v. 3, n. 36, 2023

Journal of
Engineering
Research

IMPACT OF HARMONIC CURRENT ON RESIDUAL CURRENT DEVICES PERFORMANCE IN A STEEL MAKING PLANT

Thiago Augusto Silva de Almeida
Electrical Engineering Department
Federal University of Ceará
Fortaleza, Brazil

Ruth Pastora Saraiva Leão
Electrical Engineering Department
Federal University of Ceará
Fortaleza, Brazil

Raimundo Furtado Sampaio
Electrical Engineering Department
Federal University of Ceará
Fortaleza, Brazil

Abstract: Unfortunately, it is impossible to root out faults within an electrical power system regardless its complexity. Nevertheless, it is possible to minimize the detrimental implications generated by faults by setting up an accurate protection system. Nowadays, due to the widespread usage of non-linear devices, figuring out the more suitable protection device for this kind of load has become a challenge for electrical engineers across the world, especially concerning low-voltage systems. Most commonly, residual current devices (RCD) are used to protect low-voltage devices. Nonetheless, the behavior of RCDs might be affected by non-linear loads because of harmonic components. Consequently, a false trip command might be sent out, resulting in the disconnection of important loads, significant costs, and, most importantly, jeopardizing the lives of people. The purpose of this paper is to evaluate the performance of RCDs at high frequencies caused by harmonic components. Firstly, it is evaluated a real situation that has taken place in a steel-making plant in Brazil. Secondly, an IEC Type B protection relay is set up aimed to protect non-linear loads. Thirdly, is made a comparison, in terms of performance, between an IEC Type A and IED type B relay. Finally, it is proved that the IEC Type B relay is a suitable protection device for non-linear loads.

Keywords: residual current device, type A RCD, type B RCD

INTRODUCTION

Arguably, policies aimed at the protection of organization personnel as well as assets are significantly important. These policies must be engineered towards the endorsement of the safety of employees who work within an electricity workplace encompassing generation, transmission, distribution, and consumption as well as operation and maintenance. Some countries such as Brazil have strict legislation laying out the safety procedures required to guarantee workers' safety. One of the most important safety procedures metrics consists of a suitable protection system for a given manufacturing process.

Residual current devices (RCDs) are relays by which both people and assets are efficiently protected against shocks and their ramifications. The residual current is obtained by the vectorial sum related to all three phases and neutral. In normal conditions, the system is balanced. As a result, the vectorial sum accounts for zero. Hence, no magnetic flux is generated. By contrast, when an earth fault takes place, this vectorial sum result is different than zero. Consequently, magnetic flux is generated. Once this magnetic flux is strong enough to create a current whose value reaches a predefined setting level, a trip command is sent out. Therefore, the abnormal circuit is disconnected from the system.

Despite this effectiveness, RCDs behavior is dramatically changed by the presence of frequencies higher than 50/60 Hz usually caused by harmonic components. Nowadays, it is common to be found facilities in which high-speed switching converters are used to supply speed drivers which, in turn, are applied in an array of fields.

Some previous papers have untangled the effects of harmonic components over RCDs. In [1], [2], and [4] it presented theoretical analysis and a few experiments as well. In [3], the limitations regarding an IEC type A relay are explained and an IEC Type B is recommended.

According to International Electrotechnical (IEC) 61008-1 and IEC 61009-1, IEC Type A relay must be designed in compliance with the following $I_{\Delta n} I_{\Delta n}$ ground fault profile:

- Sinusoidal currents;
- Pulsating sinusoidal currents;

- Pulsating DC currents;

Nonetheless, it is not designed for the protection of circuits which frequencies other than 60 Hz is likely to appear. IEC Type B relay is the way forward for working out this problem.

The purpose of this paper is to outline how the performance of RCD is affected by the presence of high frequencies generated by non-linear devices. Additionally, it will be demonstrated how detrimental is the usage of IEC Type A relay within an industrial facility. In this case, it will be shown a study in one facility - Coke Plant - in a Brazilian Steel Making Plant in which the protection of a low voltage system used to be performed by an IEC Type A relay. Experiments will be carried out to prove the effectiveness of the IEC Type B relay considering non-linear loads. Moreover, experiments will be played out to make a comparison between the IEC Type A relay and the IEC Type B relay endorsing the theory that the IEC Type B relay is the most suitable device for the protection of low voltage non-linear loads.

