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Power Transformer and Environment Protection Enhancement

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ABSTRACT/RESUME

Abstract: *The power transformer is considered not only as a vital and expensive component in power grid; but also the most dangerous element. Since it contains a great quantity of oil or gas SF6 in contact with high voltage elements, it may produce the risk of fire and explosion in case of abnormal circumstances or technical failures and hence affects on the envorinment. A differential protective relay that is very sensitive protection is generally used for protecting this power transformer. However, its operation may be affected by the disturbances such as inrush current, current transformer saturation and over-excitation due to external faults. Accordingly, false trips (mal-operation) of protective relay may be resulted in. This research work proposes root cause analysis based on fault tree analysis to be used for assessing disturbances that lead to false trips. When the critical root causes are identified, mitigation measures may be used. The model of security can help to quantify analytically the reliability of the considered protective relay and hence reinforcing it in order to reduce the failure risk.*

I. Introduction

Power transformers can be found at any levels of the power grid starting from the generation to the distribution passing via transmission level. The availability as well as the quality of power supply is mainly related to the transformers safety. The capital loss of an accidental power transformer outage is often counted in million dollars for output loss only, not to say the costs associated with equipment repair or replacement. A transformer fire or explosion that involves several thousand gallons of combustible insulating oil or gas can result in severe damage to nearby power plant structural components such as concrete walls and damage or destroy electrical components and hence the environment [1]. Under the deregulation policy of electric systems, each utility is trying to cut its cost. This pass evidently by the reduction of the failure of power system, where the reduction of the failure risks of power transformer represents a major marigold. If a transformer faces a fault, it is necessary to disconnect it from the grid rapidelly in order to minimize the expected damage and avoid a catastrophic incident. This can be achieved by the coherent selection and design of the protection system.

An appropriate protection such as differential relay for power transformer is necessary and plays an incredible role in maintaining high degree of availability and safety of power grid required in present day. The failure of protective relay to operate as intended may place at risk the safety of the transformer and the whole power grid and hence may lead to the blackout.

In fact, major causes of mal-operation of power transformer differential protection are the inrush current and saturation due to over-excitation of the current transformer. A high sensitivity may cause false trips due to current transformers errors at external faults with high fault currents. Major disturbances are more likely to be caused by unnecessary tripping rather than by the failure of a relay to take action [1]. In order to overcome the drawbacks of these relaying systems, many techniques have been developed such as an introduction of delay that blocks the relay to operate during the inrush phenomena [2].

The mal-operation of this relay is generally due to not only unnecessary tripping during inrush current that reduces the security of protection system and hence its reliability but also unnecessary tripping when external fault occurs accompanying an overexcitation [3]. Also this action may affect on a security of the relay and hence its reliability. Many techniques have also been developed to block the operation of the relay during the saturation associated with an external fault condition such as a harmonic restrains [4], and a combination of waveform of swing center’s voltage (WSCV) and synthetic negative vector [5]. A more advanced new blocking function based on fourth harmonic detector using digital signal processing has been proposed [6]. In addition to the second harmonic magnitude information, the proposed system uses other harmonic orders magnitudes information for different disturbances detection, which can be provided at high speed by numerical differential relay. Therefore, the proposed system blocks tripping signal during the inrush current as well as when an over-excitation occurs during external fault condition.

Moreover, protective relays can easily discriminate between fault and non-fault conditions when power quality is good. When power quality is poor, the harmonic component between normal and fault conditions becomes imprecise. In the relaying application, engineers can no longer rely on the performance of the relay under conventional normal system conditions. However, under conditions of poor power quality especially in the smart power grid including TCSC, they have improved the relay performance by designing digital filters which in turn make the relay more secure and dependable. In several cases, protective relays have undesirably operated in response to harmonics or sub-harmonics in the modern power grid [7]. In protection field, such large relative error is not permissible. The performances of these employed techniques directly establish the measurements of these protection systems and affect on their reliability. Hence, the real-time accurate measurement of the fundamental component and/or harmonic components is essential and crucial to the safe operations of protection system [8, 9].

