ZANCO Journal of Pure and Applied Sciences

TYPE Original article
DOI http://dx.doi.org/10.21271/ZJPAS.37.4.13

Enhancing the Sensitivity of Power Transformer Differential Protection in Power Systems.

Aso Farooq Hayder*, Ismael Kareem Saeed

Department of Electrical , College of Engineering, Salahaddin University-Erbil, Erbil, Iraq

OPEN ACCESS

*Corresponding author

Aso Farooq Hayder

aso.farooq1993@gmail.com

RECEIVED :13 /01 /2025
ACCEPTED :12/05/ 2025
PUBLISHED :31/ 08/ 2025

KEYWORDS:
Differential Protection, Tap changer position, PSCAD/EMTDC, Turn ratio errors, Relay Sensitivity.

ABSTRACT

Differential protection is a fundamental protection scheme used to detect and isolate internal faults in power transformers. It works on the principle of comparing the currents entering and leaving the protected zone (transformer). Under normal operating conditions or external fault, the current flowing into the transformer should equal the current flowing out, with taking into consideration the transformer's turn ratio. Under normal conditions, the differential current between primary and secondary sides should be close to zero, a small difference value may exist due to transformer magnetizing current, current transformer (CT) measurement errors and Tap changer position. The Tap changer position will cause the transformer turn ratio errors which is a cause to give trip signal from differential relay to the transformer circuit breaker if it is not compensating in the differential protection relay. Using the new technique of on-load tap changer (OLTC) position to reduce the turn ratio error in order to improve the differential protection sensitivity, the proposal technique includes new equations that are simulated by PSCAD/EMTDC software. It can be clearly shown that the proposed technique will reduce the turn ratio error to the minimum value with comparing to the conventional schemes. The study demonstrates a significant reduction in turn ratio errors. Without compensation, the error reaches 10.5% of the nominal transformer current, requiring a higher differential relay setting to avoid false trips. After applying the proposed compensation technique, the error is reduced to 1.17%, leading to a 9.33% improvement in differential protection sensitivity.

This improvement allows for a lower differential relay setting while maintaining power system reliability. The results confirm that the proposed method minimizes unnecessary transformer trips due to OLTC variations, enhances protection accuracy, and increases overall system dependability.

1.Introduction

Differential protection provides absolute selectivity and fast operation, and it is applied in numerous variations for the protection of electrical machines, transformers, busbars and feeders at all voltage levels. Differential protection calculates the sum of all currents flowing into and out of the protected zone. Apart from magnetizing currents, capacitive charging currents and turn ratio error, this current sum must always be equal to zero if the protected object is un-faulted. Internal faults are therefore detected by the appearance of a differential current. For security against mal-operation due to CT transformation errors, the pick-up threshold of the protection is increased in proportion to the total current flow (Hayder et al., 2008, Ali, 2009, Zhao et al., 2009, El-bages, 2011, Oliveira et al., 2012). Thereby, the protection sensitivity is automatically matched to the prevailing short circuit conditions. Power transformers have proven to be highly efficient in controlling power flow and regulating voltage. As a result, they are increasingly used in modern energy production, transmission, and distribution systems. To enhance the sensitivity of differential protection, it is essential to detect low-current faults, such as turn-to-turn short circuits in transformer windings. Furthermore, the concept of adaptive protection, which adjusts the relay system's operating characteristics to distinguish between internal faults, inrush currents, and external faults based on changing system conditions, has become increasingly promising. It improves the protection sensitivity and simplifies its conception as presented by (Rahmati and Sanaye-Pasand, 2012, Shah and Bhalja, 2013, Smolarczyk and Bartosiewicz, 2013, Zhang et al., 2013, Aleksandrs and Je, 2014, Paliwal and Trivedi, 2014, Syed et al., 2015) they presented an adaptive adjustment concept in relation to the position change of the on-load tap changer and distinguish between transformer internal faults and inrush currents for universal differential protection of power transformers, such a concept provides a sensitive and cost-efficient protection for power transformers. Some other methods for improving the sensitivity of the digital differential protection are presented in (Edwards et al., 2017, Parihar et al., 2017, Sevov et al., 2017, Zheng et al., 2018, Medeiros and Costa, 2018, Magrin and Tavares, 2018, Ali et al., 2018, Petrescu et al., 2019, Raichura et al., 2019, Bejmert et al., 2020, Arnautalić et al., 2021, Khare and Gatfane, 2021, Mayer, 2021, Sahu, 2021, Wang et al., 2021, Lal Moosavi et al., 2022, Moravej et al., 2023). The approaches focused on adaptive adjustment of the percentage differential protection takes into account the tap position of the power transformer with on-load tap changer and review of differential protection schemes, The digital differential protection can be more sensitive to the faults of transformer by reducing the unbalance current caused by the tap changing, In order to distinguish between internal and external faults some algorithms has been presented by above mentioned papers for power transformer differential protection which differentiates internal faults from magnetizing inrush currents and saturation of current transformers using wavelet transform. Setting the pickup current and slope of differential relays of power transformer protection is a well-known compromise. Recent studies have been exanimated the effect of OLTC operation on voltage stability, which further influences transformer protection performance. Notable contributions include (Alkahdely and Alsammak, 2023b) who analyzed normal and reverse OLTC operation and its impact on voltage stability, and their subsequent study on the non-limiting operation of OLTC in the Nineveh electrical grid (Alkahdely and Alsammak, 2023a). These studies highlight the necessity of incorporating OLTC position adjustments into differential protection schemes to enhance transformer protection reliability. And a hybrid differential protection scheme using Discrete Wavelet Transform (DWT) and Convolutional Neural Networks (CNN) has been proposed for power transformers by (Vyawhare et al., 2025), by simulating various current conditions, including normal, fault, and inrush currents, the approach leveraged DWT to extract critical statistical features and employed CNN for classification. Furthermore, another study proposed an anti-maloperation scheme to prevent undesired tripping in current differential protection due to transient currents by (Yuan et al., 2025), The approach utilizes the positive-sequence component of differential current and the least error square method to calculate transient decay and line voltage changes, the proposed scheme has been simulated in PSCAD/EMTDC to confirm that it can effectively distinguishes between transient events and internal faults, significantly enhancing current differential protection reliability. It has been the focus of study to improve both the security and sensitivity of transformer differential protection recently. All mentioned previous approaches which worked to improving the sensitivity of differential protection using various approaches has not considered the adjacent on load tap changer current and position which reduce the turn ratio errors caused by OLTC position and it has attractive effect on the sensitivity of differential protection. Accurate load forecasting is an essential aspect of power system planning and operation, as it directly influences system reliability and protection settings. Particularly in regions experiencing rapid development, such as Erbil Governorate, the ability to predict future load demand is vital for maintaining system stability and optimal performance of protection schemes(Warda Hussein, 2020). In addition to accurate load forecasting, maintaining power quality is another crucial factor influencing the reliability of transformer differential protection systems. Harmonic distortion, often caused by nonlinear industrial loads, can lead to maloperation of protective relays. A study conducted by (Asmahan et al., 2021), the research classified harmonics into current and voltage source types and showed improved power factor and system efficiency after filter implementation. Such power quality enhancements can directly contribute to more stable and accurate transformer protection performance. In areas with weak or isolated electrical networks, the integration of renewable energy sources can present unique challenges for transformer protection, including fluctuating load patterns and variable fault contributions (Amal and Ibrahim Ismael, 2023).

