UNIVERSITY POLITEHNICA of BUCURECTI

DOCTORAL SCHOOL of ENERGY

PhD THESIS SUMMARY

STUDYING THE EFFECT OF POWER QUALITY ON DIGITAL RELAYS DURING TRANSIENTS IN THE ELECTRICAL POWER SYSTEM AND THEIR MANAGEMENT

STUDIEREA EFECTULUI DE CALITATE A PUTERII PE RELEE DIGITALE ÎN TIMPUL TRANZITORII ÎN SISTEMUL DE ENERGIE ELECTRICĂ ȘI DE GESTIONARE A ACESTORA

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Bucharest
2020

ACKNOWLEDGMENTS

Firstly, I would like to thank my Prof. George Cristian LAZAROIU for his supervision of my PhD research, for his Continuous and precious advices, for understanding me and for teaching me many things I used them in my research.
All thanks to my dear wife who stand near me and supported me a lot and all the members of my family: my dad, mom, brothers and to all the other extended members of the family; for their love and moral support. Their prayers were a great support to me in all phases of my life, so that my deepest appreciation and gratitude to my family.
I would like to dedicate This work to the soul of my brother''Rami'', who is present in my mind all the time.
I would like to thank Dr. Eng. Radu Porumb, for supporting me in conducting some measurements at Baragan Photovoltaic farm and his cooperation with me especially in power quality issues.
I would like to thank Professor GUZUN BASARAB, who supported me in the first two years of doctoral studies, and he was unable to continue with me due to the difficult health conditions resulting from the death of his only son.
I would like to thank Mrs. Paula Turcan for her kindness, which provided me with all the details and information concerning the conferences and eventments and advised me through the difficult transition period that I experienced.
I would like to thank Prof. univ. dr. ing. Nicolae Golovanov, who has given me the help, especially in the transition period between Professor GUZUN BASARAB and Prof. George Cristian LAZAROIU, and provided me a lot of valuable advices that contributed to the correction of this thesis.
I would also like to thank Prof. dr. ing. Virgil Dumbrava *who* followed this research with great interest and gave me all the necessary advices for the success of this thesis.

Finally, I would like to thank the staff from the University POLITEHNICA of Bucharest, including my colleagues, professors and teachers.

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INTRODUCTION

The most important feature of power systems is the continuity of the supply of electricity to the instruments of investment reliably. This reliability is primarily provided by the so-called protection systems, whose main function is to detect electrical failure as quickly as possible and to isolate the faulty device from the power system [35], [62], [92].
The protection system does not include the relays only, but it also includes the current transformers. Therefore, the correct operation of the protection devices depends on the performance of current transformers in transient cases [151], [152].
When the current transformer enters saturation during power system disturbances, the amplitude of the secondary current will decrease and the waveshape will be distorted [157], [158].
these distortions can lead to a loss of coordination in the protection system, and inability of the protection device to isolate the damaged element as quickly as possible as planned, sometimes lead to the wrong operation of the protection unit outside the protected zone or outside its range operation, and thus have serious repercussions on the entire electrical system[112], [142],[153].
Similarly, the presence of harmonics in the electrical network leads to many problems for the elements of the power system in general and for the protection system in particular, which has serious implications for the performance of the protection system and its ability to isolate the arising faults. All these previous effects fall under the heading of power quality [187].
digital relays are multifunction relays, which is replacing the electromechanical and static relays due to the advantages of these relays, whether economic cost, performance and size [14], [133].
Despite all these advantages, digital relays suffer from many problems resulting from the influence of many effects, most notably the effect of poor power quality, which is the subject of this research.

1. BACKGROUND

Poor power quality is defined as a deviation of voltage, current and frequency from their nominal values, this deviation can be seen as a distortion in waveshape and amplitude of the signal, [2], [10], [18].
There are many resources for poor power quality, these disturbances can be due to current and voltage harmonic sources, dynamic operations and faults [5], [13].
The quality of input signal plays an important role of the correct behavior of protective relays. Digital relays use the digital signal as an input signal to the digital filter, while conventional relays use the analog signal as input signals without any converting into another form [37].
This input signal is processed by the digital filter and the making-decision is done after comparing the values of the resulting calculations with preset values [40], [92], [96], [107].
The digital filter can be considered as the decision-making center for protection relays, there are many types of digital filter and each filter has its own algorithm and mathematical equations. The most popular filters used in protection applications is Fourier filter, as well as some of the less commonly used filters such as Cosine filter, IIR filter, Kalman filter and Walsh filter [39], accuracy and speed are the most important criteria for testing the performance of these filters[42], [82], [84], [85], [88], [89].
Some researchers have tried to provide several studies for examining the effects of different disturbances on the performance of these filters independently of the power system. In addition, their research did not provide a comprehensive idea about the mutual effects of different

elements of the power system and its impact on Performance of these filters but their researches were the base for the future works [82], [83].
Many researches have studied the behavior of different types of digital relays under the effect of disturbances by using different simulation programs like EMTP-ATP, MATLAB, ... etc.
Some of these programs, such as MATLAB, require the programming of protection' blocks, because they do not contain ready-made blocks. This reduces the possibility of maneuvering for many tests and takes more time for making these blocks [84], [86], [90].
Some of the new modeling programs such as DigSILENT provide ready-blocks for all protection devices for different manufacturers and provide the possibilities to enter the protection settings accurately [95].
Protection algorithms use measurement algorithms to attenuate non-fundamental components and to estimate fundamental frequency component with high accuracy to detect faults.
The main input signals for estimation algorithms are the current and voltage signals. To ensure optimum accuracy and speed of protection functions, the input signals must only contain the fundamental frequency component [40], [82], [84], [86], [89], [92], [178].
In practice, the input signal is distorted according to the fault conditions, the fault signals generally contain non-fundamental frequencies such as harmonics, decaying DC offset and noises.
The measurement algorithm produces errors due to these undesirable signals and these errors will be propagate in the used successive algorithms and which may lead to the wrong operation of the protection device.
In this thesis, the effect of nuisance signals has investigated through simulation programs such as MATLAP and digSILENT and EMTP-ATP.
Many researches have used many mathematical methods and algorithms to estimate and correct the components of these nuisance signals. In general, the accuracy of these methods is based on the comparison between the estimated value of the sample and its actual value [162-178].
In this research, a special algorithm was developed to detect distortion and correct it for the secondary waves of current transformer based on the Newton's backward difference method. This algorithm proved its effectiveness by applying recorded waves taken from a fault recorder of a power generation and distribution station.
In the applications of protection relays, it is important to verify the performance of the protection relays in the steady state to evaluate their performance in the transient state.