The uniqueness of this paper is based on the practical standpoint approached. A real situation is brought up in which a straightforward explanation is provided. Consequently, it is easier for engineers throughout the world to take in the importance of protecting non-linear loads within a low-voltage system with an IEC Type B relay. The consequences flowing from mistakenly applying an IEC Type A relay considering the protection on non-linear loads might be catastrophic for the organization. These implications might include the unwanted disconnection of an important load that put at stake a manufacturing process as well as the lives of employees owing to the protection system malfunction.

THEORETICAL ANALYSIS: RESIDUAL CURRENT DEVICE

WORKING PRINCIPLE

A Residual current device (RCD) is widely used in industries as well as in residential circuits aimed to identify earth faults and minimize the damage caused by current leakage regardless of its cause. The device has a residual current transformer which measures the magnetic flux generated by the vectorial sum of the three phases and neutral cable. Under normal conditions, i.e., a balanced circuit, no magnetic flux is generated because three-phase current and neutral current are flowing in opposite directions. Conversely, when an earth fault takes place, the phase and neutral imbalance create a magnetic flux which, in turn, generates a current. Once this current achieves a predefined threshold, a trip command is generated. Therefore, the load is disconnected from the system.

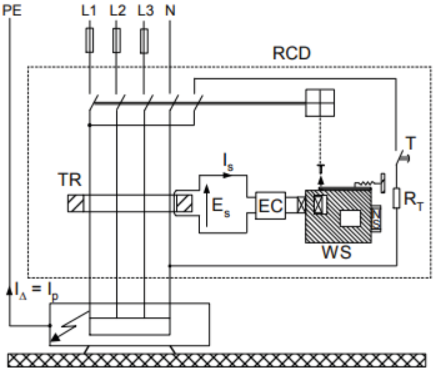

Fig. 1. Residual Current Device simplified diagram: TR - current transformer, WS - electromechanical relay, NS - permanent magnetic, T-test button, – primary current, – Secondary current, – induced secondary voltage [4]

There are three distinct types of RCDs considering the sensitivity to the earth fault waveform:

- AC – for alternating earth fault current (50/60Hz),

Journal of Engineering Research ISSN 2764-1317 DOI 10.22533/at.ed.31733623251010

- A – for alternating and pulsating earth fault current,
- B – for alternating earth fault current, pulsating direct earth fault current and smooth direct earth fault current

Even though it is mandatory for manufactures throughout the world to carry out a strict test procedure over RDC in compliance with standards [5, 6] RDCs are not tested when high-frequency currents exist.

THE IMPACT OF HARMONIC RESIDUAL CURRENTS ON RDCS PERFORMANCE

The earth fault current with high harmonic levels appears in situations when an earth fault takes place in the output terminals of inverters. In this case, the earth fault current may encompass an array of a spectrum of harmonics and inter harmonics. Therefore, the implications over the trip characteristics of RDCs are dramatically challenging because different situations bring up different impacts which, in turn, require different counteract strategies. Nevertheless, the effects might be summed up as follows:

RESIDUAL CURRENT WAVEFORM

The typical residual current waveform with harmonic components is determined as follows:

$$i_\Delta(t) = \sqrt{2} . I_{\Delta 1} . [sin(\omega t + \alpha_1) + A_2 \, sin(2\omega t + \alpha_2) + + A_3 \, sin(3\omega t + \alpha_3) + \cdots + A_n \, sin(n\omega t + \alpha_n)] \quad (1)$$

Where:

- $I_{\Delta 1}$ – rms of fundamental current,
- A_2, A_3, ... A_n – coefficient of the 2nd, 3nd, …, nnd current harmonic order
- a , a_3, ... a_n – phase angle of the fundamental, 2nd, … nnd harmonic.

The crest factor of a waveform is determined by the ratio between the waveform maximum value and rms value as shown in (2). The crest value is used to figure out whether the waveform is "peakish" or "flattish". Moreover, it is known that low-order harmonics such as 3rd and 5th may impact the waveform crest factor dramatically. Conversely, high-order harmonics do not impact a waveform crest factor whatsoever.

$$CF = \frac{I_{max}}{I_{rms}} \quad (2)$$

Where:

- CF = Crest Factor,
- I_{max} = waveform maximum value,
- I_{rms} = waveform rms value.