2.The Methodology.

This paper focuses on improving power transformer differential protection sensitivity by considering the OLTC position as a compensating factor. This approach helps reduce transformer turn ratio errors. The study involves mathematical equations for differential protection and the simulation of a model using the PSCAD/EMTDC simulator. The results of the proposed scheme demonstrate how compensating for the OLTC position can reduce turn ratio errors. These results are then compared with conventional schemes where OLTC position compensation has not been considered in differential protection algorithms. The new scheme which can be added to the (Shah and Bhalja, 2015) work to enhance the differential protection of power transformer, in order to distinguish between internal and external faults which causes a CT saturation, as in their work the adjacent tap position current measuring has not been considered for calculating the percentage value of differential protection, while in this new scheme all information from each tap of the OLTC can be recorded and considering for compensation values and improvement of the differential protection of power transformer.

The OLTC position is one of the major factors in this scheme to improve the sensitivity of power transformer differential protection. The proposed mathematical equations for the model are as follows.

Let’s consider Transformer turn ratio as *N,*

$$N = \frac{N1}{N2} = \frac{V1}{V2} = \frac{I1}{I2} \quad \text{............} \; (1)$$

In order to compare the primary and secondary current for differential calculation we should refer the primary current to secondary side by multiplying primary current with turn ratio,

$$I_{12} = I_1 * N \quad \text{...............} \; (2)$$

The protection relay reads the both sides current from current transformer (CT) secondary side current and the CT ratio is defined by equation 3. Let’s CT ratio defined as (n) in general and ($\mathbf{n1}$) for primary side CT and ($\mathbf{n2}$) for secondary side CT,

$$\mathbf{n1} = \frac{CT\ primary\ current\ (I1)}{CT\ Secondary\ current\ (I1')} \text{...... ...} \; (3)$$

$$\mathbf{n2} = \frac{CT\ primary\ current\ (I2)}{CT\ Secondary\ current (I2')} \text{.........} (4)$$

while calculating the ratio error difference between primary and secondary side without taking the OLTC position compensation if we consider this error as Er

$$Er = ABS\left[\frac{I2-I12}{I12}\right]\%100............. (5)$$

since we are seeking to reduce this error by OLTC compensation and we should taking into consideration the primary side current compensation as well by calculating the difference between two adjacent tap position load current and referring it to the secondary side in equation 6 then using this compensated primary side equation in the error equation 7 as Er'.

$$I_{12}' = N [I_1 - (T^* - T_n) (i_1 - i_2)] .... (6)$$

$$Er' = ABS\left[\frac{I2-I12'}{I12'}\right]\%100.......................... (7)$$

$$ID = ABS[I1' - I2']............................... (8)$$

$$IRC = ABS\left[\frac{ID}{2}\right]................... (9)$$

$$\% Slope = \left[\frac{ID}{IRC}\right] * 100\% .... (10)$$

Where:

$N1$: Primary side number of turn; $N2$: Secondary side number of turn;

$V1$: Primary side measured voltage; $V2$: Secondary side measured voltage;

$I1$: Primary side current; $I2$: Secondary side current;

$I1'$: Primary side CT secondary $I2'$: Secondary side CT secondary

I_{12}: Primary side current referred to secondary side without OLTC position compensation;

I_{12}': Primary side current referred to secondary side with OLTC position compensation;

T^*: Current OLTC position; T_n: Nominal OLTC position;

i_1: Primary side current tap position ampere.; i_2: Primary side adjacent tap position ampere;

ID: Differential current; IRC: Restraint current;

$\% Slope$: Setting value of differential protection.

Er: Turn ratio error before compensation

Er': Turn ratio error after compensation

A general flow chart is shown in figure (1) for the proposed work.

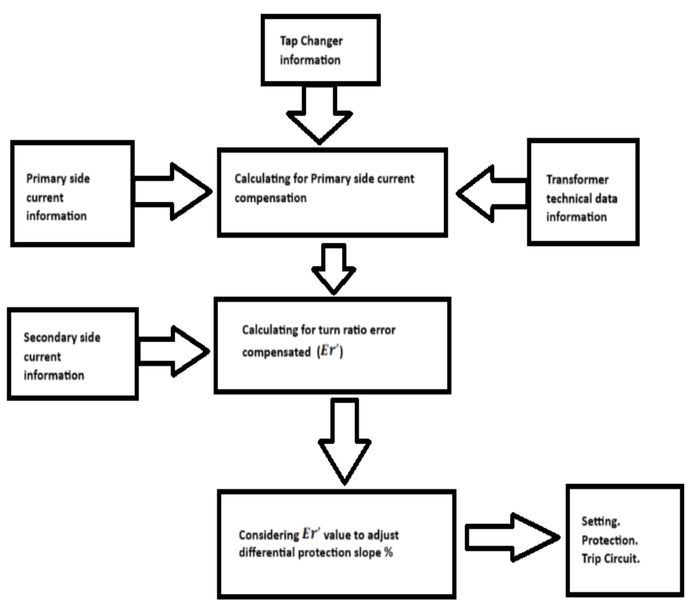

Figure (1). General Flow Chart

3.Case study.

A power transformer according to IEC60076 standard and Iraqi specification took as a reference for this study, its technical values explained below, and the technical information of this transformer showed in table (1).

Rated power = 31.5MVA
Rated primary voltage = 33KV
Rated secondary voltage = 11.5KV
Vector Group: Dyn11
OLTC has 13 positions as showing in table (1).
N=33/11.5 = 2.87 according to equation (1).

Table (1) Power Transformer voltage and current data.

OLTC Position	$V1$ (V)	$I1$ (A)	I_{12} (A)	$V2$ (V)	$I2$ (A)
1	35475	512.658	1471.10	11500	1581.44
2	34980	519.912	1491.92	11500	1581.44
3	34485	527.375	1513.34	11500	1581.44
4	33990	535.055	1535.38	11500	1581.44
5	33495	542.963	1558.07	11500	1581.44
6	33000	551.107	1581.44	11500	1581.44
7	32505	559.500	1605.52	11500	1581.44
8	32010	568.152	1630.35	11500	1581.44
9	31515	577.075	1655.96	11500	1581.44
10	31020	586.284	1682.38	11500	1581.44
11	30525	595.791	1709.66	11500	1581.44
12	30030	605.612	1737.84	11500	1581.44
13	29535	615.762	1766.97	11500	1581.44

The new model has been applied on this transformer and simulated in PSCAD/EMTDC software with results shown in section of simulation and results of this paper.