2. OBJECTIVES

The main objective of the research thesis is to provide an assessment of the effects of poor power quality on the performance of digital relays and suggest mathematical and practical solutions, because of the importance of these protections in maintaining the stability of the power system during different disturbances.
By achieving the main objective, the research achieves a set of secondary objectives which are summarized as follows:

- The effect of different parameters of digital relays on its performance.
- the effect of poor power quality such as harmonics, frequency deviation and CT saturation on the measurement algorithms of digital relays such as Fourier filter and Walsh filter have been investigated by using MATLAB.
- Study the effect of poor power quality on distance, differential and over current relays have been investigated by using DigSILENT and EMTP-ATP.

The final objective of this thesis is proposing practical solution for the wrong behavior of differential relays by adding metal oxide varistor element to secondary circuit of current transformers and developing an algorithm for correcting the secondary currents of current transformers in saturation cases.

3. OUTLINE OF THE THESIS

This thesis is organized into seven chapters. This introduction presents an explanation of the contents of the thesis and this explanation is divided into:

- A general introduction to the power quality definition from the point of view of research and from the point of view of the research that preceded it.
- A reference study for digital relays.
- A reference study of the effect of the undesired signals on the performance of the different digital filters.
- An explanation of the measurement algorithms used in the previous research and of the developed algorithm used in this thesis.
- The software package used to study the effect of power quality on protection relays' performance was mentioned, in addition to a simplified explanation of the proposed solutions.

Chapter I presents all definitions, classifications and problems related to power quality. Finally, a comparison is done between the practical measurements and standards related to power quality.

Chapter II This chapter analyses the characteristics and mathematical formula of some digital filters which are used in digital relays, the performance of these filters was investigated by applying different current waves to these filters. Furthermore, this chapter includes a comparison of responses between these filters.

Chapter III presents low flow calculations and short circuit calculations for an electrical power system which contains all levels of voltage; low, medium and high.

The resultant values will be used in the next chapter for calculating the settings of over current relays and the permissible operation statements.

Chapter IV presents the setting calculations of over current relays for busbars and distant relays for overhead line and cable line and under frequency protections for generators.

All these calculations are done according to the international standards and the user manuals of used relays.

Chapter V presents the behavior of distance relays under the effect of harmonics in the network, also analyses the behavior of over current relays under the effect of magnetization curve of power transformers which distort the current and voltage waveshapes.

Also, this chapter presents a power system consists of a Busbar of three ends which is protected by using differential protection.

This study shows that the differential protection is working when a fault occurs outside the protection zone because the saturation of current transformers.

A practical solution is done by adding a non-linear element (MOV) to the secondary circuit of the current transformer. This practical proposed solution is done and investigated by using EMTP-ATP program.

Chapter VI has suggested a new algorithm for detecting and correcting of the distorted secondary current due to CT saturation, this algorithm estimates the samples of saturated section depending on the samples of unsaturated section of the current signal, the estimation method depend on the Newton’s Backward Difference Interpolation method.

The m-file for the proposed algorithm was created by using MATLAB and the simulation results indicate that the proposed algorithm can efficiently detect and correct each saturation period when the secondary current is severely distorted.

Chapter VII Provides a summary of the results and conclusions obtained during accomplishment this study. Also, includes a list of future works which contains a set of suggestions for practical suggestions, especially the possibility of developing and using the nonlinear elements in conventional and digital relays, as well as developing the measurement and correction algorithms used to obtain the optimal performance of protection relays, thus maintaining stability of the power system and ensuring continuity of feeding for consumers.

CHAPTER 1. POWER QUALITY

1.1. INTRODUCTION

Power quality problems can cause processes and equipment to malfunction or shut down, and the consequences can range from excessive energy costs to complete work stoppage.

1.2. DEFINITIONS AND CLASSIFICATION OF POWER QUALITY

Power Quality is defined as any deviation in voltage, current, and/or frequency value from its nominal value, that results in the mal-operation of end user's equipment.

Fig. 1.1 shows normal voltage signal and voltage signals with disturbances where: (a)nominal, Voltage signal, (b) oscillatory transient, (c) harmonics, (d) notching, (e) Sag, (f) swell, (g) spikes and (h) outage.

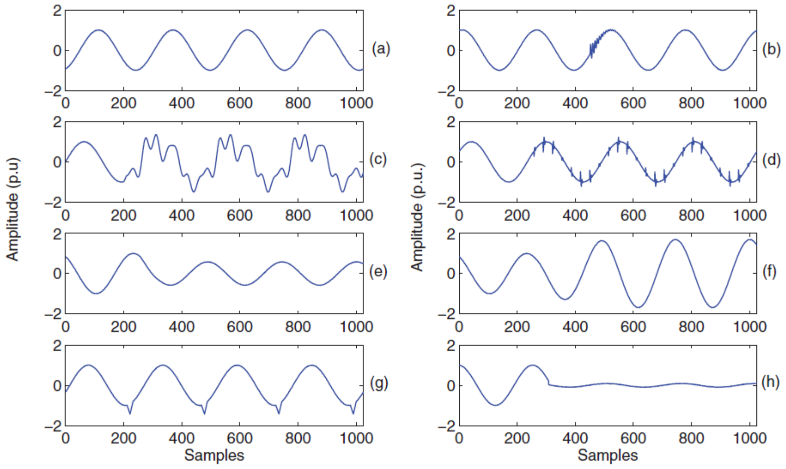

Fig. 1. 1. Examples of voltage signals and disturbances

1.3. ANALYZING POWER QUALITY DATA BY PC APPLICATIONS SOFTWARE (POWER ACCEPTABILITY CURVE)

Power Acceptability Curves regulate the minimum PQ level that equipment should have to operate properly when the power supplied is within the standards. The most commonly used curves are CBEMA curve and ITIC Curve. These curves are divided into two regions as shown in figure 1.2 And figure 1.3 [11], [14-21]:

-permitted zone: any voltage disturbance lie in that area should not cause malfunction at all.

-prohibited zone: any voltage disturbance lie in that area will cause malfunction.

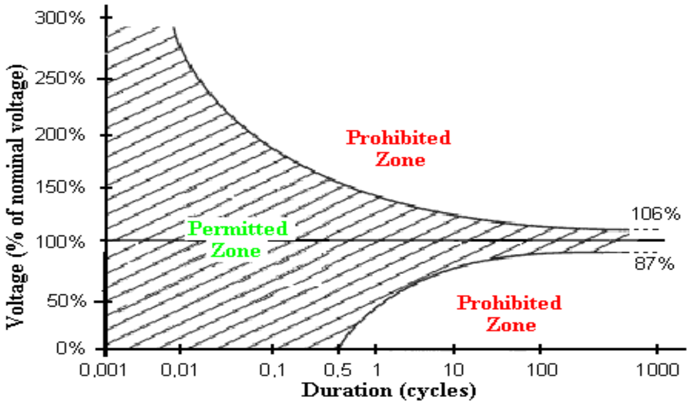

Fig. 1. 2. CBEMA curve for equipment Susceptibility

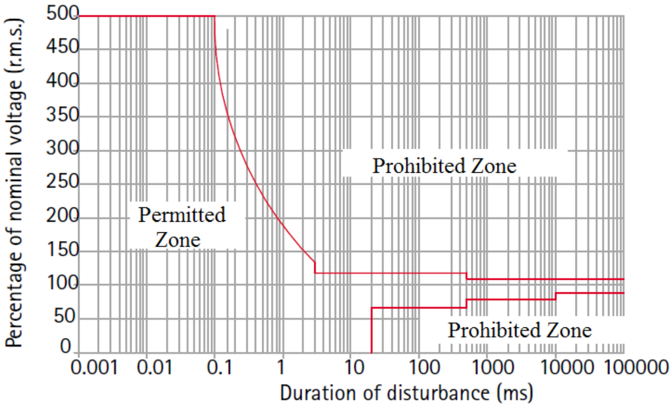

Fig. 1. 3. ITI curve for equipment Susceptibility

1.4. PRACTICAL MEASUREMENTS OF POWER QUALITY

We execute some measurements at BARAGAN Photovoltaic farm by using FLUKE SET for one week; we download the data by using Power Log software version 4.3.1. these measurements were recorded during the date from 12/12/2014 2:54:04 PM to 19/12/2014 9:44:04 AM.

Case 1. power frequency variations

Figure 1.4 shows frequency deviations, the maximum value of frequency is 50.039Hz, the minimum value is 49.952 Hz, and these values are within the acceptable limits.

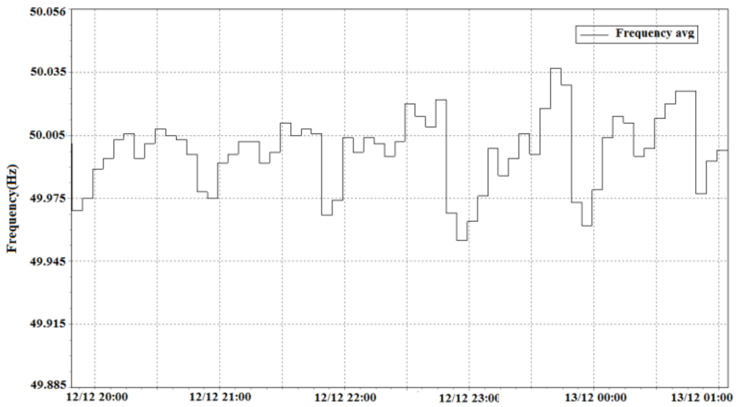

Fig. 1. 4. Frequency deviations

Case2. voltage fluctuation

Figure 1.5 shows voltage fluctuations, the maximum value of voltage for three phases is 0.330%, the minimum value is 0.125%, and these values are within the acceptable limits.

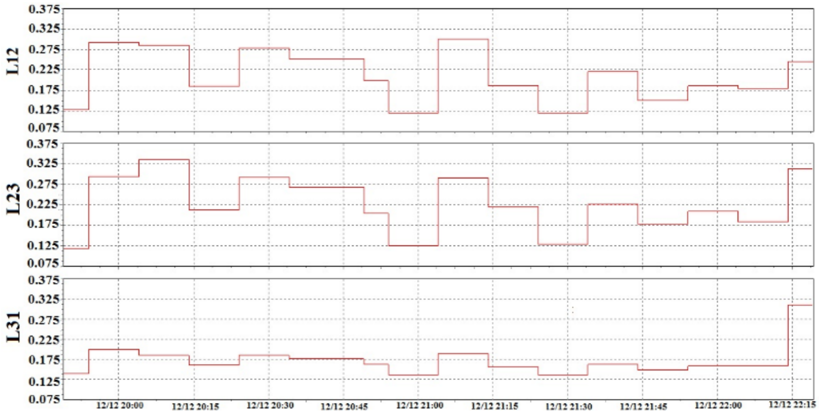

Fig. 1. 5. Voltage fluctuations (flickers)

Case 3. over voltage

Figure 1.6 shows recorded voltage waveform of duration 200ms, we note that the maximum value of voltage is 20950V and this value is within the accebtable limits.