In this study, Root Cause Analys (RCA) is based on fault tree analysis is used to identify disturbances first and root cause of false trips of a differential relay which may lead to power transformer damage. Once the critical root causes are identified, conventional mitigation measures have been used first and then proposed blocking functions and digital filters in view of increasing the reliability of the considered protection system. Previous works [10-11] proposed some efficient solutions (based mainly on using digital filters) to obtain accurate and disturbance-free measurements. As a result, the reliability of the measuring block of the protection system has been significantly improved. However, this improvement concerns one part of the protection system reliability. In the present work, the reliability of the global protection system is considered. This new approach has many advantages compared to those published in previous researches as it allows obtaining an important quantitative figure (security). This permits selectively to reinforce the elements of the protecting system which are most likely appropriate to failure and hence the impact on the overall system's cost is significant. Another main advantage is to take also into account the reliability of the software part of the numerical protective relay.

II. Materials and methods

II.1. Differential Relay

Differential protective relay replaces over-current relay and Buchholz relay as the main protection for large power transformers. A typical differential protective relaying system for three phase power transformer is shown in Fig.1. Multiple circuits may exist, but the example is sufficient to explain the basic principle of differential protective relay. In Fig.1, it can be noted that the protection zone is delimited by current transformers (CT). Due to its characteristic, differential protection does not provide backup protection to other system components. For this reason, differential protection is categorized as a unit protective scheme. The conductors bringing the current from the current transformers to the differential relay are named pilot wires.

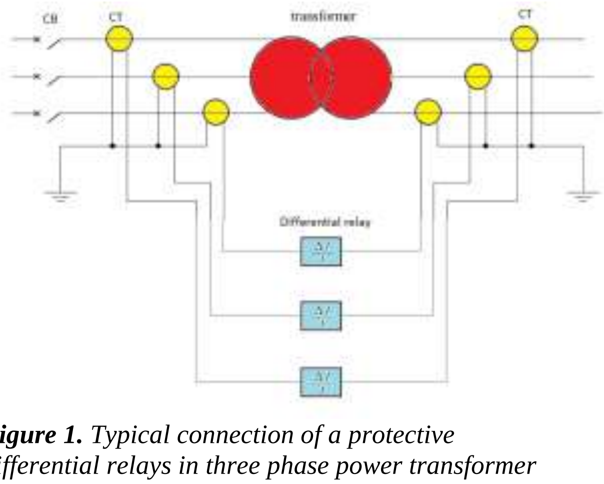

Figure 1. *Typical connection of a protective differential relays in three phase power transformer*

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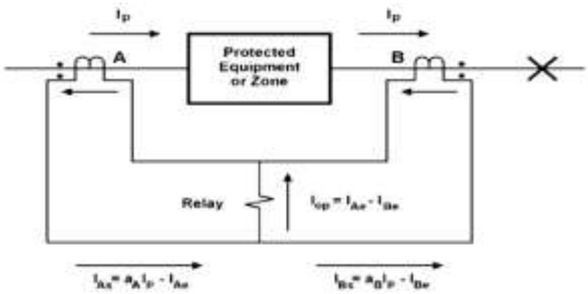

Figure 2. *Differential relay currents during normal operation or external fault*