4.Simulation and Results.

Apart from theoretical with mathematical equations, this new model has been simulated and tested through PSCAD/EMTDC software, as shown in Figure (2) below the model consists from a Power Transformer with OLTC connected its primary side to the grid or a generator source and its secondary side connected to an inductive load.

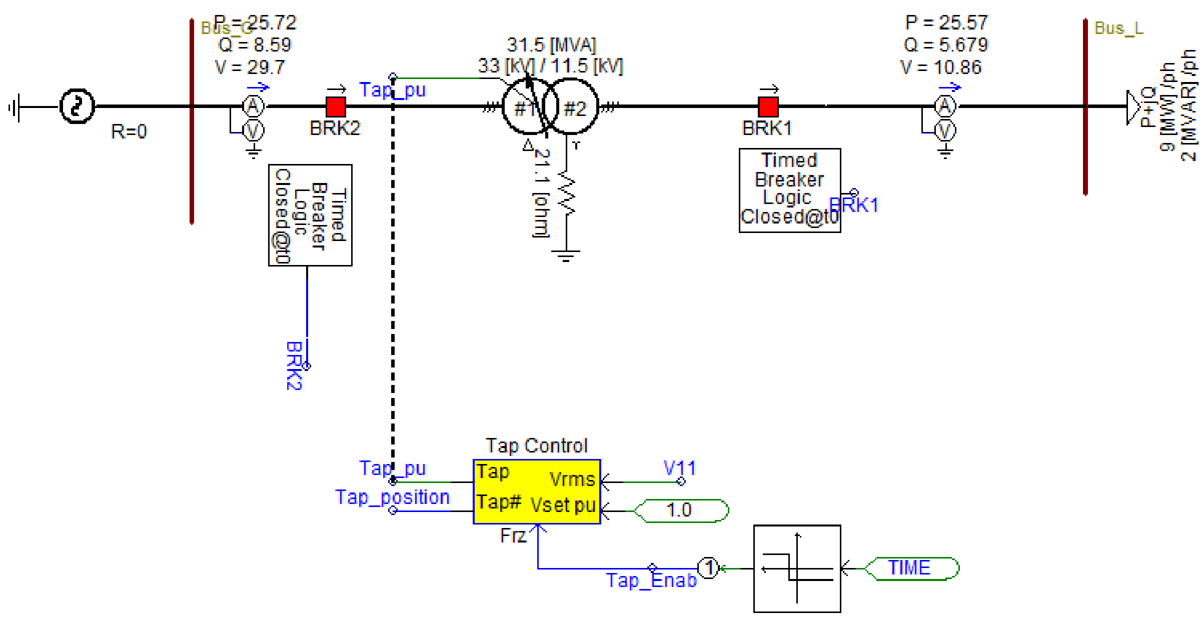

Figure (2). A model of Power transformer with OLTC.

Transformer differential protection is one of the major protection scheme in power transformer to protect it from internal faults, this protection sensitivity is the most important factor to keep transformer under operation during normal condition without interruption of electricity to the consumer, there are more than factors which can be affect on differential protection sensitivity and can cause trip of transformer main circuit breaker due to false trip command if sensitivity of the differential protection is ignored, and some of them are well explained and improved through previous researches, but the factor of transformer turn ratio error compensation which caused by OLTC is also has a robust impact on transformer differential protection sensitivity and it is explained and improved through this research, while turn ratio error of a power transformer is not compensated during calculation and setting of the differential protection relay the differential pick up setting must consider around 10% of the nominal current only due to turn ratio error happen during OLTC operation according to equations (2 and 5), but if we compensate the OLTC position and match it with the equations (6 and 7) then we can reduce this error from 10.5% to 1.17% of the nominal current and this tells us the differential protection sensitivity has been more sensitive and we could improve it by 9.33%, along with that the differential setting can be 9.33% lower with regards to the conventional scheme of the setting of the relay and after applying this new scheme to the power system the reliability and dependability of the system will increase as well because of no more transformer trip under normal operation due to false trip caused by OLTC position and no more high differential current setting values needed, means the transformers will be more protected and more safe.By applying equations (2) and (5) to calculate the turn ratio error without compensating for the OLTC position, the results have been showed in table (2) that the highest value of this error which should be taken into consideration during setting of the differential relay is 10.5% of the nominal current of transformer which noticed at tap position number 13. The simulated model results are shown from figure (3) to figure (6) for different OLTC positions. In contrast, when compensating for the OLTC position using equations (6) and (7), the turn ratio error is significantly reduced to the minimum value. The highest error value in this improved model is 1.17% of the nominal current, also observed at tap position number 13. The improved simulation results for different OLTC positions are shown in Figures (7) to (10) for the different OLTC positions. There may be slight variations between theoretical calculations and simulated values of the turn ratio error due to load and voltage fluctuations during the simulation model.

Table (2) Turn ratio error calculation.

OLTC Position	I_{12} (A)	Er (%)	I_{12}'(A)	Er' (%)
1	1471.10	7.50	1575.19	0.396475771
2	1491.92	6.00	1577.58	0.244343891
3	1513.34	4.50	1579.45	0.125581395
4	1535.38	3.00	1580.76	0.043062201
5	1558.07	1.50	1581.44	0
6	1581.44	0.00	1581.44	0
7	1605.52	1.50	1581.44	0
8	1630.35	3.00	1580.69	0.047120419
9	1655.96	4.50	1579.13	0.145945946
10	1682.38	6.00	1576.68	0.301675978

11	1709.66	7.50	1573.25	0.520231214
12	1737.84	9.00	1568.76	0.808383234
13	1766.97	10.50	1563.09	1.173913043

