for stable operation of the relay and F1 and F2 coefficients presented in the algorithm should be 0.3F1<F2<0.7F2 for the Harmonic examination to be performed. The tests made in different faults of the relay based on these coefficients obtained from experimental measurements revealed that,

- The breakers don't open the system if the fault is outside the protection zone.
- The relay generates output signal in all faults occurring within the electrical system and properly performs the opening process.
- Opening times determined comply with the literature.
- When test results are examined, it is seen that the opening time is less than 7 ms even in the worst-case faults.

A similar method can be used for step-down transformers supplying EAF's with higher power. However, proper coefficients should be determined by considering the variances in inrush and harmonic currents as presented in the study.

References

[1] A. Phadk, J. Thorp, Computer Relaying of Power System, Research Studies Press Ltd. United Kingdom, 1988.
[2] Barış Gürsu, "Ceza Fanksiyonuyla Durdurmalı Genetik Algoritmalar ile Transformatör Merkezlerinde Optimum Aşırı Akım Röle Koordinasyonu", Gazi Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi, Cilt 29, No 4, 665-676, 2014.
[3] J. Blackburn, T. Domin, Protective Relaying: Principles and Applications, Third ed., Thaylor & Francis, 2006.
[4] S. Horwitz, A. Phadke, Power System Relaying, 2nd ed. Herdfordshire, United Kingdom, 1995.
[5] M. Zaman, M. Rahman, "Experimental Testing of The Artificial Neural Network based Protection of Power Transformer", IEEE Transaction on Power Delivery, Vol. 13 No. 2, pp. 510-517, April 1998.
[6] T. Sidhu, M. Sachdev, H. Wood, M. Nagpal, "Design, Implementation, and Testing of a microprocessor-based high-speed relay for detecting transformer widding faults", IEEE Transaction on Power Delivery, Vol. 7, No. 1, pp. 108-117, January 1992.
[7] T. Sidhu, M. Sachdev, On-Line Identification of Magnetizing Inrush and Internal Faults in Three-Phase Transformers, IEEE Transaction on Power Delivery, Vol. 7, No. 4, pp. 1885-1891, October 1992
[8] P. Liu, D. Chen, Y. Guo, O.P. Malik, G.S. Hope, Improved Operation of Differantial Protection of Power Transformer for Internal Faults, IEEE Transaction on Power Delivery, Vol. 7, pp. 1912-1919, 1992.
[9] M. Sanaye-Pasand, M. Zangiabadi, A. Fereidunian, An Extended Magnetizing Inrush Restrain Method Applied to Digital Differantial Relays for Transformer Protection, IEEE Power Engineering Society General Meeting, Vol. 4, pp. 2077-2082, 2003.
[10] M.E.H. Golshan, M. Saghaian-Nejad, A. Saha, H. Samet, A New Method for Recognizing Internal Faults from Inrush Current Conditions in Digital Different Protection of Power Transformer, Electrical Power System Research, pp. 61-71, 2004.

[11]A. Aktaibi, M.A. Rahman, A Software Design Technique for Differantial Protection of Power Transformers, Proceedings of IEEE Int. Electr. Mach. Drives Conference, pp. 1456-1461, 2011.

[12] S.R. Wang, S. Kumar, V. Sreeram, Extraction of DC Compenent and Harmonic Analysis for Protection of Power Transformer, Proceedings of IEEE 8th Conf. Ind. Electron. Appl. (ICIEA), pp. 32-37, 2013.

[13] A.G. Phadke, J.S. Thorp, A New Computer-Based flux-restrained current-differantial relay for Power Transformer Protection, IEEE Transaction on Powet Apparature Systems, PAS-102, pp. 1456-146, 2011.

[14] S. Member, A Novel Transformer Protection Method Based on the ratio of voltage and fluxional Differantial Current, Proceedings of IEEE Transm Disturbution Conference Expo. pp. 342-347, 2003.

[15] Y.C. Kang, B.E. Lee, S.H. Kang, Transformer Protection Relay Based on the Induced Voltage, International Journal of Electrical Power Energy Systems, Vol. 29, pp. 281-289, 2007.