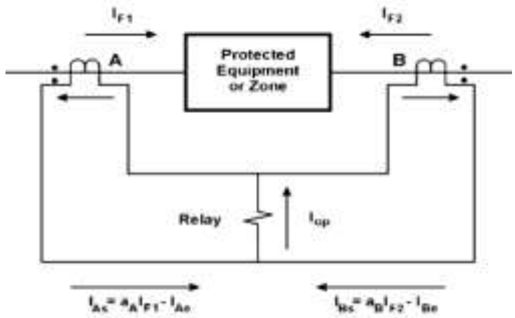

Figure 3. *Differential Relay currents during internal faults*

Figures 2 and 3 show a diagram illustrating the principle of the differential relay protection. Current transformers with similar characteristics and ratio are connected on the both sides of the transformer and a relay is connected between the two current transformers by using pilot wires. Under healthy or external fault conditions, as shown in Fig.2, no current flows in the relay. When the internal fault occurs, as shown in Fig.3, the conditions of balance are upset and current flows in the relay to cause the tripping. It can also be noted that the protected zone of this differential relay is between the two current transformers. If the fault had occurred beyond, as shown in Fig.2, than it does not operate as the fault current flow through both current transformers and hence maintaining the balance. Differential relays perform well for external faults as long as the current transformers reproduce the primary currents correctly [4].
When one of the current transformers saturates, or if both current transformers saturate at different levels, false operating current appears in the differential relay and causes mal-operation of the relay. Some relays use the harmonics caused by the current transformer saturation for adding restraint [5].
Under normal conditions, the current Ip entering the protected unit would be equal to the current leaving it at every instant as shown in Fig.2. The secondary current of current transformer A is equal to,

$$I_{As} = \alpha_A I_p - I_{Ae} \qquad (1)$$

where, α_A is the transformation ratio of current transformer A, and I_{Ae} is the excitation current of current transformer A on the secondary side.
For current transformer B, the equation is similar and is as follows.

$$I_{Bs} = \alpha_B I_p - I_{Be} \qquad (2)$$

where, α_B is the transformation ratio of current transformer B, and I_{Be} is the excitation current of current transformer B on the secondary side.
Assuming transformation ratios are equal, $\alpha_A = \alpha_B = \alpha$, the relay operation current I_{op} is given by:

$$I_{op} = I_{Ae} - I_{be} \qquad (3)$$

During normal system operation and during external faults, the relay operating current I_{op} is too small, but it is never equal zero ($I_{op} \neq 0$).
If the fault occurs in the protection zone, the input current is no longer equal to the output current. The operating current of the differential relay is now the sum of the input currents feeding the fault as shown in Fig.3,

$$I_{op} = \alpha(I_{F1} + I_{F2}) - I_{Ae} - I_{be} \qquad (4)$$

Transformer differential relay is subjected to several factors that can cause mal-operation such as: magnetizing inrush currents, in which differential relay sees as internal faults, over-excitation due to the external faults and current transformer saturation.

II.2. Root Cause Analysis

Root cause analysis is a step by step approach that leads to identify a disturbance's first or root cause, it is applied as one of the basic methods of analysis in predictive maintenance [12]. Recently it is used to develop new model of fault diagnosis of power systems [13,14]. There are specific successions of events (disturbances) that lead to a failure such as false trip. A root cause analysis investigation follows the cause and effect path from the final outcome back to the root cause [12]. In this case, a Fault Tree is constructed to determine all possible causes that can lead to the undesirable top event that is false trip.

Table 1. *Disturbances causes with their weights (proportions)*

Disturbances	Abbreviation	Causes	W (%)
Inrush current	IC	Energization of Power Transformer.	45
Over-Excitation	OE	Switching actions	20
Relaying system	RS	Self technical failures in hardware or software parts and or incorrect setting, current transformer saturation	15
Others	UP	Unknown phenomena	20

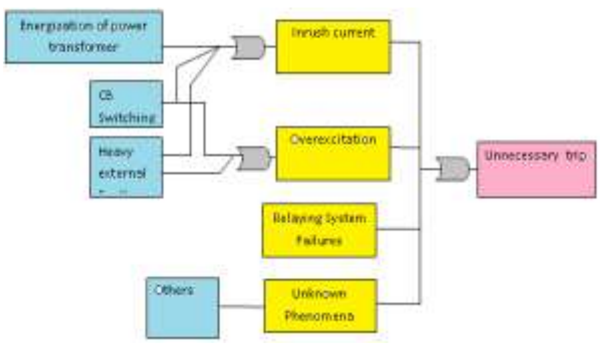

Figure 4. *Root Cause Analysis based on FTA of unnecessary trips.*

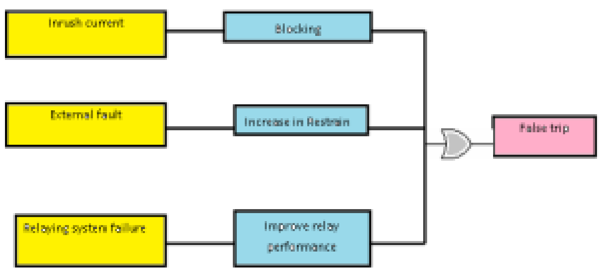

Figure 5. *Root Cause Analysis (FTA) of unnecessary trip after providing mitigations*