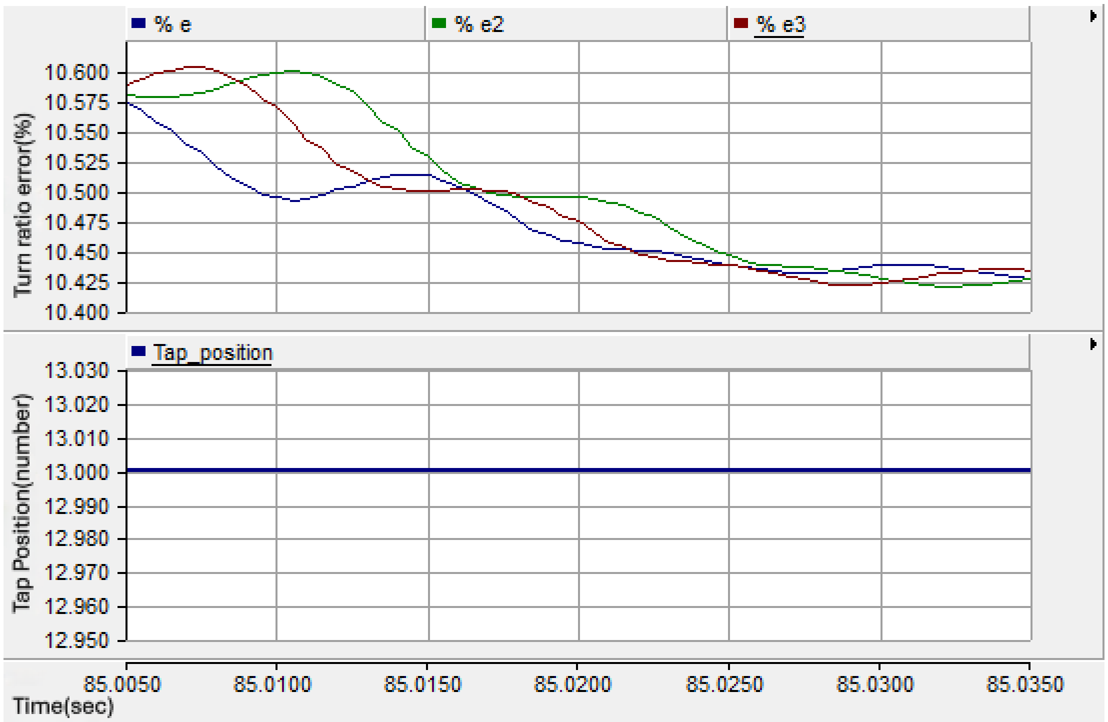

Figure (3) three phase turn ratio error without tap compensation with OLTC position (13)

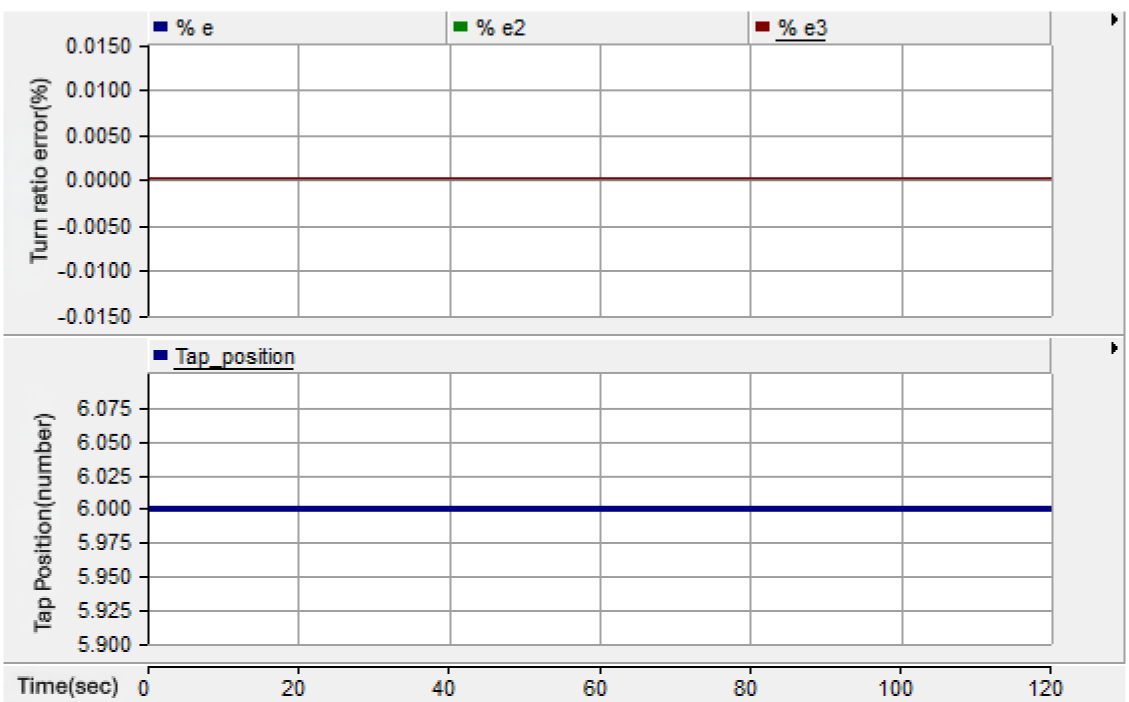

Figure (4) three phase turn ratio error without tap compensation with OLTC position (6)

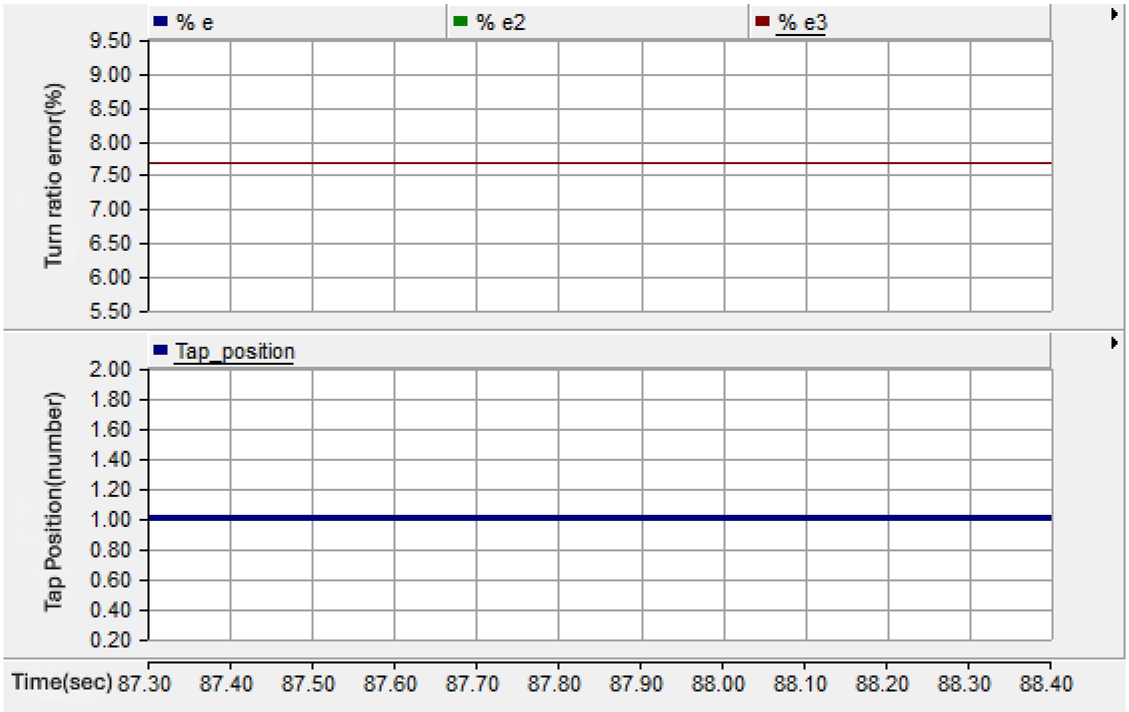

Figure (5) three phase turn ratio error without tap compensation with OLTC position (1)