[16] K. Inagaki, M. Higaki, Y. Matsui, K. Kurita, M. Suzuki, K. Yoshida, T. Maeda, Digital Protection Method for Power Transformer Based on an Equivalent Circuit Composed of Inverse Inductance, IEEE Transaction on Power Delivery, Vol. 29, pp. 281-289, 2007.

[17] G.Baoming, A.T. Almeida, Z. Qionglin, W. Xiangheng, An Equivalent Instantaneous Inductance Based Technique for Discrimination between Inrush Current and Internal Faults in Power Transformers, IEEE Transaction on Power Delivery, Vol. 20, pp. 4276-2483, 2005.

[18] D.Q. Bi, X.H. Wang, W.X. Liang, W.J. Wang, A Ratio Variation of Equivalent Instantaneous Inductance Based Method to Identify Magnetizing Inrush in Transformer, Proceedings of 8th Confernce Electr. Electr. Power Delivery, pp. 1775-1779, 2005.

[19] K. Inagaki, M. Higaki, Digital Protection Method for Power Transformer Based on a Equivalent Circuit Composed of Inverse Inductance, IEEE Transaction on Power Delivery, Vol. 3, No.4, pp. 1501-1510, October 1998.

[20] K. Yabe, Power Differantial Method for Discrimnation between Fault and Magnetizing Inrush Current in Transformer, IEEE Transaction on Power Delivery, Vol. 12, No. 3, pp. 1109-1117, July 1997.

[21] A. Rahmati, M. Sanaye-Pesand, Protection of Power Transformer using Multi Criteria Decition Making, International Journal of Electrical Power Energy Systems, Vol. 68, pp. 51-63, 2014.

[22] M. Shin, C. Park, J.Kim, Fuzzy Logic-based Relaying for Large Power Transformer Protection, IEEE Transaction on Power Delivery, Vol. 18, pp. 718-724, 2003.

[23] A. Wiszniewski, B. Kasztenny, A multi Criteria Differantial Transformer Relay Based on Fuzzy Logic, IEEE Transaction on Power Delivery, Vol. 10, pp. 1786-1792, 1995.

[24] F. Zhalefar, M. Sanaye-Pasand, A new Fuzzy Logic Based Extended Blocking Scheme for Differantial Protection of Power Transformer, Electrical Power Compenent System, Vol. 38, No. 6, pp. 675-694, 2010.

[25] D.Barbosa, U.C. Netto, D.V. Coury, M. Oleskovicz, Power Transformer Diferantial Protection Based on Clarke's Transformer and Fuzzy Systems, IEEE Transaction on Power Delivery, Vol. 26, pp. 1212-1220, 2011.

[26] D. Bejmert, W. Rebizant, L. Schiel, Transformer Digital Protection with Fuzzy Logic Based Inrush Stabilization, Vol. 26, pp. 1212-1220, 2011.

[27] M.R. Zaman, M.A. Rahman, Experimental Testing of Artificial Neural Network Based Protection of Power Transformer, IEEE Transaction on Power Delivery, Vol. 13,pp. 510-517, 1998.

[28] Z. Moravej, D.N. Vishwakarma, S.P. Singh, Application of Radial Basis Function Neural Network for Differantial Relaying of a Power Transformer, Computational Electrical Engineering, Vol. 25, pp. 102-112, 2010.

[29] M. Tripathy, R.P. Maheshwari, H.K. Verma, Power Transformer Differential Protection Based on Optimal Probabilistic Neural Nwetwork, IEEE Transaction on Power Delivery, Vol. 25, pp. 102-112, 2010.

[30] H. Balaga, N. Gupta, D.N. Vishwakarma, GA Trained Parallel Hidden Layered ANN based differential Protection of Three Phase Power Transformer, Electrical Power and Energy System, Vol. 67, pp. 286-297, 2015.

[31] M. Kezunovic, A Survey of Neural Network Application to Protective Relaying and Fault Anaysis, Engineering International Journal, Vol. 5, No. 4, pp. 185-192, December 1997.