A power transformer can be considered in this research paper as shown in Fig.1. The differential relay is used for protecting this power transformer. The relay can monitor the electrical line current variables using appropriate number of current Transformers (CT).
From field data, false trips may generally be caused by inrush current, over-excitation due to heavy external faults, the relay system failures or other unknown phenomena as given in Table 1 [15, 16]. These phenomena may include harmonics and sub-harmonics generated by power electronic devices in the modern power grid. The fault tree diagram of the false trips (incorrect operations) has been illustrated in Fig.4.

III. Protection system Reliability Modelling

A reliable relaying system can be achieved by redundancy i.e. duplicating the relaying system. Obviously redundancy can be a costly proposal. However, it is important to realize that back-up protection for safe operation of relaying system.
A quantitative measure for reliability is defined as follows:

$$R = \frac{N_c}{N_d + N_u} \tag{5}$$

Where, Nc : Number of corrected trips, Nd: Number of desired trips, Nu : Number of unnecessary trip.
Protection system reliability is characterized by following two important terms:
-Dependability,
-Security.

III.1. Dependability

A relay is said to be dependable if it trips only when it is expected to trip. This happens either when the fault is in its primary control (primary protection) or when it is called upon to ensure the back-up protection. However, false tripping of relay due to faults that are either not within its jurisdiction or within its purview may lead to power system instability. Power transformer may get unnecessarily stressed or else there can be loss of service. Dependability (D) is the degree of certainty that the relay will operate correctly:

$$D = \frac{N_c}{N_d} \tag{6}$$

III.2. Security

On the other hand, security is a property used to characterize false tripping of the relays. A relay is said to be secure if it does not trip when it is not expected to trip. It is the degree of certainty that the relay will not operate incorrectly during a given time interval according to the IEEE/PSRC Working Group [17].

$$S = 1 - \frac{N_m}{N_t} \tag{7}$$

Where S: security, and Nt =Nc+Nm: total number of trips.

III.3. Software Reliability Model

In software engineering, most of failures are due to errors, 'Bugs' or defect built into software from the beginning at design stage or exploitation and this

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may cause malfunction or halt in digital relaying system.
Assuming that an error is eliminated without causing any new errors, the simplest model that takes this into account is the following; let the number of errors N initially equal to No and let each have the same probability of detection p (and hence elimination) per unit time, then the failure rate is expressed as follows [18] :

$$\lambda(t) = pN(t) = pNo\exp(-pt) \quad (8)$$

Under this model the failure rate is decreasing with time in exponential fashion with the essential tasks of debugging in order to eliminate the errors. The expression for reliability growth is given as follows:

$$Rs = \exp(+N) = \exp[\exp(-pt)] \quad (9)$$

IV. Protection Relay Reliability (security)

Subsequent to the identification of potential root cause of false trips (mal-operation), the preventive mitigation (barriers) for enhancing the security and hence reliability of the relay has been proposed.
The previously obtained cause weighted important factor of the disturbance will provide the priority on mitigations and barriers which can be provided first against inrush current, over-excitation and relaying system failures as shown in Fig.5. This accurate reliability model of a conventional protection system of Power Transformers has been obtained by combining the powerful RCA method with the Fault Tree Analysis using data colleted over many years of industrial knowhow from professional ingeneers in the field. Hence, the information gathered in table 1 is a key element in our work as it describes accurately the behavior of protection systems from root-cause point of view since our approach is based on a block-system view of the protection systems. The different details related to each internal sub-system components are not of high importance compared to the overall performance of the sub-system as it is clearly reported on the table.
Traditional techniques for detecting inrush current in the power transformer when the first time is energized as shown in Fig.6, introduce the second harmonic pass filter [19].
Currents of disturbances entering the power transformer which contain a dc offset which decays exponentially, and/or a large number of unwanted significant harmonics due to switching actions may cause false trip of the relay. In digital relay, Discrete Fourier Transform (DFT) is the most widely used filtering algorithm [20, 21] for computing the fundamental components and illuminating these disturbances.