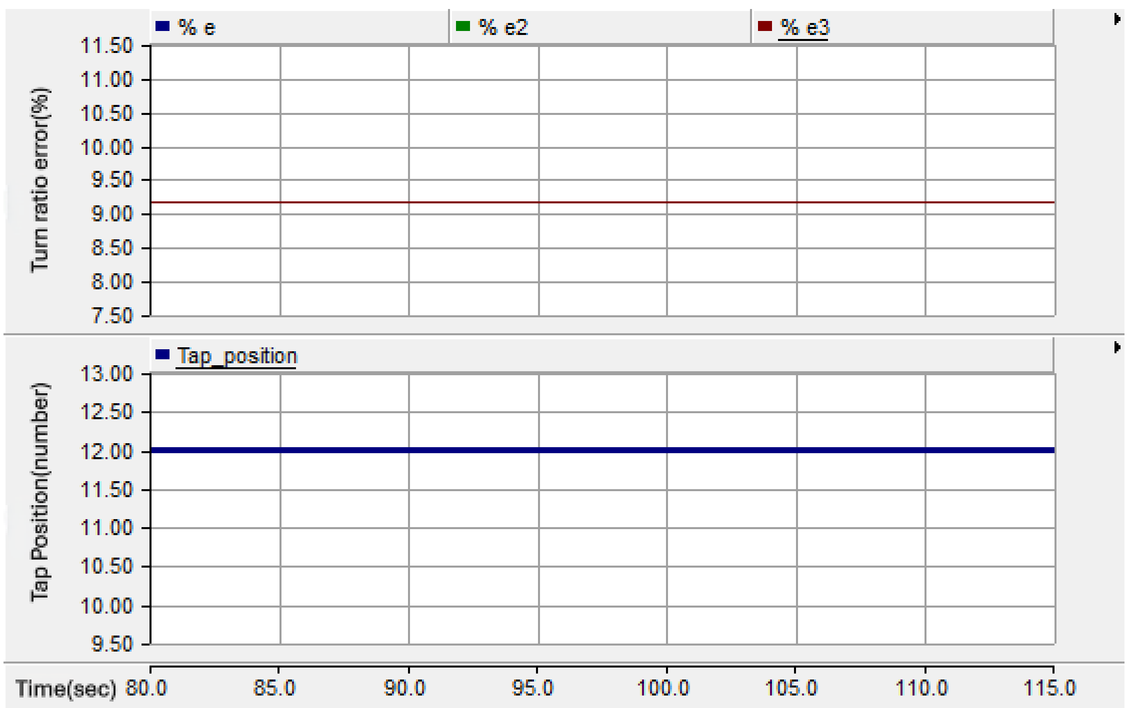

Figure (6) three phase turn ratio error without tap compensation with OLTC position (12).

While the protection relays are connected with current transformer (CT) secondary side for measuring and protection purpose so we can calculate CT secondary values for the primary and secondary side of this power transformer if the connected CT ratios are **n1** is 600/1A for primary side and **n2** is 2000/1 for secondary side, table (3) shows all values in details which will be reading by the protection relay.

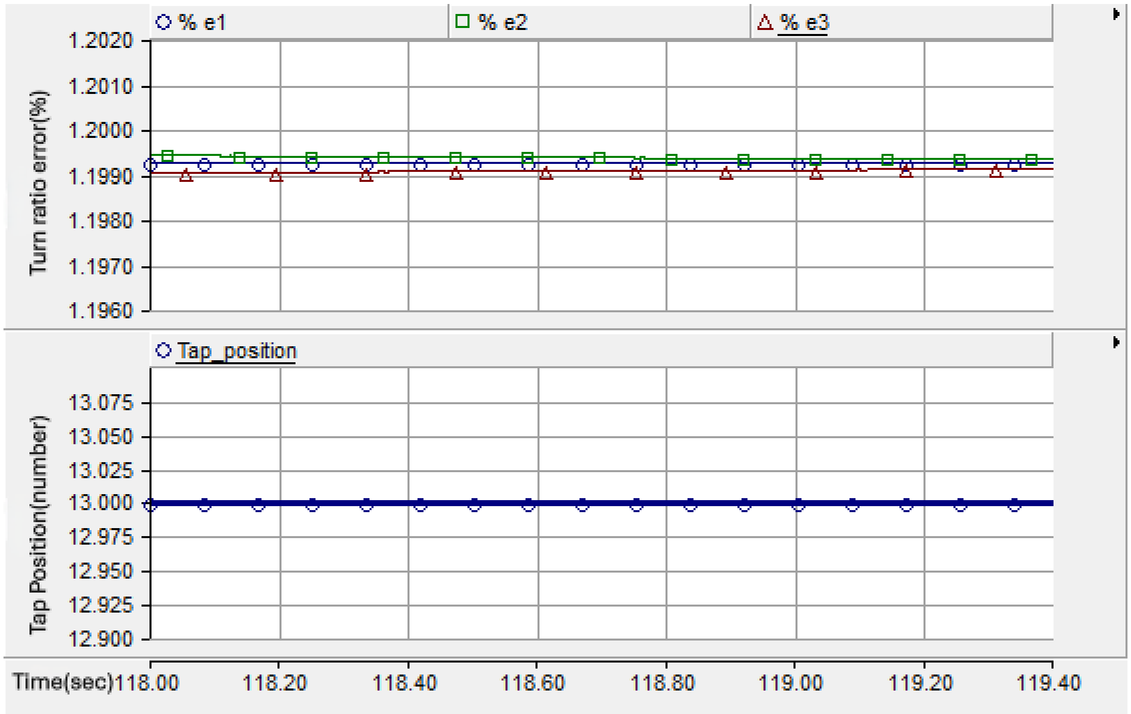

Figure (7) three phase turn ratio error with tap compensation with OLTC position (13).