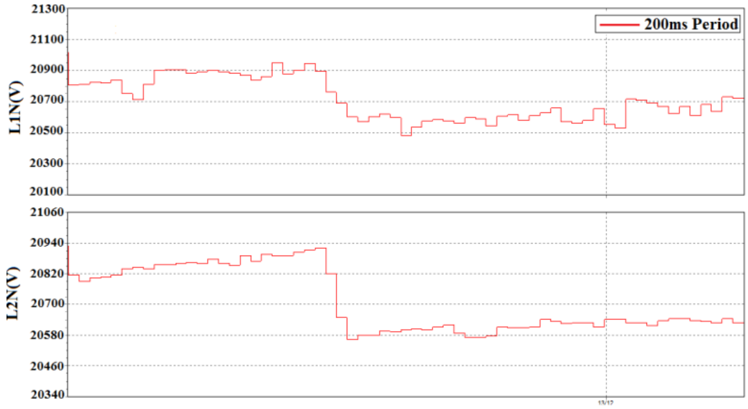

Fig. 1. 6. Over- voltage waveform

Case 4. Harmonics

Figure 1.7 shows total harmonic distortion in percent (THD %). we note that the maximum value of total harmonic distortion is 3.7% and this value is within the acceptable limits.

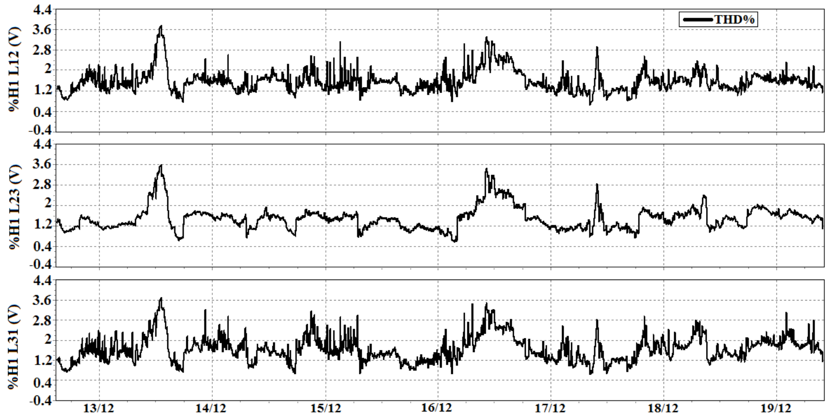

Fig. 1. 7. Total Harmonic Distortion

Case 5. Dips and Swells

Figure 1.8 shows dips points, we note that there are two dips points and that points located into permitted zone according to table 1.2, figure 2.3 and figure 1.8.

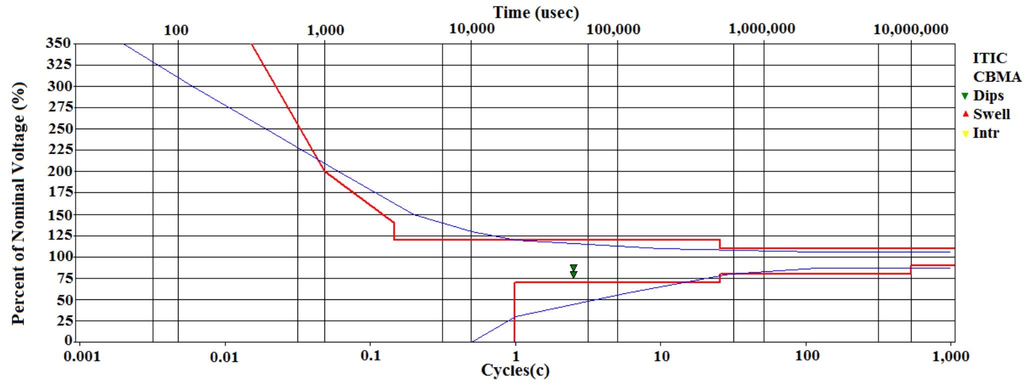

Fig. 1. 8. Shows dips points

1.5. Conclusion

- Analytical tools benefit from the increased level of monitoring and characterization. Models should be improved and the tools themselves should become easier to use.
- The quality of electrical power in industrial facilities has become an important area of concern due to its impact on the cost of energy and the reliability of feeding and operation networks Productivity as a whole.
- It is therefore important that these facilities study Characteristics Electrical feeding of the various sections of the establishment by means of measurements and collection Data and information on different loads in each section, determine the values of the disturbance on

CHAPTER 2. DIGITAL PROTECTIVE RELAYING OF POWER SYSTEMS

2.1. INTRODUCTION

Protection relays represent a particular importance in electrical power systems, they are responsible for the sense of any malfunction or defect may occur in any component of such systems starting from generation to transportation to distribution and use, after it sense of malfunction and defect so they issuing orders to the circuit breakers to isolate the specific defect element selectively.

2. 2. DIGITAL RELAY STRUCTURE

Figure 2.1, shows the main structure of the digital relay.