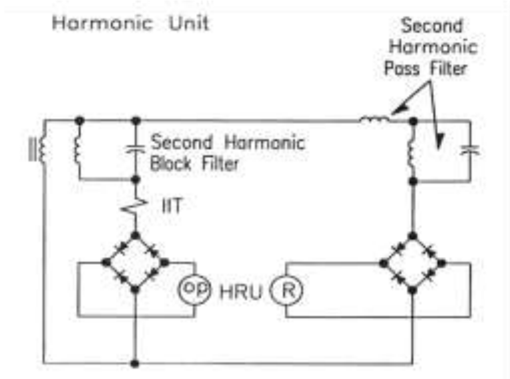

Figure 6. *Blocking of Differential Relay during the inrush condition*

These false trips may be produced from inrush current and over-excitation due to external fault or switching actions. They do not just create trouble. They can even compromise system security. One way to categorize the data from the chosen utilities' relay operations is as follows: Over (Ne=134) total events or disturbances during a period of 5 years: from 2006 till 2010, we have the following data indicated in table 2 [22]. Since the main objective of this work is to propose a method to demonstrate the ability of the RCA approach based on the FTA technique in order to obtain a quantitative estimation of the reliability of power transformers protection systems then, the set of data we have used which, is the best set found in literature with regard to its consistence, serves for demonstration purpose. Yet any other set of data can also be used for the same purpose.

The probability of occurrence of power system disturbances leading to false tripping relative to the total number of disturbances or events can be evaluated as follows:
PDT= Nm /Ne (10)

Table 2. *Statistics for different operations*

Operations	Symbole	value
Corrected trips	Nc	9
incorrect operations (unnecessary Trips)	Nu	124
Desired trips	Nd	10
Failure to operate	Nf	1

Table 3. *False trips causes' probability*

Disturbance	W (%)	False trips causes' probability	False trips causes' probability
IC	45	PIC	0.4164
OE	20	POE	0.1851
RS	15	PRS	0.1388

The average value of disturbances leading to incorrect tripping is evaluated 92.5 % for a given time interval. Then, the probability of occurrence of each cited disturbance leading to the false trip can be obtained as follows:

Pft=PDT*w (11)

The quantitative evaluations associated with the weight values are given in table 3.

The total probability of occurrence of the known disturbance leading (with the assumption of independency) to unnecessary tripping is evaluated as follows:

Pun=PIC U POEU PRS (12)

Pun ≈ΣPft =0.7403 (13)

Hence, the security value is deduced as the complement of the previous probability:

S = 1- Pun= 0.2597 (14)

The existing security for the given protective system can be obtained using Eq. (7) which is Se= 0.2597 or through the use of Eq.(14). It can be noted that they are approximately equals.

V. Differential Relay Reliability Enhancement

After identifying a root cause of false trips (incorrect trips), the previous preventive mitigation has been used. However, for further enhancing the reliability of the relay, recent developed techniques used as barriers have been proposed.

Recently a new approach has been proposed by integrating software measurement algorithm that will detect the magnetizing inrush current to enable and to give order to block or unblock the trips [6]. In that research work, the second and the fourth order of harmonic magnitudes may be used for detecting the inrush current. On the base of these measurements, the ratio of the fundamental to the second and then to the fourth are calculated and used in developed algorithm for detecting and distinguishing the inrush current from the internal fault current. The algorithm is implemented as a set of Matlab routines and its performance is successfully tested by simulation. This technique is commonly used in research works where reliability is concerned and it proved to be very efficient.