SATURATION EFFECT

Basically, as previously mentioned, the RDCs operation is based on the transformer secondary residual current measurement which is obtained by the flux created by the vectorial sum of the three phases and neutral currents. A predefined setting value is assessed and, depending on the secondary current value measured, a trip signal is sent out. It is mentioned in [4] an ideal transformer stands for a transformer with no losses, i.e., both primary and secondary residual currents have the same waveform. However, the ideal transformer hypothesis has proved invalid. Therefore, phenoms such as saturation and hysteresis undeniably affect RDCs behavior significantly because the residual secondary current measured is affected.

A residual current waveform with a high crest factor tends to drag the core of the current transformer into the saturation area. In this case, even during an earth fault condition, the amount of flux variation generated might not be enough to achieve the predefined RDC sensitive level. Hence, this situation is massively dangerous owing to a short circuit taking place and the abnormal circuit is not detached from the system. This situation is defined as a "negative effect" in [1] or "DC blinding" in [3].

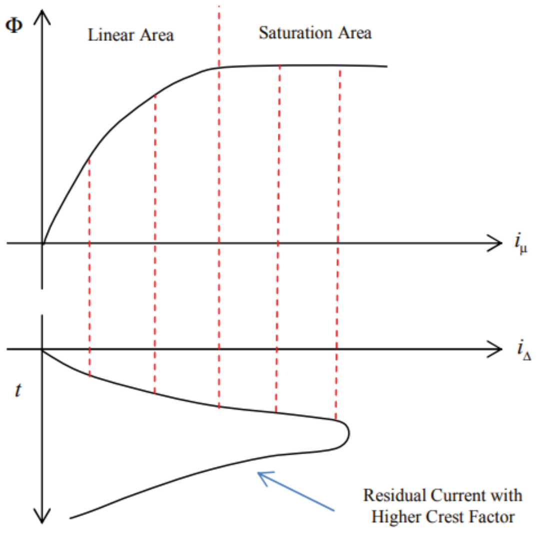

Fig. 2. Saturation curve of current transformer [1]

MAGNETIZING EFFECT

It is known by Faraday's law that the higher the frequency the lower the magnetizing current $I_u I_u$ required to generate the same voltage level on the secondary side. As a result, the high harmonic order of the residual current is inclined to generate more secondary current from less magnetizing current needed. This situation is dramatically detrimental for industrial facilities because an unwanted trip might be generated under circumstances when there is no earth fault taking place, wrongly disconnecting circuits that might be vital for a manufacturing process, leading up to massive costs. This situation is described as a "positive effect" in [1].

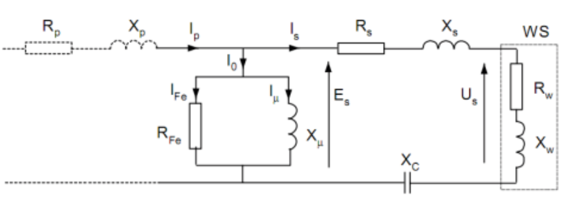

Fig. 1. Equivalent circuit: TR - current transformer [1]

SUMMARY

In [1] is provided a table aimed to illustrate the effects of harmonic components over RDCs performance. "Negative effect" means that the sensitivity of the RDC decreases leading up to a situation in which the earth fault current might not generate de magnetic flux required to generate a trip signal. By contrast, the "Positive effect" means that the sensitivity of the RDC is increased creating a situation in which low current but with high harmonic order might cause a mistaken trip signal to be generated resulting in undesirable equipment outage.

RESEARCH METHODOLOGY

Firstly, it was made a technical analysis, based on electrical engineering literature, aimed to figure out some possible causality relationship between non-linear loads and RDCs performance.

Secondly, among the possible causality relationship outlined by technical literature, by carrying out observation analyses based on the RDC behavior within the electrical power system, it was found, precisely, how the RDC trip characteristics were impacted. In this case, it was identified that magnetizing effect was the problem owing to the constant unwanted trip situations (positive effect) when speed-switching converters were used to manage speed drivers.

Thirdly, power quality analysis instruments class A was applied aimed to map out the system harmonic profile as well as reinforce the assumption made during the observation analysis. In this particular case, it was identified that high-frequency harmonic components were overwhelmingly present, leading up to the magnetizing effect, resulting in unwanted trip commands.

Finally, experimental analysis was played out by using an IEC Type B relay to check out whether it was a suitable earth fault protection device for this particular situation. In this case, the Omicron protection test device simulator was used, and harmonic components were generated similar to the system's harmonic profile mapped out by the energy analysis instrument class A. Moreover, it was made a comparison, from an effectiveness standpoint, between the IEC Type A relay and IEC Type B relay under a vast array of harmonic spectrum aimed to prove that the IEC Type B relay outperform the IEC type A relay with respect to a system with non-linear loads.

