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IMPACT STUDIES OF TOTAL HARMONIC DISTORTION ON DIRECTIONAL OVERCURRENT RELAY PERFORMANCE

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This paper study impact of harmonics on the performance of the Directional Over-Current Relays (DOCR) and causes an untimely relay tripping under normal operating conditions. This paper details the impact of Total Harmonic Distortion Current (THD_I) levels on DOCR on meshed power systems. Our study is focused on fault current (I_F), operating times of primary and backup relays, and their Coordination Time Interval (CTI). The pre-fault voltage values in the presence of harmonics are computed using harmonics power flow program and used to calculate the three phase fault. The WSCC 9-bus power transmission test system, the obtained results show that the harmonics have a great impact on the relays and may cause a miss of coordination between the primary and the backup relays.

Keywords: Directional Overcurrent Protection, Total Harmonic Distortion, Fault Current, Operation Time, Coordination Time Interval

1. Introduction

In recent years, major changes appear in the characteristics of electrical installations, which are evident when analyzing the waveforms of voltage and current in those circuits. These waveforms are increasingly different from pure sinusoidal signals, due to various disturbances, one of them are the harmonics [1]. Distortion of sinusoidal voltage and current waveforms caused by harmonics is one of the major power quality concerns in electric power industry. Considerable efforts have been spent in recent years to improve the management of harmonic distortion in power systems.

Harmonic standards provide useful preventive solutions to harmonics. International standards emphasize placement of limits on harmonic currents

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produced by nonlinear loads for customer and network bus harmonic voltage distortion for electric utilities. In power systems, harmonics are not desirable in most of the applications and operations, the effects of harmonics have been focused in various power systems fields such as: Power measurement [2], power transformer loss [3], rotating machines [4], brushless doubly fed reluctance machine [5], permanent magnet synchronous machine [6], compact fluorescent lamps [7], wind energy using doubly fed induction generator [8], optimal capacitor placement in distribution system [9],small-signal stability [10], optimal dispatch economic [11], reconfiguration of the conventional power load flow [12, 13], high voltage direct current [14], distributed generation configuration in distribution system [15].

In practice the electrical power systems have a variety of loads that must be operated safely under various operating conditions. Therefore, the electric protection must be designed to detect any type of symmetrical and asymmetrical faults. Further, it is necessary to make distinctions among the various types of current available, normal as well as abnormal: such as motor’s current starting, overload current, operating current, transformer energizing inrush current. It is also important to detect the magnitude and the direction of the fault current especially in the overcurrent protection.

In order to enhance the reliability of the protection system, a backup protective scheme is provided to act as a second line of defense in case of any failure in the primary protection (the first line of defense). Therefore, the back-up scheme shouldn’t come in to action unless the primary (main) fails to take the appropriate action. In other words, it should operate after a certain time delay known as coordination time interval (*CTI*), giving the chance for the primary protection to operate. The fore mentioned situation leads to the formulation of the really coordination strategy, that consists of the selection of a suitable setting of each relay such that their fundamental protective function is met under the desirable qualities of protective relaying, namely sensitivity, selectivity, reliability, and speed [16]. Power system problems associated with harmonics are not new to utility and industrial systems. Waveform distortions and harmonic injections are caused by nonlinear loads and electromagnetic devices. Impact of harmonics on directional overcurrent relay has been treated : on tripping time relays installed on transmission power system [17], effects of non-sinusoidal voltages and currents on the performance of static under-frequency and relay on distribution systems [18], on the performance of electro-mechanical relay [19], solid state relay [20], and digital relay [21, 22], effects of waveform distortion on relays is described theoretically with the results of laboratory test [23], computer based harmonic simulation and testing the performance electromechanical and microprocessor relays in [24], influence of low order harmonic phase angles on tripping time under non-sinusoidal operating conditions in [25], effect of non-sinusoidal current waveforms on electromechanical and solid-state relay operation [26], for impact of harmonics on distance relays in [27] and differential relay for a power transformer in [28].

In this paper, we present the impact of the current *THD* values on the overcurrent relays setting and coordination. In the presence of nonlinear loads, the pre fault buses voltage is calculated using the harmonic power flow program. After that, we calculate the three phase fault current seen by each relay. Our study is mainly focused on the impact of THD_I level on the following relays parameters, namely: current fault, primary and backup relays tripping time and coordination.