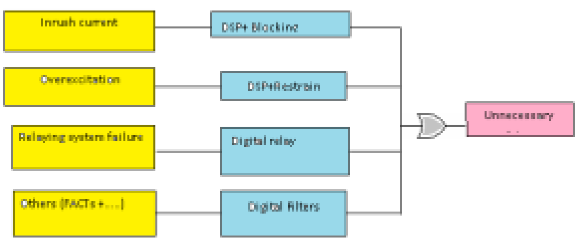

Figure 7. *FTA of unnecessary trip after improving barriers*

Besides, other approaches have been proposed by integrating software measurement algorithm that will detect the over-excitation to enable and to increase in restraining zone and decrease in zone of trips [6]. In that research work, the third and the fifth order of harmonic magnitudes may be used for detecting this over-excitation. On the base of these measurements, the ratio of the fundamental to the third and then to the fifth are calculated and used in developed algorithm for detecting and distinguishing the difference in the currents measured at both sides of the transformer due to the over-excitation from which is due to the internal fault current. The algorithm is implemented as a set of Matlab routines and its performance is successfully tested by simulation. This technique is commonly used in research works where reliability is concerned and it proved to be very efficient.

The thyristor-controlled switched capacitor (TCSC), which may be used to enhance and optimize the use of the transmission network facilities, may also generate these DC components and harmonics [7]. This latter always needs few cycles (10– 20 cycles) for obtaining accurate fundamental phasors by DFT algorithm. Such waveform distortion caused by the insertion of TCSC, may affect the reliability of the protective relays and may cause relays false trips.

The weaknesses of the previous algorithms have been overcome by many other research works [8, 9]. For removing the DC-components and associated unwanted signals, digital filters such as IIR filters have been proposed.

Using the model illustrated in Fig.7, assuming in each case the probability of success in removing the disturbances leading to false trip in each barrier is given in table 4.

Then, the new probability after improving the barrier will be:

Pn= PD*Pr = PD (1-Ps) (16)

The overall probability of occurrence of disturbance leading to unnecessary trips (false trips) is approximated as the sum of Pni:

Po= ∑Pni=0.2822 (17)

Table 4. *Probability of success*

Disturbance (False trip)	Probability of success Ps	Probability Residual Pr	Poccurrence Pni
Inrush current (IC)	0.55	0.45	0.1874
Overexcitation (OE)	0.80	0.20	0.0370
Relaying System (RS)	0.85	0.15	0.0208
UP (FACTs)	0.80	0.20	0.037

The ratio of the obtained result with the initial is given:

R= Pno/Pun=0.3812 (18)

Comparing the results: the Pnu has been reduced by approximately 40 %.
And hence the new security will be evaluated as follows:

$$Sn=1- Pno= 0.7178 \quad (19)$$

Then, the new Security Sn has been substantially improved with respect to the existing one (Se = 0.2597) and hence the safety and the protection of the power transformer will also be enhanced.

VI. Conclusion

In this paper, Root Cause Analysis (RCA) based on fault tree analysis has been used to identify root cause of false trips of differential relay. Once the critical root causes have been identified and their weights quantified, barriers such as blocking and unblocking functions using harmonic restraining techniques have been introduced. By applying recent developed techniques to the barriers, a considerable increase in the security and hence protection system reliability has been noticed. One of the main advantages of the RCA is to make possible to perform quantitative analysis on the protection system before and after using improved barriers. The quantitative analysis of the improved model shows an increase of about 3% of the security which implies an appreciable enhancement of the reliability of the considered protection system.
Thus the overall cost of the system may be significantly optimized, since it is possible to selectively reinforce the elements of the protecting system which are most likely apt to failure and hence avoid the use of unnecessary redundancy.
If the protection system reliability has been improved, the safety of the power transformer also will be enhanced and hence the risk of fire and explosion that affects on the envorinment will be reduced.