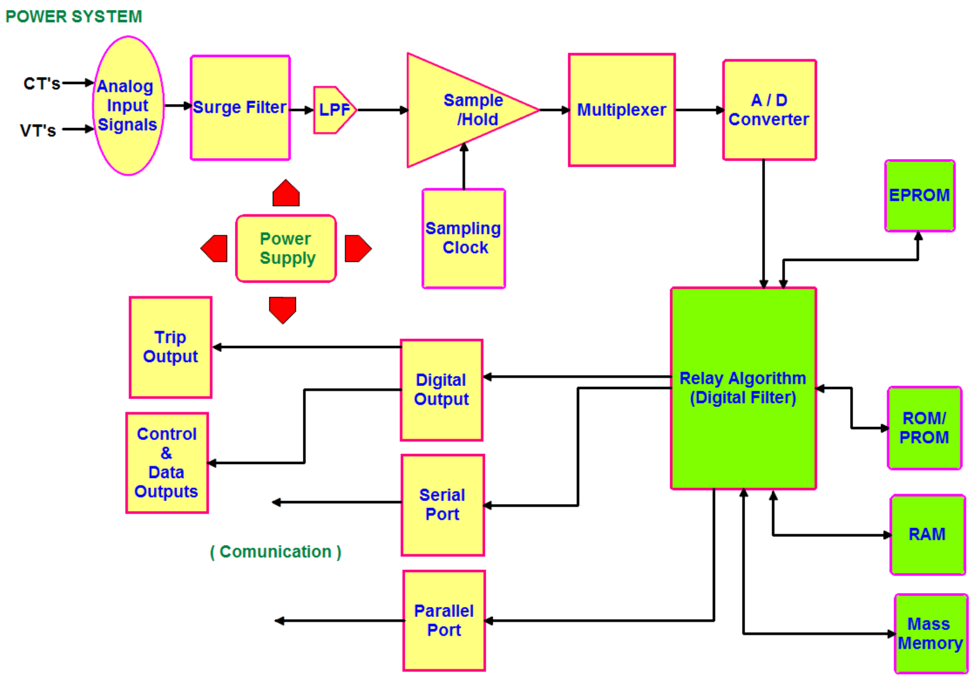

fig. 2. 1. Typical functional block diagram of a digital relay

2. 3. DIGITAL FILTERS USED IN DIGITAL RELAYS

This section analyzes the characteristics and mathematical formula of some digital filters which are used in numerical relays.

2. 3.1. Digital filters for one-element relay

One-element relay uses only a single input signal either current or voltage.

Many well-known digital filters use a single input signal for its calculation such as Fourier, Walsh, and Kalman filters.

2.3.1.1. Fourier filters

Fourier Filters are the most used filters in digital relays. The fundamental component can be calculated by the following equations [35], [40], [81], [83], [84], [85], [86], [87], [88]:

$$\hat{Y}_S = \frac{2}{K}\sum_{K=1}^{K} y_k \sin(k\theta) \qquad (2.4)$$

$$\hat{Y}_C = \frac{2}{K}\sum_{K=1}^{K} y_k \cos(k\theta) \qquad (2.5)$$

$$\theta = \frac{2\pi}{k} = 2\pi\frac{f_0}{f_s} \qquad (2.6)$$

Where:

$\hat{Y}_S$: the imaginary component of the input signal yk;

$\hat{Y}_C$: the real component of the input signal yk;

θ: the fundamental frequency angle between samples [85];

k: samples number per cycle;

f0: the frequency of the system (50 or 60 Hz);

fs: the sampling frequency.

The magnitude of Fourier filter is calculated by the equation:

$$|Y| = \sqrt{\left(\hat{Y}_S\right)^2 + \left(\hat{Y}_C\right)^2} \qquad (2.7)$$

To analyze the performance of this filter, we test number of input signals, as in the following cases.

case1**:** the input signal y_i contains the fundamental frequency only.

$$y_i = 22 * \sin(2\pi f t) \qquad (2.8)$$

Figure 2.2 displays the input signal and the output of the Fourier filter (DFT).

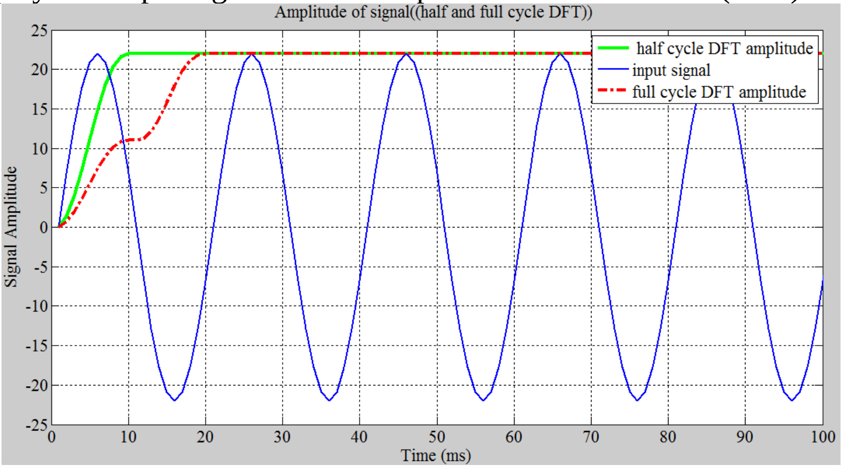

Fig. 2. 2. Input signal and its resultant amplitude by means of Fourier filter

From the previous figure, the filter half cycle needs less time than full cycle to calculate the amplitude of the input signal, but the accuracy is identical for both of them, these calculations is done at the fundamental frequency

Case 2: the input signal contains only odd harmonics as shown in table 2.1

Table 2. 1 The Harmonics content of the input signal

Harmonics Order “n”	% of true RMS
1’fundemental’	22

3	11
5	6
7	9
9	8
11	7

Figure 2.3 shows the input signal which contains odd harmonics and the amplitude of input signal (r.m.s value) after calculating it by half / full-cycle DFT.