In conclusion, the research methodology applied to untangle this problem was the inductive method which the relationship among phenoms is investigated based on observation or experimental analysis aimed to achieve a general outcome.

CASE STUDY: STEEL-MAKING PLANT IN BRAZIL

COKE PLANT FACILITY

ELECTRICAL POWER SYSTEM

Non-linear loads are heavily applied within a Coke Plant manufacturing process. As a result, harmonic components are an intrinsic part of this electrical power system. In this facility, all the 0.460 kV earth fault protection systems used to be performed by IEC Type A relay with zero phase current transformer whose bandwidth is limited to 50/60 Hz.

Many times, up until this research, several unwanted trip commands have been reported by the operational team, which were leading up to the disconnection of important circuits, putting the manufacturing process continuity at stake, and generating a significant cost.

Fig. 4. Zero phase current transformer of an IEC Type A relay

LABORATORY TEST

Laboratory tests were carried out aimed to assess IEC Type B relay efficacy within the coke plant electrical system considering its harmonic component profile as well as a comparison, from an effectiveness perspective, between IEC type A relay and IEC type B relay regarding an array of harmonic components. Furthermore, it was used Omicron test simulator to generate the harmonic components signals.

Firstly, it was carried out a simple measurement test. It generated simple current values within 60 Hz frequency and checked out whether the values read by the IEC Type B relay matched up with the values generated by the Omicron test simulator or not.

Current Measurement Test		
	Omicron test simulator (amp)	IEC Type B relay measurements (amp)
Measurement 1	1	0.99
Measurement 2	2	1.98
Measurement 3	0.5	0.5

TABLE I. IEC Type B relay Measurement Test

Secondly, it was made a protection test. In this case, it was adopted 3 amperes as a predefined current threshold as well as 3 seconds as a time predefined setting value.

Protection Test			
Current predefined value (amp)	Time predefined value (sec)	Omicron teste simulator (amp)	IEC Type B relay actuation time (sec)
3	3	3	3.089

TABLE II. IEC Type B relay protection Test

Journal of Engineering Research ISSN 2764-1317 DOI 10.22533/at.ed.31733623251010

Thirdly, as previously mentioned, a power quality analysis instrument class A was used to map out the harmonic profile concerning the circuit under analysis. An Omicron test simulator was used to check out whether the IEC Type B relay was an earth fault protection device suitable for this harmonic profile i.e., sizing up whether no unwanted trip command was generated.

The outcome was successful. There was no unwanted trip signal. In other words, the IEC Type B relay has performed successfully concerning a situation in which the harmonic profile illustrated by table XVI is present.

Finally, a comparison between the IEC Type A relay and the IEC Type B relay, from a performance standpoint was made, regarding a multiplicity of harmonic components and an earth fault protection predefined setting value, aimed to assess whether an unwanted trip command is generated or not. Precisely, it generated balanced current values with a variety of harmonics distortion rates until the Omicron test simulator full capacity. Moreover, the predefined setting value was 3 amperes and 3 seconds.

Omicron test simulator values						
	IL1		IL2		IL3	
Harmonic order	Mag.	phase	Mag.	phase	Mag.	phase
5	17.8%	0.00%	17.8%	0.00%	17.8%	0.00%
7	6.4%	0.00%	6.4%	0.00%	6.4%	0.00%
11	4.4%	0.00%	4.4%	0.00%	4.4%	0.00%
13	2.5%	0.00%	2.5%	0.00%	2.5%	0.00%

TABLE III. Omicron test simulator values

Harmonic Order	THD (%)	IEC Type B relay current value	Outcome
3	20	0.59	No unwanted trip command
3	30	0.89	No unwanted trip command
3	60	1.68	No unwanted trip command
3	90	2.68	**IEC Type A relay trip**

TABLE IV. Performance comparison test harmonic order 3

Harmonic Order	THD (%)	IEC Type B relay current value	Outcome
5	20	0	No unwanted trip command
5	30	0	No unwanted trip command
5	60	0	No unwanted trip command
5	90	0	No unwanted trip command

TABLE V. Performance Comparison Test harmonic order 5

Harmonic Order	THD (%)	IEC Type B relay current value	Outcome
7	20	0	No unwanted trip command
7	30	0.02	No unwanted trip command
7	60	0	No unwanted trip command
7	90	0	No unwanted trip command