2. Root means square and total harmonics distortion currents

It is imperative to size the overcurrent device to true Root Mean Square (*RMS*) as measured by a true *RMS* meter. Average sensing, *RMS* equivalent meters do not correctly respond to harmonic current. Harmonic-rich currents will have higher effective RMS as compared to non-distorted sinusoidal waveforms [24]. The *RMS* value of a pure sinusoidal current waveform (I_{RMS}) is defined by:

$$I_{RMS} = I_{1RMS} \tag{1}$$

Where,

$$I_{1RMS} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_{1\max}^2 \sin^2(\omega t).dt} \tag{2}$$

$$\Rightarrow I_{1RMS} = \frac{I_{1\max}}{\sqrt{2}} \tag{3}$$

The *RMS* value of a non-sinusoidal current waveform ($I_{NS.RMS}$) is defined as:

$$I_{NS.RMS}^2 = \frac{1}{2\pi}\int_0^{2\pi} i^2(t).dt \tag{4}$$

$$I_{NS.RMS}^2 = \frac{1}{2\pi}\int_0^{2\pi} \begin{bmatrix} I_{1\max}\sin(\omega t+\varphi_1)+ \\ I_{2\max}\sin(2\omega t+\varphi_2)+.......+ \\ I_{n\max}\sin(n\omega t+\varphi_n) \end{bmatrix}^2 .dt \tag{5}$$

Where, φ_n is phase angle of n harmonic, and n is rang of harmonic.

$$I_{NS.RMS}^2 = \frac{I_{1\max}^2}{2} + \frac{I_{2\max}^2}{2} + ... + \frac{I_{n\max}^2}{2} \tag{6}$$

Simplifying the above equation results in:

$$I_{NS.RMS} = \sqrt{\frac{I_{1RMS}^2 + I_{2RMS}^2 + ... + I_{nRMS}^2}{2}} \tag{7}$$

The total harmonic distortion of load current is defined as:

$$THD_I = \frac{I_H}{I_{1RMS}} \times 100\% \tag{8}$$

Where,

$$I_H = \sqrt{I_{2RMS}^2 + I_{3RMS}^2 + ... + I_{nRMS}^2} \tag{9}$$

3. IDMT directional overcurrent relay coordination

When a fault occurs on a power system, the fault current is usually greater than the pre fault current in any power system element [29]. Therefore, one of the very effective methods to protect the power system is to use the current magnitude as an indicator of the fault. The overcurrent relay is based on this principle and it is used to protect any power system element. When the measured current by the overcurrent relay is greater than the pickup current, the relay sends a trip signal to the breaker after a time delay $T(s)$. If the delay time is independent on the current fault, this type of relay is termed as an instantaneous relay. Otherwise, if the time delay depends on the fault current, the relay is an Inverse Definite Minimum Time (IDMT). The DOCR employed in this paper are considered as numerical and directional with standard IDMT characteristics that comply with the IEC 60255-3 standard, and have their tripping direction away from the bus [30].

$$T_i = TDS \times \frac{\beta}{\left(I_F / I_P \right)^{\alpha} - 1} \tag{10}$$

Where, TDS is the time dial setting and I_P is pickup current setting of the relay respectively, and I_F is the fault current in the protected transmission line. α and β are constants depending on the characteristic curve [31, 32, 33].

However, it can be shown that the proposed method can be easily applied to a system with combination of DOCRs with different characteristics as presented in Fig. 1.

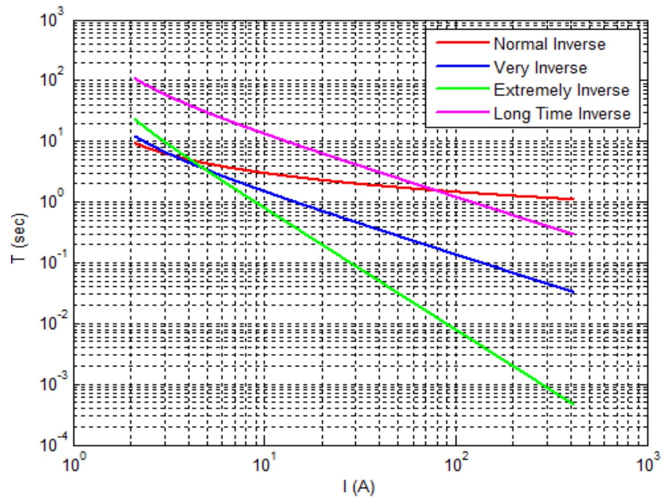


Fig. 1. Time-current of IDMT overccurent relaying characteristics.