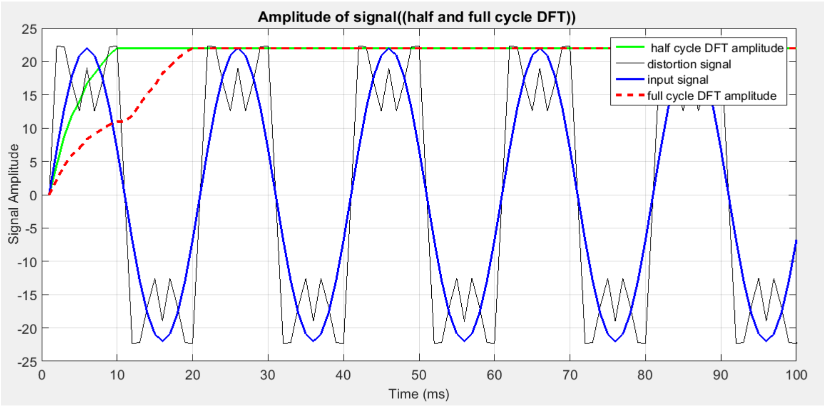

Fig. 2. 3. Input signal and its resultant amplitude by means of Fourier filters in case 2

From the previous figure, it can be noticed that DFT eliminates all odd harmonics, so that the amplitude of that signal equals to the amplitude of the fundamental component, and the filter performance is not affected by the presence of odd harmonics.

Case3: Sometimes the occurred slight shift of the fundamental frequency compared with the rated frequency (f=50 Hz).

$$y_i = 22 * sin(2\pi f t) \qquad (2.9)$$

f=49.5 Hz

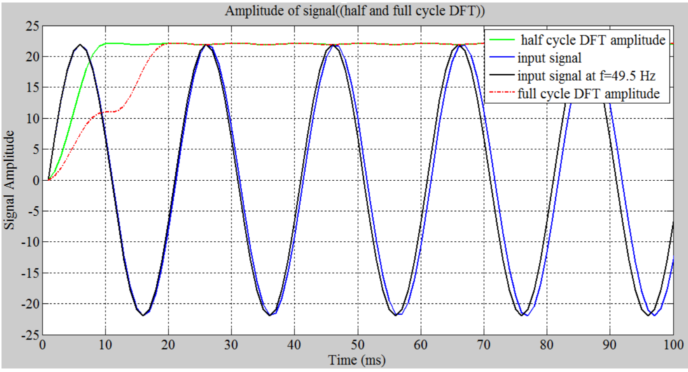

Fig. 2. 4. Input signal and its resultant amplitude by means of Fourier filters

From figure 2.22, it can be noticed clearly that in the case of the shift of the fundamental frequency, slight changes will happen in the output of the DFT (full- cycle &half-cycle), and these changes are increased by the increasing of the frequency shift.

Case 4: Saturation of current transformers

Figure 2.5 shows current waves downloaded from disturbances recorder in Banias Thermal Power Plant; the recorded wave shows severe saturation of current transformer.

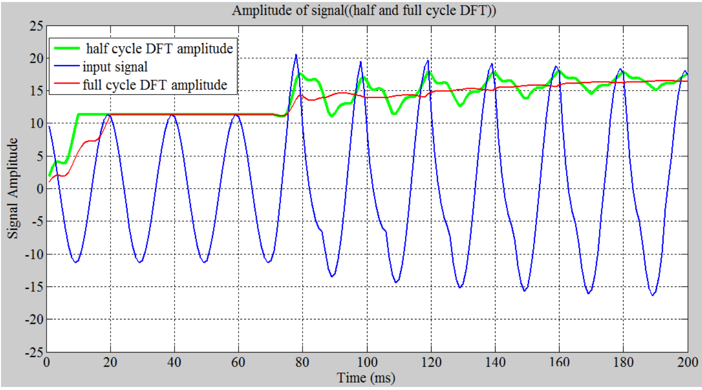

Fig. 2. 5. Saturated wave current and its amplitude by using DFT

As it was shown, the response of DFT full-cycle is better than DFT half-cycle, but the accuracy of DFT full-cycle is better than DFT half -cycle.

Case 5: The input signal contains odd and even harmonics as shown in figure 2.6 All of nonlinear loads, power transformer (saturation case) and power electronics elements are considered as main sources of harmonics distortion.

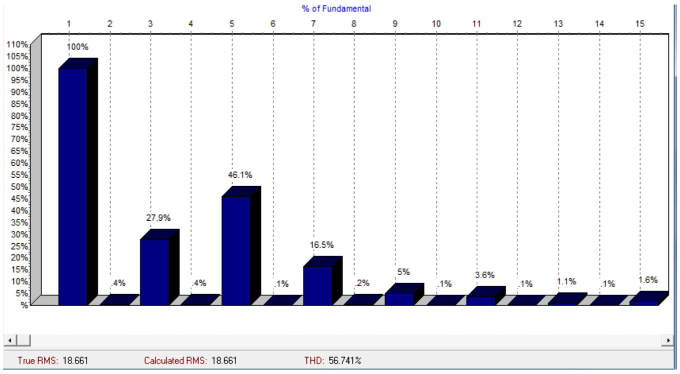

Fig. 2. 6. Harmonics analysis of input signal by using Micom S1 Agile

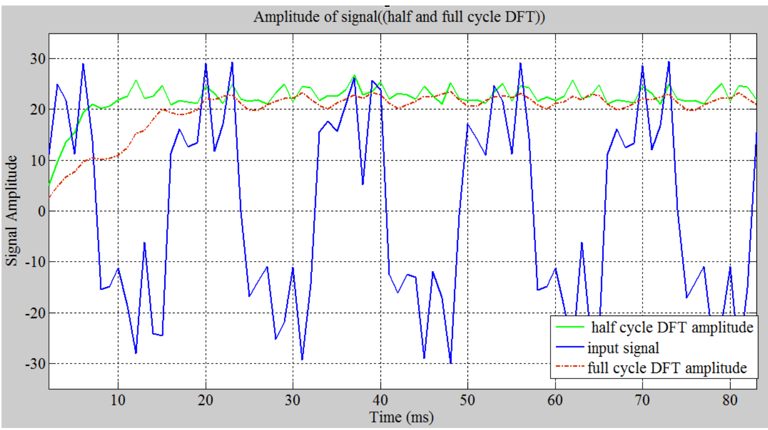

Fig. 2. 7. Input signal and its resultant amplitude by means of Fourier filter

The performance of DFT is unstable in these cases, so that the usage of anti-aliasing filter is important to attenuate the effect of harmonics as much as possible.