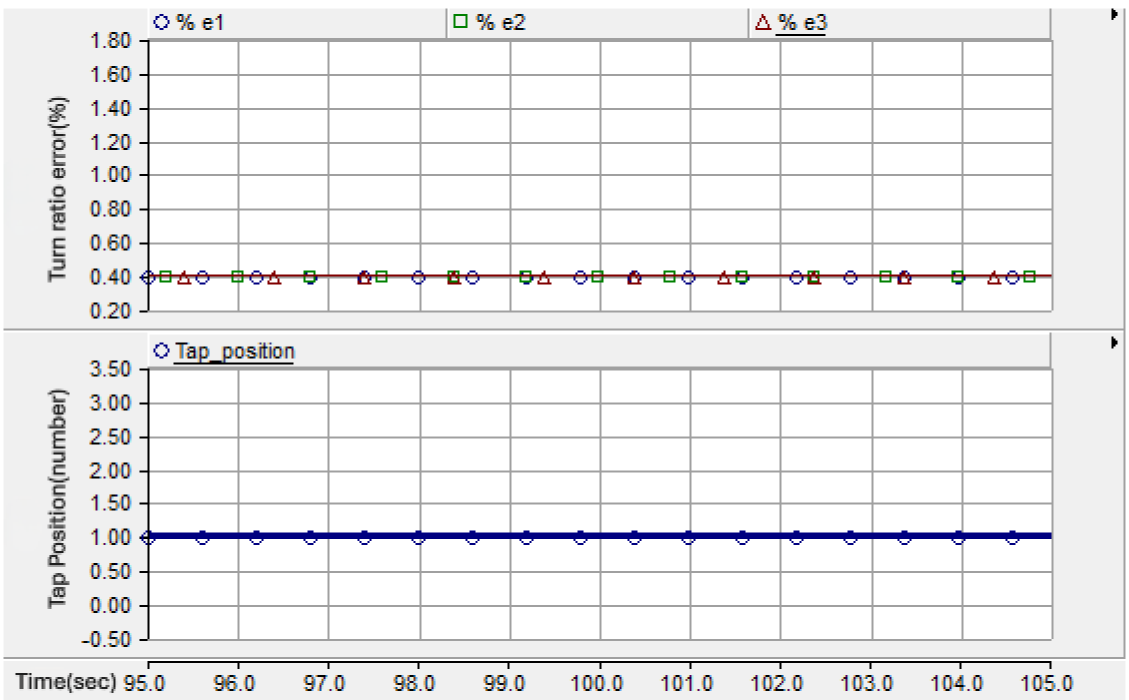

Figure (8) three phase turn ratio error with tap compensation with OLTC position (1).

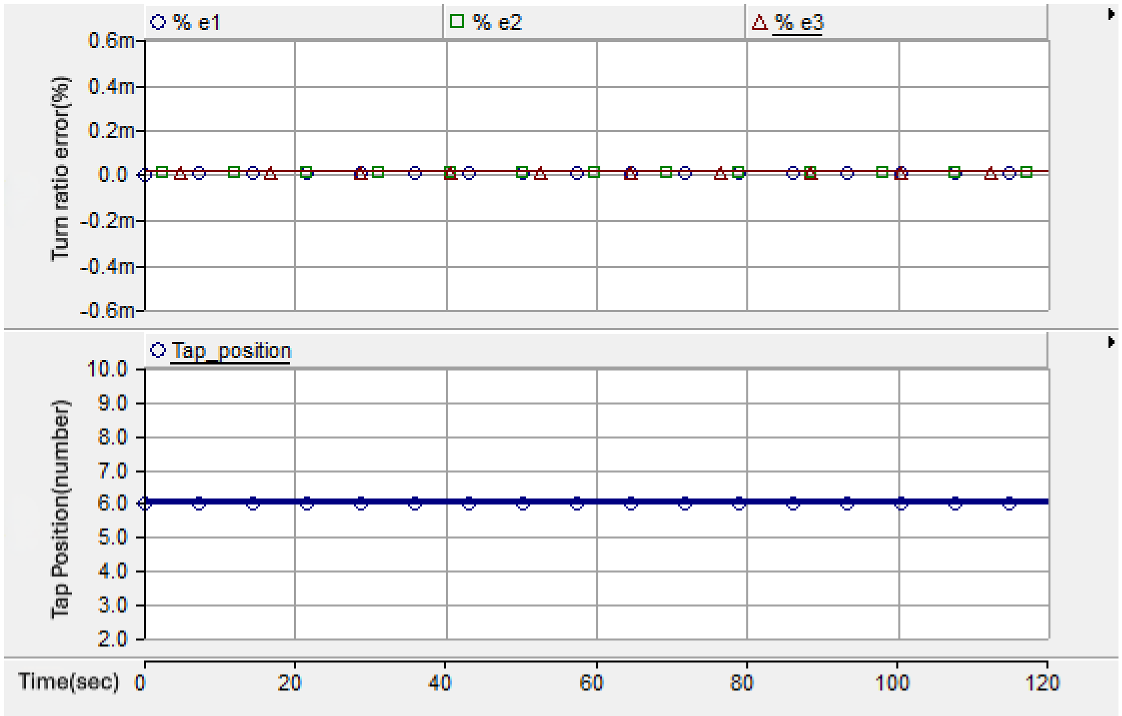

Figure (9) three phase turn ratio error with tap compensation with OLTC position (6).

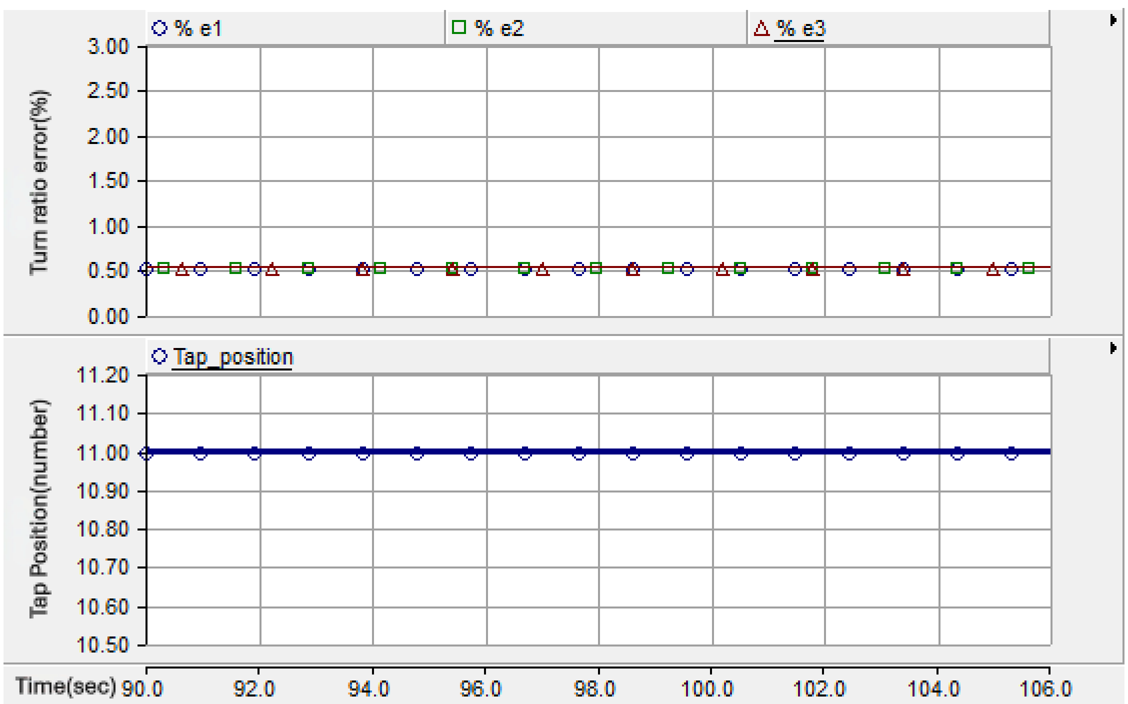

Figure (10) three phase turn ratio error with tap compensation with OLTC position (11).