In practice, the overcurrent protection is ensured by two different relays: the primary relay and the backup relay. If a fault (*F*) is occurred in the bus *C* like presented in the Fig. 2, the primary overcurrent relay R_B will trip firstly. If this last fails to trip, the backup overcurrent relay R_A will trip after a time delay. This last is used in order to give the chance for the primary protection to operate.

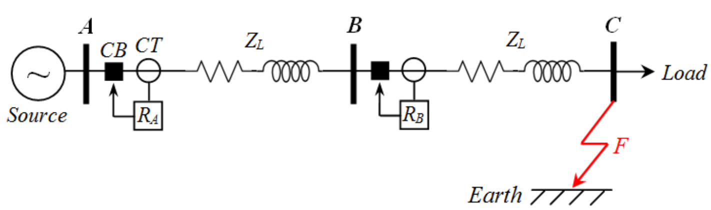


Fig. 2. The primary and the backup protections

On the other hand, the overcurrent relays lose of efficiency in the interconnected power system. As presented in Fig. 3, the relay *B* is set to trip for a fault a F_1 would also trip for a fault F_2 which is outside its zone of protection.

To solve this problem, an option named "directional" is implemented in the overcurrent relay to prevent its tripping if the fault is away of the protection zone. In this case, the relay trips only if the fault is in the forward direction [29].

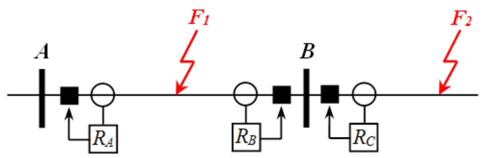


Fig. 3. Directional overcurrent relays in interconnected power system.

The direction of the fault current can be detected by using the phase angle between the fault current and a reference quantity such as the voltage. Since the transmission line is pure inductive, therefore, for a forward fault the current lags the voltage by almost 90°, and for a reverse fault the current leads the voltage by almost 90 (see Fig. 4) [29, 33]. Hence, according to the phase angle between the voltage and the current, the DOCR can be defined as follows:

$$-\pi/2 \leq \theta \leq 0, \quad \text{operate} \tag{11}$$

$$0 \leq \theta \leq \pi/2, \quad \text{Block} \tag{12}$$

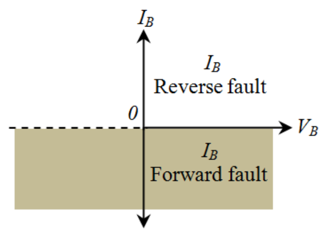


Fig. 4. Voltage and current phasors for directional overcurrent relays.

4. Case study and simulation results

In order to highlight the impact of harmonics on the IDMT directional overcurrent relays efficiency, the WSCC 9-bus power system is used in this paper. According to the THD_I value, we consider the following two simulation scenarios *A*, and *B*, where the scenario *B* has three simulation cases.

- *Scenario A:* Without nonlinear loads (sinusoidal condition),
- *Scenario B:* With nonlinear loads (non-sinusoidal condition):
  - *Case 1* : THD_I = 22 %, in the presence harmonics of ranks 3rd, and 5th.
  - *Case 2* : THD_I = 34 %, in the presence harmonics of ranks 3rd, 5th, and 7th.
  - *Case 3* : THD_I = 46 %, in the presence harmonics of ranks 3rd, 5th, 7th and 9th.

As presented in Fig. 5, the WSCC 9 bus has 12 IDMT overcurrent relays with IEC normal inverse characteristic, three generators, six transmission lines, three power transformers and three non linear loads connected to buses 3, 6 and 9.