VII. References

1. Power Plant and Transmission System Protection Coordination, *NERC Technical Report*, July 2010.
2. Brunke, J. H.;. Fröhlich, J. K. Elimination of Transformer Inrush Currents by Controlled Switching. *IEEE Transactions On Power Delivery*, vol. 16 (2001) no. 2.
3. Guzmán, A.; Zocholl, S.; Altuve, H. Performance analysis of traditional and Improved differential Protective transformer relays. *SEL Paper*, (2000).
4. IEEE Standard C37.91- 2000. Guide for Protective Relay Applications to Power Transformers. *The Institute of Electrical and Electronics Engineers*, October (2000).
5. Bouderbala, R.; Bentarzi, H.; Ouadi, A. Digital Differential Relay Reliability Enhancement of Power Transformer. International Journal of Circuits, Systems and Signal processing 5 (2011) 263-270.
6. Bouderbala, R.; Bentarzi, H. Differential relay reliability enhancement using fourth harmonic for a large power transformer. *International Journal of Syst. Assur. Engineering Mang*., Springer, (2016).
7. Zitouni, A.; Ouadi, A.; Bentarzi, H. Measurement Quality Enhancement using Digital Filter in Power Grid integrating TCSC. *EPE2015, Koutynad Desnou*, Czech Republic, May 20 – 22, (2015).
8. Recioui, A.; Ouadi, A.; Bentarzi, H. Design of an IIR Digital Filter for Phasor Measurement Improvement Based on a Hybrid Optimization Algorithm. *3rd international conference on electric power end energy conversion systems, EPECS'2013*, October 2-4, Istanbul, Turkey,(2013).
9. Ouadi, A.; Bentarzi, H.; Recioui, A. Optimal Multi-Objective Design of Digital Filters Using Taguchi Optimization Technique. *Journal of Electrical Engineering*, Vol.65, N°1 (2014) 21-29.
10. Li, J.; Xie, X.; Xiao, J.; Wu, J. The framework and algorithm of a new phasor measurement unit. *IEEE Int. Conf. on Elec. Util. Dereg., Restruc. And Power Tec. (DRPT2004)*, (2004) 826-831,.
11. Guzman, A.; Altuve, H.; Tziouvaras, D. Power Transformer Protection Improvements with Numerical Relays.
12. Mobley, R. K. Root cause failure analysis, Butterworth-Heinemann (1999).
13. Peng, P.; Liao, Z.; Wen, F.; Huang J. A Root-Cause-Analysis Based Method for Fault Diagnosis of Power System Digital Substations. In: Madani K., Dourado A., Rosa A., Filipe J. (eds) *Computational Intelligence. Studies in Computational Intelligence*, vol 465. Springer, Berlin, Heidelberg, (2013).
14. Haas, D.; Painter, F. D.; Wilkinson, M. Root-Cause Analysis of Simultaneous Faults on an Offshore FPSO Vessel. *59th Annual Petroleum and Chemical Industry Technical Conference*, New Orleans, Louisiana, September 24–26, (2012).
15. Anderson, P. A.; Flemming, B.; Lee, T. J.; Schweitzer, E. O. Reliability Analysis of Transmission Protection Using Fault Tree Methods. *Proceedings of the 24th Annual Western Protective Relay Conference*, Washington, USA, (1997).
16. Sonalgaz Company internal report, Algiers, Algeria, (2013).
17. IEEE Power System Relay Committee Working Group I17 Report, Transmission Relay System Performance Comparison.
18. Moxley, R. Analyse relay fault data to improve service reliability. *Schweitzer Engineering Laboratories, Inc.* Pullman, WA USA, (2010).
19. Bogdan, K.; Ara, K. An Improved Transformer Inrush Restraint Algorithm Increases Security While Maintaining Fault Response Performance. *53rd Annual Conference for Protective Relay Engineers*.
20. Phadke, A. G.; Thorp, J. S. *Computer Relaying for Power Systems*. New York: John Wiley and Sons, (1988).
21. Johns, A.T.; Salman, S.K. Digital protection for power system. *IEE power series N° .15*, London (1995).
22. Gavrilos, G.; Vitolina, S. Identification of Power Transformer's Failure and Risk Sources. *Proceeding of the 52th International Scientific Conference of RIGA Technical University on Power and Electrical Engineering*, October (2011).

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