2.4. DISCUSSION AND CONCLUSION

- Full-cycle Fourier Filters have a good ability to remove DC Component and all harmonics of integer orders.

- Half-cycle DFT improves the speed of the relay at the expense of accuracy, while full-cycle DFT improves the accuracy of the relay at the expense of speed.
- It is clear that from the previous comparison between Fourier filters and Walsh filters for the same accuracy, Fourier filters have higher speed than Walsh filters, thus Fourier filters are widely used than other filters in computer relaying applications and by manufacturers of protection units.
- The choice option of any filters depends on the protection system structures and the economic considerations.

CHAPTER 3. SHORT CIRCUIT CALCULATIONS FOR THE STUDIED POWER SYSTEM

3.1. INTRODUCTION

For setting of the protective relays, we need to do short circuit calculations of the studied power system.

In this chapter we will do short circuit calculations at a part of Syrian grid, which contains all levels of voltage; low, medium and high. This calculation will be done by using Power Factory Software (DigSILENT).

3.2. ELECTRICAL POWER SYSTEM OF BANIAS REFINERY COMPANY AND SYRIAN ELECTRICAL GRID

Fig. 3.1, displays the single line diagram of the studied power system, DigSILENT or power factory software is used to achieve that study.

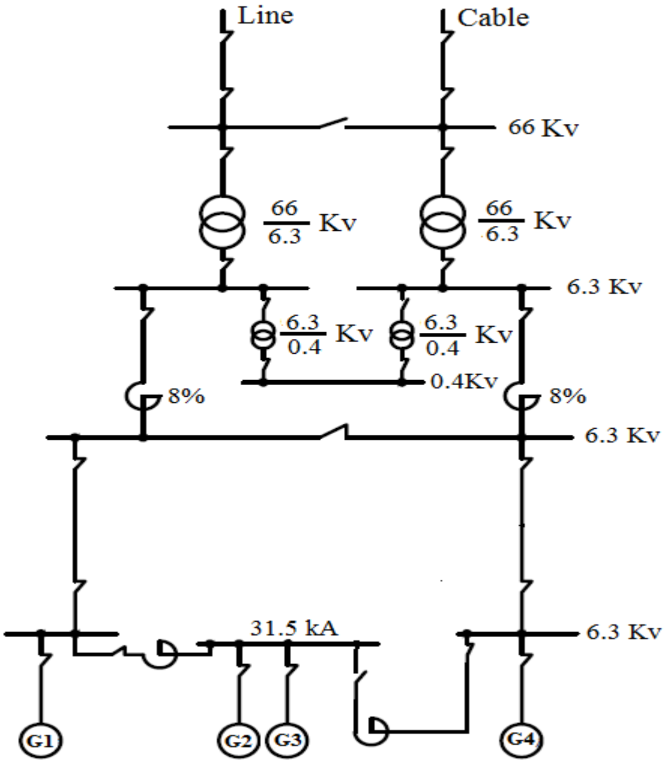

Fig. 3. 1. Single line diagram of Studied power system

3.3. SHORT CIRCUIT CACULATIONS ACCORDING to IEC60909

3.3.1. Cable line 66 kV is connected

Initial status:

- One 66 kV inlet cable is ON.
- Coupler 66 kV is on, tow transformers 1BAT10 (35MVA) and 2BAT10 (35MVA) are ON.
- Reactors are considered between substation and main station.
- Four generators running parallel, main station couplers are ON.
- Substation coupler is of.

3.3.1.1. Comparison Between the Maximum Short Circuit Current Values According to Its Location in The System

Table 3.1 contains maximum short circuit values on all bus bars of the power system, where one inlet line 66 kV is connected.

Table 3. 1 Maximum short circuit values comparison

Name	Ik"	Sk"	ip	Ib	Sb	Ik	Ith
	kA	MVA	kA	kA	MVA	kA	kA
1BAT 6kV	43.19198	448.86	115.4611	42.26578	439.2389	43.19198	45.0112
2 BAT 6kV	39.91951	414.85	106.6397	39.00005	405.3004	39.91951	41.58045
AEA-W11	14.13055	1615.33	33.09405	14.02141	1602.863	14.13055	14.29719
AEA-W12	14.13055	1615.33	33.09405	14.02141	1602.863	14.13055	14.29719
BBA-1	30.29613	330.58	81.3857	28.4528	310.4747	30.29613	31.69449
BBA-2	29.28696	319.57	78.53089	27.44597	299.4882	29.28696	30.59211
BFT10	7.520071	5.210	20.27686	7.520071	5.210058	7.520071	7.894306
MS-A1	28.96103	316.02	75.96429	26.84474	292.9276	28.96103	29.86929
MS-B2	20.93285	228.41	54.83407	16.70357	182.2681	20.93285	21.57774
MS-C2	28.14387	307.10	73.87409	26.02764	284.0115	28.14387	29.03524

3.3.1.2. Comparison Between the Minimum Short Circuit Current Values According to Its Location in The System

Table 3.2 contains minimum short circuit values on all bus bars of the power system, where one inlet line 66 kV is connected.