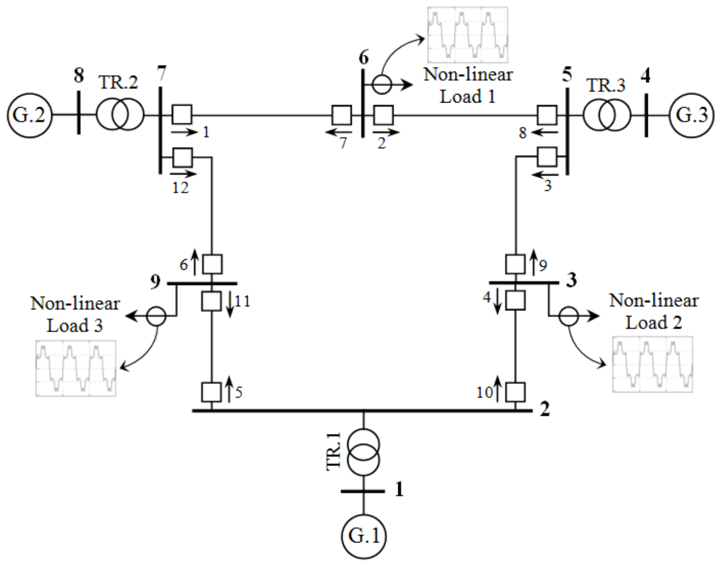
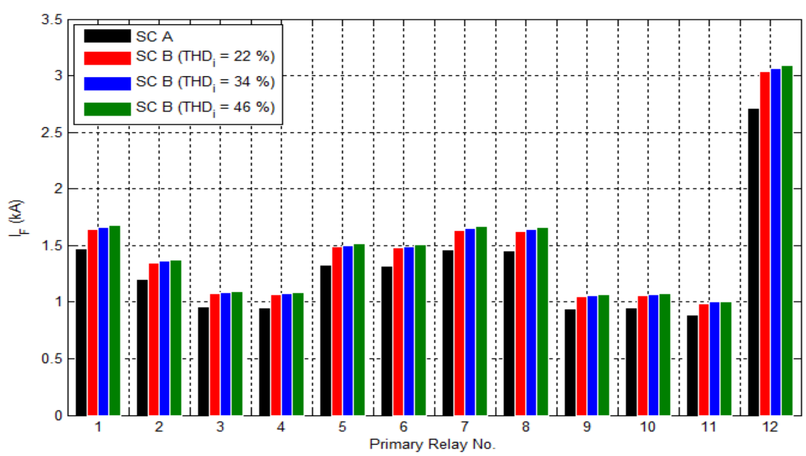


Fig. 5. Diagram of the WSCC 9 bus study with non linear loads.

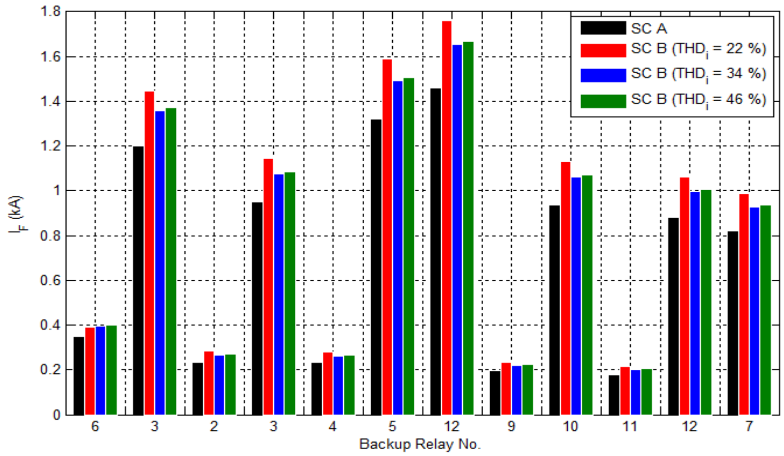
4.1. Impact on fault currents

Fig. 6 presents the evolution of three phase fault currents (I_F) on primary and backup overcurrent relays with the different THD_I values.



(a)

Fig. 6. Three Phase Fault current for all scenarios: a). Primary relays



(b)

Fig. 6. Three Phase Fault current for all scenarios: b).Backup relays

From Figs. 6.a and 6.b, we can see that the fault currents seen by the primary and backup relays are increased with THD_I values. Therefore, we can conclude that the harmonics have a clear impact on the current fault values seen by the primary and the backup relays, which contribute to its increase.

4.2. Impact on tripping time of primary and backup relays

The tripping time of primary and backup relays in function of harmonics is presented in tables 1 and 2 and illustrated in Figs. 7 and 8.