Table (3) CT secondary current values.

OLTC Position	HV side CT secondary (A) without tap compensation	HV side CT Secondary referred to MV side (A)without tap compensation	MV CT Secondary (A)	HV side (A) With tap compensation CT secondary	HV side (A) With tap compensation CT secondary referred to MV side
1	0.8544296	0.74	0.7907	0.9149	0.7876
2	0.8665206	0.75	0.7907	0.9163	0.7888
3	0.8789587	0.76	0.7907	0.9174	0.7897
4	0.891759	0.77	0.7907	0.9181	0.7904
5	0.9049377	0.78	0.7907	0.9185	0.7907
6	0.9185118	0.79	0.7907	0.9185	0.7907
7	0.9324993	0.80	0.7907	0.9185	0.7907
8	0.9469194	0.82	0.7907	0.9181	0.7903
9	0.9617925	0.83	0.7907	0.9172	0.7896
10	0.9771402	0.84	0.7907	0.9157	0.7883
11	0.9929857	0.85	0.7907	0.9138	0.7866
12	1.0093536	0.87	0.7907	0.9111	0.7844
13	1.0262702	0.88	0.7907	0.9079	0.7815

The percentage slope, I_D and I_{RC} of differential protection can be found only for Turn Ratio Error Differential current using equations (8,9 and 10) without OLTC position compensation which table (4) shows the various results as per OLTC positions then the highest value of percentage slope can be add to the overall percentage slope setting value of the differential equation by taking into consideration the CT ratio and CT wire resistance error, Inrush current and Excitation current, in this case the overall percentage slope setting may reach between 30% to 50% according to transformer rating.

Table (4) ID & IRC and Slope % calculation without OLTC position compensation.

OLTC Position	ID	IRC	$\%\ Slope$
1	0.055166	0.763136	7.228915663
2	0.044758	0.768340	5.825242718
3	0.034050	0.773694	4.400977995
4	0.023031	0.779204	2.955665025
5	0.011686	0.784876	1.488833747
6	0.000000	0.790719	0
7	0.012041	0.796740	1.511335013
8	0.024455	0.802946	3.045685279
9	0.037259	0.809348	4.603580563
10	0.050471	0.815955	6.18556701
11	0.064112	0.822775	7.792207792
12	0.078203	0.829820	9.42408377
13	0.092766	0.837102	11.0817942

using the same equations of (8,9 and 10) for various OLTC position with tap compensation model which table (5) shows the different values as per OLTC positions, in this case the overall percentage slope setting may reach between 20% to 40% according to transformer rating.

As a result of this research, it could reduce around 10% of differential protection slope and improve the sensitivity of this protection scheme by 9.33%. and figure (11) shows that the three phase differential current output and circuit breaker trip command is zero for this new model for the highest OLTC position error value.

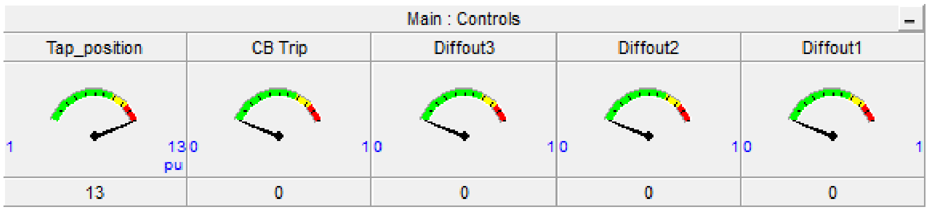

Figure (11) three phase differential current output and circuit breaker trip signal.

Table (5) ID & IRC and Slope % calculation with OLTC position compensation.

OLTC Position	ID	IRC	$\%\ Slope$
1	0.003123	0.789158	0.3957
2	0.001927	0.789755	0.2440
3	0.000992	0.790223	0.1255
4	0.000340	0.790549	0.0431
5	0.000000	0.790719	0.0000
6	0.000000	0.790719	0.0000
7	0.000000	0.790719	0.0000
8	0.000372	0.790533	0.0471
9	0.001152	0.790143	0.1458
10	0.002378	0.789530	0.3012
11	0.004092	0.788673	0.5189
12	0.006341	0.787548	0.8051
13	0.009175	0.786132	1.1671

5.Conclusion.

By taking into consideration the (OLTC) position we can reduce the transformer turn ratio errors, hence the sensitivity of differential protection relay will be much higher in comparison to existing models due to compensating the tap position of the transformer which affects on turn ratio for each tap position. Based on the primary and secondary side currents of the power transformer, which are obtained from the CT secondary readings for each side, the OLTC position is incorporated into the equations of the proposed model. By simulating these equations in PSCAD/EMTDC software, the results demonstrate that using this scheme the turn ratio error of power transformer can be reduced from 10% to 1.17% and this will improve the differential protection settings by 9.33%, hence the pickup current by dual – slop characteristic will be reduced by 9.33%. This reduction in error allows for a lower differential relay setting, enhancing both protection sensitivity and reliability. Additionally, the proposed scheme minimizes the risk of false trips caused by OLTC position variations, leading to improved transformer protection.

Future work can focus on further refining this model by integrating real-time OLTC feedback systems and machine learning algorithms for adaptive protection settings. Additionally, testing the proposed method in real-world transformer networks and expanding its application to multiwinding transformers could further validate its effectiveness. The implementation of this technique in modern power grids will contribute to improved stability, reduced maintenance costs, and enhanced transformer lifespan.

6.References.

ALEKSANDRS, D. & JE, K. 2014. Improvement of the sensitivity of differential protection of power transformers. Электротехнические и информационные комплексы и системы, 10, 5-13.

ALI, A. 2009. Power Transformer Protection by Using Fuzzy Logic. Iraq Journal for Electrical and Electronic Engineering, 5, 1-11.

ALI, E., HELAL, A., DESOUKI, H., SHEBL, K., ABDELKADER, S. & MALIK, O. P. 2018. Power transformer differential protection using current and voltage ratios. Electric Power Systems Research, 154, 140-150.

ALKAHDELY, S. M. A. & ALSAMMAK, A. N. B. 2023a. Non-Limiting Operation of The On-Load Tap Changing Transformer, and Its Effect on Voltage Stability, with Regards to The Nineveh Electrical Grid. Przeglad Elektrotechniczny, 99.

ALKAHDELY, S. M. A. & ALSAMMAK, A. N. B. 2023b. Normal operation and reverse action of on-load tap changing transformer with its effect on voltage stability. Bulletin of Electrical Engineering and Informatics, 12, 650-658.

AMAL, T. M. & IBRAHIM ISMAEL, H. 2023. Design and Simulation of a Hybrid Wind/Solar/Diesel/ Battery Off-Grid System for Rural Areas: A case Study in Al-Mahmudiyah Tribal Zone of Iraq. Zanco Journal of Pure and Applied Sciences, 35, 9-21.