TABLE VI. PERFORMANCE COMPARISON TEST HARMONIC ORDER 7

Harmonic Order	THD (%)	IEC Type B relay current value	Outcome
11	20	0	No unwanted trip command
11	30	0	No unwanted trip command
11	60	0	No unwanted trip command
11	90	0	No unwanted trip command

TABLE VII. PERFORMANCE COMPARISON TEST HARMONIC ORDER 11

Harmonic Order	THD (%)	IEC Type B relay current value	Outcome
13	20	0	No unwanted trip command
13	30	0	No unwanted trip command
13	60	0	No unwanted trip command
13	90	0	No unwanted trip command

TABLE VIII. PERFORMANCE COMPARISON TEST HARMONIC ORDER 11

Harmonic Order	THD (%)	IEC Type B relay	Outcome
15	20	0.58	No unwanted trip command
15	30	0.87	No unwanted trip command
15	60	1.75	No unwanted trip command
15	90	2.63	No unwanted trip command

TABLE IX. performance comparison test harmonic order 15

Tests consisting in unbalanced current values were also carried out with the same total harmonic distortion rate regarding the balanced current values. In this case, this test was made aimed to find out whether both IED Type A and Type B relays would generate an unwanted trip signal even though the predefined protection setting value has not been achieved.

It is significantly important to evaluate the IEC Type B relay with unbalanced currents which, even though have some harmonic distortions, are not big enough to achieve the protection predefined setting values. In this case, it is important to assess whether these currents will generate an unwanted trip command or not despite the presence of harmonic currents which are inherently part of the system.

It used the same current magnitude and angle considering a range of harmonic distortion rates.

Harmonic Order	THD (%)	IEC Type B relay current	Outcome
3	20	2.09	No unwanted trip command
3	30	2.5	IEC Type A relay trip
3	60	3.96	Both IEC relays trip
3	90	5.63	**Both IEC relays trip**

TABLE X. Performance comparison test harmonic order 3 unbalanced currents

Harmonic Order	THD (%)	IEC Type B relay current	Outcome
5	20	1.75	No unwanted trip command
5	30	1.79	No unwanted trip command
5	60	2	No unwanted trip command
5	90	2.31	**IEC Type A relay trip**

TABLE XI. performance comparison test harmonic order 5 unbalanced currents

Harmonic Order	THD (%)	IEC Type B relay	Outcome
7	20	1.75	No unwanted trip command
7	30	1.79	No unwanted trip command
7	60	2	**IEC Type A relay trip**
7	90	2.2	**IEC Type A relay trip**

TABLE XII. performance test harmonic order 7 unbalanced currents

Harmonic Order	THD (%)	IEC Type B relay current measured value	Outcome
11	20	1.75	No unwanted trip command
11	30	1.79	No unwanted trip command
11	60	2	**IEC Type A relay trip**
11	90	2.3	**IEC Type A relay trip**

TABLE XIII. performance test harmonic order 11 unbalanced currents

Harmonic Order	THD (%)	IEC Type B relay current	Outcome
13	20	1.75	No unwanted trip command
13	30	1.79	No unwanted trip command
13	60	2	**IEC Type A relay trip**
13	90	2.3	**IEC Type A relay trip**

TABLE XIV. performance test harmonic order 13 unbalanced currents

Harmonic Order	THD (%)	IEC Type B relay current	Outcome
15	20	2.08	No unwanted trip command
15	30	2.43	**IEC Type A relay trip**
15	60	3.9	Both IEC relays trip
15	90	5.55	Both IEC relays trip

TABLE XV. Table 1: performance test harmonic order 15 unbalanced currents

LABORATORY TEST ANALYSIS

Firstly, this research attests that RDCs performance may be impacted by harmonic currents. Additionally, it proves that the IEC Type B relay is suitable for an electrical power system in which the presence of harmonic components is inherently present.

Secondly, interestingly, by assessing the comparison performance test, there was an unexpected outcome. In this particular case, condition given in table IV which illustrates a system with harmonic component order 3 and 90% total harmonic distortion, has made the IEC Type B relay generate an unwanted trip command. It was used as an explanation for the fact that the current value (2.68 amperes) has reached the TC error margin.

Finally, based on the performance test concerning unbalanced current values, undoubtedly the IEC Type B relay has turned out to be a better earth fault protection device. In this case, there were many no unwanted trip commands set off by the IEC Type A relay. Considering every single harmonic order (3, 5, 7, 11, 13, and 15) with unbalanced currents, there was at least one wrong trip signal which was set off.