Table 1

Impact of *THD* value on primary relays tripping time

PR	*SC A*	*SC B*		
		Case 1 THD_I = 22%	*Case* 2 THD_I = 34%	*Case 3* THD_I = 46%
1	0.2726	0.2605	0.2595	0.2587
2	0.2968	0.2826	0.2814	0.2804
3	0.7943	0.7021	0.6952	0.6893
4	0.3311	0.3135	0.3121	0.3109
5	0.4835	0.4473	0.4445	0.4420
6	0.2851	0.2719	0.2708	0.2699
7	0.4221	0.3941	0.3919	0.3900
8	0.2738	0.2616	0.2606	0.2597
9	0.2774	0.2649	0.2639	0.2630
10	0.4748	0.4399	0.4372	0.4348
11	0.3437	0.3248	0.3233	0.3220
12	0.4574	0.4248	0.4223	0.4201

Table 2

Impact of *THD* value on backup relays tripping time

BR	*SC A*	*SC B*		
		Case 1 THD_I = 22%	*Case* 2 THD_I = 34%	*Case 3* THD_I = 46%
6	0.6458	0.5832	0.5785	0.5744
3	0.6292	0.5374	0.5651	0.5612
2	1.0313	0.8071	0.8708	0.8616
3	0.8006	0.6582	0.7001	0.6941
4	1.0555	0.8219	0.8880	0.8784
5	0.4851	0.4283	0.4459	0.4434
12	0.7796	0.6438	0.6839	0.6782
9	0.7742	0.6402	0.6798	0.6741
10	0.4775	0.4223	0.4394	0.4370
11	1.7561	1.1944	1.3383	1.3169
12	1.8034	1.2161	1.3657	1.3433
7	0.6574	0.5579	0.5878	0.5836

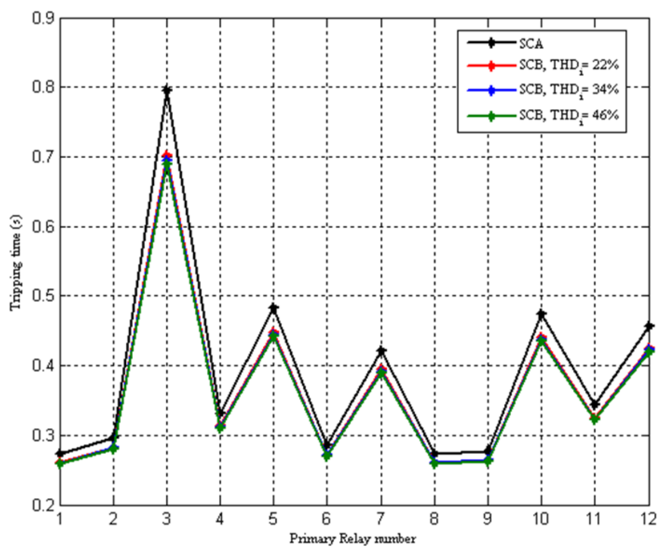


Fig. 7. Impact of THD value on primary relays tripping time.

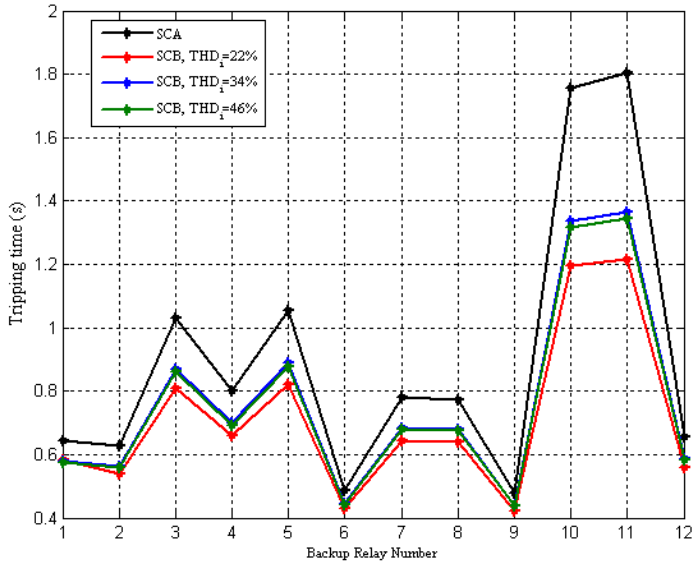


Fig. 8. Impact of *THD* value on backup relays tripping time.