ARNAUTALIĆ, S., MUJČINAGIĆ, E. H. & PETROVIĆ, S. 2021. Influence of Current Transformer Saturation on Numerical Protection Relays – A Case Study of Circuit Breaker Failure Protection. B&H Electrical Engineering, 15, 78-85.

ASMAHAN, Y. H., KAMAL, H. Y. & AMEEN, A. F. 2021. High Harmonic Reduction Using Passive Filters of Mountain Steel Company. Zanco Journal of Pure and Applied Sciences, 33, 178-187.

BEJMERT, D., KEREIT, M., MIESKE, F., REBIZANT, W., SOLAK, K. & WISZNIEWSKI, A. 2020. Power transformer differential protection with integral approach. International Journal of Electrical Power & Energy Systems, 118, 105859.

EDWARDS, B., WILLIAMS, D. G., HARGRAVE, A., WATKINS, M. & YEDIDI, V. K. Beyond the nameplate - Selecting transformer compensation settings for secure differential protection. 2017 70th Annual Conference for Protective Relay Engineers (CPRE), 3-6 April 2017 2017. 1-23.

EL-BAGES, M. S. IMPROVEMENT OF DIGITAL DIFFERENTIAL RELAY SENSITIVITY FOR INTERNAL GROUND FAULTS IN POWER TRANSFORMERS. 2011.

HAYDER, T., SCHAERLI, U., FESER, K. & SCHIEL, L. 2008. Universal Adaptive Differential Protection for Regulating Transformers. IEEE Transactions on Power Delivery, 23, 568-575.

KHARE, A. A. & GATFANE, S. D. 2021. Review on Different Techniques for Differential Protection of Power Transformer.

LAL MOOSAVI, S. M., DAMCHI, Y. & ASSILI, M. 2022. A new fast method for improvement of power transformer differential protection based on discrete energy separation algorithm. International Journal of Electrical Power & Energy Systems, 136, 107759.

MAGRIN, F. & TAVARES, M. C. 2018. Increasing sensitivity for transformer protection using incremental differential. The Journal of Engineering, 2018, 1209-1215.

MAYER, D. 2021. Protection of power transformers against the effect of magnetic storms. Journal of Electrical Engineering, 72, 249-255.

MEDEIROS, R. P. & COSTA, F. B. 2018. A Wavelet-Based Transformer Differential Protection With Differential Current Transformer Saturation and Cross-Country Fault Detection. IEEE Transactions on Power Delivery, 33, 789-799.

MORAVEJ, Z., EBRAHIMI, A., PAZOKI, M. & BARATI, M. 2023. Time domain differential protection scheme applied to power transformers. International Journal of Electrical Power & Energy Systems, 154, 109465.

OLIVEIRA, M. O., FERREIRA, G. D., GARCÍA, F. H., BRETAS, A. S., PERRONE, O. E. & REVERSAT, J. H. Adaptive differential protection for power transformer based on transient signal analysis. 2012 IEEE Power and Energy Society General Meeting, 22-26 July 2012 2012. 1-7.

PALIWAL, N. & TRIVEDI, A. 2014. Analysis of Modern Digital Differential Protection for Power Transformer. International Journal of Interdisciplinary Research and Innovations, 2, 46-53.

PARIHAR, V. R., NIMKAR, S. D., WARUDKAR, S., DESHMUKH, R. & THAKARE, M. 2017. Power transformer protection using fuzzy logic based controller. International Journal of Engineering Research, 6, 366-370.

PETRESCU, L., CAZACU, E., IONIŢĂ, V. & PETRESCU, M.-C. 2019. An Experimental Device for Measuring the Single-Phase Transformers Inrush Current. The Scientific Bulletin of Electrical Engineering Faculty, 19, 18-22.

RAHMATI, A. & SANAYE-PASAND, M. 2012. A fast WT-based algorithm to distinguish between transformer internal faults and inrush currents. European Transactions on Electrical Power, 22, 471-490.

RAICHURA, M., CHOTHANI, N. G. & PATEL, D. 2019. Real-Time Monitoring & Adaptive Protection of Power Transformer to Enhance Smart Grid Reliability. Electrical, Control and Communication Engineering, 15, 104-112.

SAHU, V. K. 2021. A review of various protection schemes of power transformers. Turkish Journal of Computer and Mathematics Education (TURCOMAT), 12, 3220-3228.

SEVOV, L., KHAN, U. & ZHANG, Z. 2017. Enhancing Power Transformer Differential Protection to Improve Security and Dependability. IEEE Transactions on Industry Applications, 53, 2642-2649.

SHAH, A. M. & BHALJA, B. 2015. A New Adaptive Differential Protection Scheme for Tap Changing Power Transformer. 16, 339-348.

SHAH, A. M. & BHALJA, B. R. 2013. Discrimination Between Internal Faults and Other Disturbances in Transformer Using the Support Vector Machine-Based Protection Scheme. IEEE Transactions on Power Delivery, 28, 1508-1515.

SMOLARCZYK, A. & BARTOSIEWICZ, E. Modeling Differential Protections of Power Transformers and Their Testing Using PSCAD / EMTDC Software. 2013.

SYED, S. N., RADHIKA, S. & RANI, M. S. 2015. Differential current protection of transformer using Arduino with voice alert. International Journal of Innovations in Engineering and Technology (IJIET), 6, 206-212.

VYAWHARE, D., CHAUDHARI, J., PAREKH, C., CHATURVEDI, M. & SHAH, K. Differential Protection of Power Transformers Using Discrete Wavelet Transform and Convolutional Neural Network. 2025 IEEE Texas Power and Energy Conference (TPEC), 2025. IEEE, 1-6.

WANG, Y., ZHONG, X. & CHEN, X. 2021. Influence of saturation levels on transformer equivalent circuit model. Journal of Electrical Engineering, 72, 381-387.

WARDA HUSSEIN, A. 2020. Midterm Load Forecasting Analysis For Erbil Governorate Based On Predictive Models. Zanco Journal of Pure and Applied Sciences, 32, 20-29.

YUAN, T., GAO, H., PENG, F. & LI, L. 2025. Scheme to Prevent Maloperation of Current Differential Protection due to Non-internal-fault Events in Active Distribution Networks. IEEE Transactions on Smart Grid.

ZHANG, W., TAN, Q., MIAO, S., ZHOU, L. & LIU, P. 2013. Self-adaptive transformer differential protection. IET Generation, Transmission & Distribution, 7, 61-68.

ZHAO, W. K., HE, J. H., BO, Z. Q. & KLIMEK, A. The improvement of the digital differential relay in on-load tap changer transformer. 2009 International Conference on Sustainable Power Generation and Supply, 6-7 April 2009 2009. 1-4.

ZHENG, T., LIU, X., LU, G. & HU, X. 2018. Adaptive algorithm for identifying oltc position and its application on UHV voltage-regulating transformer differential protection. International Transactions on Electrical Energy Systems, 28, e2518.