[32] J. Pihler, B. Grcar, D. Dolinar, Improved Operation of Power Transformer Protection using Artificial Neural Network, IEEE Transaction on Power Delivery, Vol. 12, No. 3, pp. 1128-1135, July 1997.

[33] H. Khorashadi-Zadeh, M. Sanaye-Pasand, Correction of Saturated Current Transformers Secondary Current Using ANN, IEEE Transaction on Power Delivery, Vol. 21, No. 1, pp. 73-79, January 2006.

[34] D. Guillen, H. Esponda, E. Vazguez, G. Idarraga-Ospina, Algorithm for Transformer Differantial Protection Based on Wavelet Corelation Methods, IET General Transmission and Disturbution, Vol. 10, pp. 2871-2879, 2016.

[35] O. Youssef, A Wavelet-based Technique for Discrimination between Faults and Inrush Currents in Power Transformers, IEEE Transaction on Power Delivery, Vol. 18, No. 1, pp. 170-176, January, 2003.

[36] M. Gomez-Morente, D.W. Nicoletti, A Wavelet-based Differantial Transformer Protection, IEEE Transaction on Power Delivery, Vol. 14, pp. 1351-1356, 1999.

[37] H. Khorashadi-Zadeh, M. Sanaye-Pasand, Power Transformer Differantial Protection Scheme based on wavelet transform and Artificial Neural Network Algorithms, Proceedings of 39nd International Universities Power Engineering Conference, pp. 747-753, September, 2004.

[38] S.A. Saleh, M.A. Rahman, Real Time Testing of WTP-based protection Algorithm for Three Phase Power Transformers, IEEE Transaction on Industrial Application, Vol. 41, pp. 1125-1132, 2005.

[39] P. Mao, R. Aggarwal, A Novel Approach to the Classification of the Transient Phenomena in Power Transformer Using Combined Wavelet Transform and Neural Network, IEEE Transaction on Power Delivery, Vol. 16, No. 2, pp. 215-218, April, 2001.

[40] M.M. Eissa, A Novel Digital Directional Transformer Protection Technique Based on Wavelet Packed, IEEE Transaction on Power Delivery, Vol. 20, pp. 1830-1836, 2005.

[41] Mustafa Şeker, Computer Aided Modelling and Experimental Investigation of the effect of Electric Arc Furnace, İnonu University, Institute of Science and Technology, Electrical and Electronics Depertmant, Ph.D Thesis, Malatya-Turkey, 2017.

[42] B. Vahidi, E. Esmaeeli, Matlab-SIMULINK-Based Simulation for Digital Differential Relay Protection of

Power Transformer for Educational Purpose', Computer Applications in Engineering Education , Volume21, Issue3, pp 475-483, September 2013

[43] H. Zadeh, J.F. Wen, P. Liu, O.P. Malik, Discrimination between Fault and Magnetizing Inrush Current in Transformer Using- short-time Corelation Transform, Electrical Power and Energy System, Vol. 24, pp. 557-562, 2002.

[44] G. Zigler, Digital Differential Protection, SIEMENS Differential Protection Symposium, 2005.

[45] Seker, M., Memmedov, A.. An Experimental Approach for Understanding V-I Characteristic of Electric Arc Furnace Load. Elektronika ir Elektrotechnika, North America, 23, jun.2017. Availableat:http://eejournal.ktu.lt/index.php/elt/article/view/18328

[46] Mustafa Şeker ; Arif Memmedov ; Rafael Hüseyinov , The modelling and simulation of static VAR compensator (SVC) system for electric arc furnace with Matlab/Simulink, 2016 National Conference on Electrical, Electronics and Biomedical Engineering (ELECO), pp. 262 – 268, 2016,

[47] Seker, M., Memmedov, A., Huseyinov, R., Kockanat, S.. Power Quality Measurement and Analysis in Electric Arc Furnace for Turkish Electricity Transmission System. Elektronika ir Elektrotechnika, North America, 23, dec. 2017.