From these result, we can observe that the tripping time of primary relays (*PR*) and backup relays (*BR*) is decreased with the increase of harmonics, the fault current in the presence harmonics increase.

This is due to the IDMT overcurrent relays characteristic which is based on the decrease of tripping time as the fault current increases.

4.3. Impact on coordination time interval

As we presented above, in the presence of fault; the backup relays must operate after a certain time delay known as *CTI*, giving the chance for the primary relays to operate. In this paper the *CTI* value is set to 0.2 second.

In this section, we present the impact of harmonics on relay coordination. The coordination time of primary and backup (*P/B*) relays for *SCA* and *SCB* is presented in table 3 and illustrated in Fig. 9.

Table 3

Coordination time interval of each *P/B* Pair of relays

PR	*BR*	*SC A*	*SC B*		
			Case 1 THD_I = 22%	*Case* 2 THD_I = 34%	*Case 3* THD_I = 46%
1	6	0.3732	0.3227	0.3190	0.3157
2	3	0.3324	0.2548	0.2837	0.2808
3	**2**	0.2370	**0.1051**	**0.1756**	**0.1723**
4	3	0.4695	0.3447	0.3880	0.3832
5	4	0.5720	0.3746	0.4435	0.4364
6	**5**	0.2000	**0.1564**	**0.1750**	**0.1735**

7	12	0.3575	0.2497	0.2919	0.2881
8	9	0.5004	0.3786	0.4192	0.4144
9	**10**	0.2000	**0.1574**	**0.1755**	**0.1740**
10	11	1.2812	0.7545	0.9012	0.8821
11	12	1.4596	0.8913	1.0424	1.0213
12	**7**	0.2000	**0.1331**	**0.1655**	**0.1635**

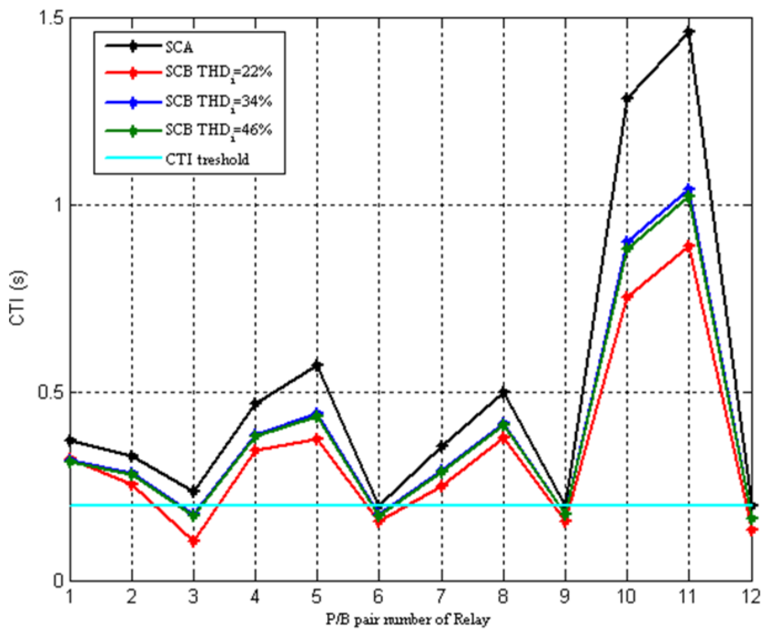


Fig. 9. Impact of *THD* on *P/B* overcurrent relays coordination time.

From these results, we can notice that the overcurrent relays are well coordinated in *SC A* (without harmonics). Unfortunately, four pairs of *P/B* relays (depicted in bold) lose coordination in the *SC B* due to the harmonics.

Therefore, more attention must be given to the setting and coordination of relays in the presence of non linear loads.

5. Conclusions

In this paper we highlight the impact of harmonics on the performance of IDMT directional overcurrent relay on transmission power system. Our study was focused on the impact of harmonics measured by the total harmonic distortion on the following parameters: three phase fault currents, tripping time and coordinated time of primary and backup relays.

The obtained results show that the harmonics have a great impact on the relays efficiency in terms of setting and coordination. As we are see, the fault current seen by the *P/B* overcurrent relays increase with the THD_I current that cause the loss of coordination of some *P/B* pairs of relays due to the harmonics.