CONCLUSION

This paper was engineered towards describing a real technical problem in a steel-making plant in Brazil concerning a mistaken low voltage protection system. In this case, an IEC Type A relay was applied in a system in which harmonic currents are heavily present. Consequently, several unwanted trip situations were taking place, dramatically affecting the manufacturing process, and generating significant costs. It accounts to engineers to bring up a science-based lasting solution to work out this problem.

Firstly, research was carried out aimed to figure out some possible causality relationships between harmonic components and RDC's behavior. Based on the literature, both high and low current harmonics can impact RDC's performance. This causality relationship is not simple since, distinct implications stem from different harmonic profile which requires a different solution.

Secondly, the harmonic profile system was mapped out by using a class A Energy Analysis instrument. According to the literature, the IEC Type B relay is the protection device suitable for a system in which harmonic currents are present.

Thirdly, laboratory test analysis was made aimed to prove that an IEC Type B relay is the solution. In this case, Omicron test simulator was applied to generate current signals identical to the system harmonic profile. Not surprisingly, a successful outcome was achieved i.e., no unwanted trip signal was generated.

Finally, laboratory test analysis was made to draw a comparison, from a performance standpoint, between IEC Type A relay and IEC Type B relay. It was used an array of harmonic orders until the maximum Omicron test simulator capacity regarding both balanced and unbalanced currents. Not surprisingly, the IEC Type B relay has outperformed the IEC Type A relay. The IEC Type B relay is able to reliably read currents values up to 2000 Hz frequency whereas the IEC Type A relay is limited between 50/60 Hz. The situation regarding unbalanced currents vividly endorses the theory brought up by the literature which claims that IEC Type B is the suitable device for the earth fault protection in low voltage systems which harmonics are inherently presence. It is worth mentioning that the IEC Type B relay has mistakenly performed in one situation which is illustrated by Table IV. Moreover, this paper was designed to emphasize the seriousness of low voltage protection system. Unfortunately, it is played down by some electrical engineers. Nevertheless, a proper RDC is essential for safety of employees as well as assets.

REFERENCES

[1] Yu Xiang, V. Cuk, J.F.G. Cobben, "Impact of Residual Current on Operation of Residual Current Devices". Eidhoven University of Technology, Faculty of Electrical Engineering, 2011, pp. 978-4244-8782-0/11.

[2] Freschi, F., "High Frequency Behavior of Residual Current Devices", IEEE Transactions on Power Delivery, vol. 27 n.3, 2012, pp. 1629-1635

[3] T. Gruhn, J. Glenney, M. Savostianik "Type B Ground-Fault Protection on Adjustable Frequency Drives,", 2017, pp. 10.1109/TIA.2017.2758342.

[4] S. Czapp., "The Effect of Earth Fault Current Harmonics on Tripping of Residual Current Devices", Gdansk University of Technology, Faculty of Electrical and Control Engineering, Gdansk, Poland, 2008, pp. 978-1-4244-2130-5/08

[5] EN 61008-1 Residual Current Operated Circuit Breakers Without Integral Overcurrent Protection for Household and Similar Uses (RCCB's). Part 1. General rules.

[6] IEC 60755 General Requirements For Residual Current Operated Protective Devices.

[7] Pengkang Xie, Zhen Fang, Jianping Hu, "Tripping Characteristics of Residual Current Devices Under Different Working Conditions". State Key Laboratory of Disaster Prevention & Reduction for Power Grid Transmission & Distribution Equipment. 2019. pp. 978-1-7281-3137-5/19

[8] Yordan Shopov, Simona Filipova-Petrakieva, Borislav Boychev "Investigation of Residual Current Devices in High Frequencies". Electrical Faculty Technical, University of Sofia, Bulgaria. 2018. pp. 978-1-5386-7565-6/18

[9] Types of RCDs - Electrical Installation Guide (electrical-installation.org) (current Feb. 5, 2023).

Harmonic order	5	7	11	13	17	19	23	25	29	31	35	37	41	43	47	49	TDD (%)
Harmonic current (%)	17.8	6.4	4.4	2.5	2.1	1.5	1.2	1	0.7	0.6	0.4	0.4	0.3	0.3	0.2	0.2	19.5
Harmonic current amp)	138	49	33	19.6	16.6	11.6	9.2	7.4	5.3	4.7	3.2	3	2.2	2.1	1.7	1.6	0

TABLE X. Coke Plant Facility Harmonic Profile