Thus, we suggest that more attention should be given to the setting and coordination of relays in the presence of non linear loads.

For the continuity of this work, we propose an off line setting and coordination of relays considering various values of THD_I current using heuristic methods, and also the development of an automation system based on the adaptive relay setting and coordination according to the THD_I value using optimization algorithms and multi agents system.

REFERENCES

[1]. *I.F. De La Rosa*, Harmonics and Power Systems, Electric Power Engineering Series, published by CRC Press, USA, May 2006.

[2]. *I. Purkayastha, and P.J. Savoie*, “Effect of Harmonics on Power Measurement”, IEEE Transactions on Industry Applications, **vol. 26**, no. 5, pp. 944-946, 1990.

[3]. A. Elmoudi, M. Lehtonen, and H. Nordman, “Effect of Harmonics on Transformers Loss of Life”, IEEE International Symposium on Electrical Insulation, Canada, 11-14 June, 2006.

[4]. G.J. Wakileh, “Harmonics in Rotating Machines”, Electric Power Systems Research, **vol. 66**, no. 1, pp. 31-37, 2003.

[5]. *E.M. Schulz, and R.E. Betz*, “Impact of Winding and Gap Flux Density Harmonics on Brushless Doubly Fed Reluctance Machines”, 2nd IEE International Conference on Power Electronics, Machines and Drives (PEMD), Edinburgh - UK, 31 March - 2 April, 2004.

[6]. *J.D. M. De Kooning, J.V. de Vyver, T.L. Vandoorn, B. Meersman, and L. Vandevelde*, “Impact of Speed Ripple on the Back-emf Waveform of Permanent Magnet Synchronous Machines”, IET Electric Power Applications, **vol. 7**, no. 5, pp. 400-407, 2013.

[7]. *A.B. Nassif, and W. Xu*, “Characterizing the Harmonic Attenuation Effect of Compact Fluorescent Lamps”, IEEE Transactions on Power Delivery, **vol. 24**, no. 3, pp. 1748-1749, 2009.

[8]. *M. Kiani, and L. Wei-Jen*, “Effects of Voltage Unbalance and System Harmonics on the Performance of Doubly Fed Induction Wind Generators”, IEEE Transactions on Industry Applications, **vol. 46**, no. 2, pp. 562-568, 2010.

[9]. *T. Ghose, and S.K. Goswami*, “Effects of Unbalances and Harmonics on Optimal Capacitor Placement in Distribution System”, Electric Power Systems Research, **vol. 68**, no. 2, pp. 167-173, 2004.

[10]. *M. Ladjavardi, M.A.S. Masoum, and S.M. Islam*, “Impact of Time and Space Harmonics on Small-Signal Stability of Power System”, Australasian Universities Power Engineering Conference (AUPEC), Melbourne - Australia, 10-13 December, 2006.

[11]. *A. Ulinuha, M. A. Masoum, and S. M. Islam*, “Optimal Dispatch of LTC and Shunt Capacitors in the Presence of Harmonics Using Genetic Algorithms”, IEEE/PES Power Systems Conference & Exposition (PSCE), Atlanta - USA, 29 October - 1 November, 2006.

[12]. *M. Valcarcel, and J.G. Mayordomo*, “Harmonic Power Flow for Unbalanced Systems”, IEEE Transactions on Power Delivery, **vol. 8**, no. 4, pp. 2052-2059, 1993.

[13]. *S. Herraiz, L. Sainz, and J. Clua*, "Review of Harmonic Load Flow Formulations", IEEE Transactions on Power Delivery, **vol. 18**, no. 3, pp. 1079-1087, 2003.

[14]. *Z. Emin, F. Ghassemi, and J.J. Price*, "Harmonic Performance Requirements of an HVDC Connection: Network Owner Perspective", 9th IET International Conference on AC and DC Power Transmission (ACDC), London - UK, 19-21 October, 2010.

[15]. *F. Pan, and M. Zong*, "Harmonic Impact of DG Configuration in Distribution System", 21st International Conference on Electricity Distribution (CIRED), Germany, 6-9 June, 2011.

[16]. *P.M. Anderson*, "Power System Protection", published by McGraw-Hill, USA, 1999.

[17]. *H. Tin, A. Abu Siada, and M.A. Masoum*, "Impact of Harmonics on the Performance of Over-Current Relays", 21st Australasian Universities Power Engineering Conference (AUPEC), Brisbane - Australia, 25-28 September, 2011.

[18]. *J.F. Fuller, E.F. Fuchs, and D.J. Roesler*, "Influence of Harmonics on Power Distribution System Protection", IEEE Transactions on Power Delivery, **vol. 3**, no. 2, pp. 549-557, 1988.

[19]. *W.F. Horton, and S. Goldberg*, "The Effect of Harmonics on the Operating Points of Electromechanical Relays", IEEE Transactions on Power Apparatus and Systems, **vol. PAS-104**, no. 5, pp. 1178-1186, 1985.

[20]. *A.A. Girgis, J.W. Nims, J. Jacomino, J.G. Dalton, and A. Bishop*, "Effect of Voltage Harmonics on the Operation of Solid-State Relays in Industrial Applications", IEEE Transactions on Industry Applications, **vol. 28**, no. 5, pp. 1166-1173, 1992.

[21]. *I. Zamora, A.J. Mazón, V. Valverde, J.I. San Martín, G. Buigues, and A. Dyśko*, "Influence of Power Quality on the Performance of Digital Protection Relays", IEEE Russia Power Tech, Saint Petersburg - Russia, 27-30 June, 2005.

[22]. *A. Medina, and F. Martínez-Cárdenas*, "Analysis of the Harmonic Distortion Impact on the Operation of Digital Protection Systems", IEEE Power Engineering Society - General Meeting, San Francisco - USA, 12-16 June, 2005.

[23]. *W.A. Elmore, C.A. Kramer, and S.E. Zocholl*, "Effect of Waveform Distortion on Protective Relays", IEEE Transactions on Industry Applications, **vol. 29**, no. 2, pp. 404-411, 1993.

[24]. *R.A. Rob, W.T. Jewell, and A. Teshome*, "Computer based Harmonic Simulation and Testing for Directional Overcurrent Relays", Electric Power Systems Research, **vol. 31**, no. 2, pp.125-135, 1994.

[25]. *M.A.S. Masoum, A.S. Masoum, and A.S. Masoum*, "Influence of Low Order Harmonic Phase Angles on Tripping Time of Overcurrent Relays", 40th North American Power Symposium (NAPS), Calgary - Canada, 28-30 September, 2008.

[26]. *P.M. Donohue and S. Islam*, "The Effect of Non-sinusoidal Current Waveforms on Electromechanical and Solid-State Overcurrent Relay Operation", IEEE Transactions on Industry Applications, **vol. 46**, no. 6, pp. 2127-2133, 2010.

[27]. *R.A. Rob, and W.T. Jewell*, "Computer based Harmonic Simulation and Testing for Microprocessor-based Phase Distance Relay with Phase Locator", Industrial and Commercial Power Systems Technical Conference, St. Petersburg - USA, 2-6 May 1993.

[28]. *J.M. Ho, and C.C. Liu*, "The Effects of Harmonics on Differential Relay for a Transformer", 16th International Conference and Exhibition on Electricity Distribution (CIRED), Amsterdam - Netherlands, 18-21 June 2001.

[29]. *A. G. Phadke, and J. S. Thorp*, Computer Relaying for Power Systems, 2nd Edition, published by Wiley, USA, July 2009.

[30]. Standard, "IEC 60255-3 Electrical Relay", published by International Electrotechnical Commission, Geneva, Switzerland, 1998.

[31]. *M. Zellagui, R. Benabid, A. Chaghi, and M. Boudour*, "Impact of GCSC on IDMT Directional Overcurrent Relay in the Presence Phase to Earth Fault", Serbian Journal of Electrical Engineering (SJEE), **vol. 10**, no. 3, pp. 381-398, 2013.

[32]. *M. Ojaghi, Z. Sudi, and J. Faiz,* "Implementation of Full Adaptive Technique to Optimal Coordination of Overcurrent Relays", IEEE Transactions on Power Delivery, **vol. 28**, no. 1, pp. 235-244, 2013.
[33]. *C.R. Chen, C.H. Lee, and C.J. Chang,* "Optimal Overcurrent Relay Coordination in Power Distribution System using a New Approach", International Journal of Electrical Power and Energy Systems, **vol. 45**, pp. 217-222, 2013.