Table 3. 2 Minimum short circuit values comparison

Name	Ik"	Sk"	ip	Ib	Sb	Ik	Ith
	kA	MVA	kA	kA	MVA	kA	kA
1BAT 6kV	35.18	365.69	92.91	34.44	357.99	35.189	36.39
2 BAT 6kV	32.56	338.42	85.90	31.82	330.77	32.561	33.67
AEA-W11 66kV	8.218	939.50	19.58	8.134	929.84	8.218	8.32
AEA-W12 66 kV	8.218	939.50	19.58	8.134	929.84	8.218	8.36
BBA-1	26.15	285.43	69.59	24.63	268.68	26.15	27.17
BBA-2	25.24	275.52	67.03	23.71	258.79	25.24	26.19
BFT10	6.794	4.707	18.31	6.794	4.707	6.794	7.131
MS-A1	25.15	274.51	65.32	23.38	255.15	25.15	25.85
MS-B2	18.98	207.16	49.69	15.43	168.47	18.98	19.56
MS-C2	24.41	266.39	63.44	22.63	247.02	24.41	25.09

3.4. RESULTS DISCUSSION

Previous results of simulation are necessary to design the protection relaying system and the capacity of circuit breakers for each section of the studied power system.

From simulation results, it be noticed for the first case (Tow 66 kV inlet lines is ON (PP Hama and PP Banias are connected)) that most values of short circuit currents are out of limit (40 kA & 31.5 kA) with a Value equal to twice the maximum value accepted, so that this case is impossible in practical applications.

For the third case (One 66 kV inlet Cable is ON), it be noticed that some values of short circuit currents are out of limit (40 kA & 31.5 kA) and others are into limits, so that it is very important to study accurately the power system protection to avoid the huge damage of the electrical components of electrical power system during different disturbances.

These values of minimum short-circuit currents will be used in the next chapter for designing and setting of protective relaying system.

CHAPTER 4. EVALUATION AND VERIFICATION OF PROTECTION RELAY SETTINGS FOR THE STUDIED POWER SYSTEM

4.1. INTRODUCTION

Protection relays (AFA01, AFA02, AFA03, AFA04, Distance Relay_PPHama and Distance Relay_PPBanias) are designed for the protection of the main parts of lines 66 kV and Bus Bars (AEA-W11 and AEA-W12) and primary side of power transformers (1BAT10 and 2BAT10), inlets and outlets for lines 6,3 kV are protected by the relays BBA02, BBA03, BBA04 and BBA05. figure 4.1 shows the protection relay system used for electrical power system of Banias Refinery– Syria.

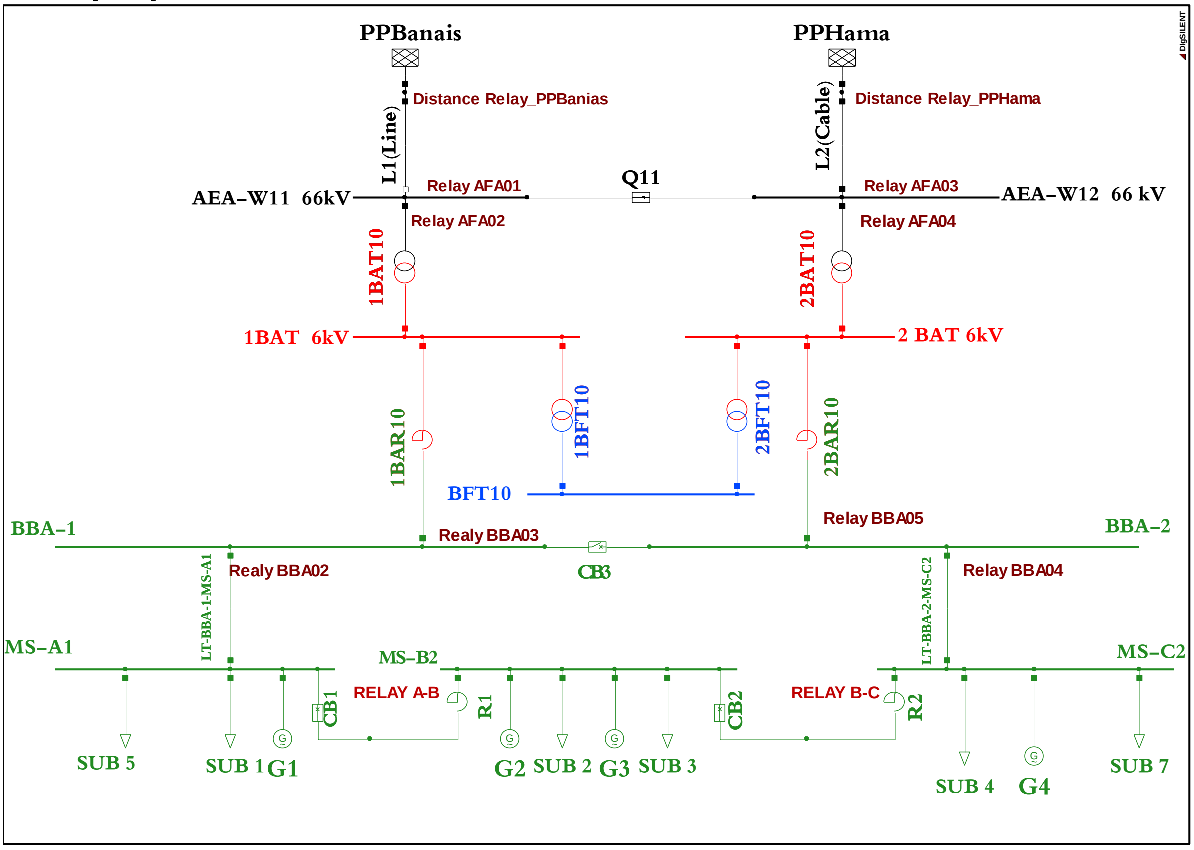

Fig. 4. 1. Distribution of relays for different elements of the studied power system

4.2. VERIFICATION THE PERFORMANCE OF RELAYING SYSTEM IN DIFFERENT FAULT CASES

4.2.1. Three-Phase Short Circuit on Cable Line 66 kV

PPHama feeder and four generators are connected, the excitation systems of four generators are considered. The fault is executed at the cable line between PPHama and Bus-Bar AEA-W12, at the distance 3.23 Km from the Distance Relay_AFA03 location as shown in figure 4.2.

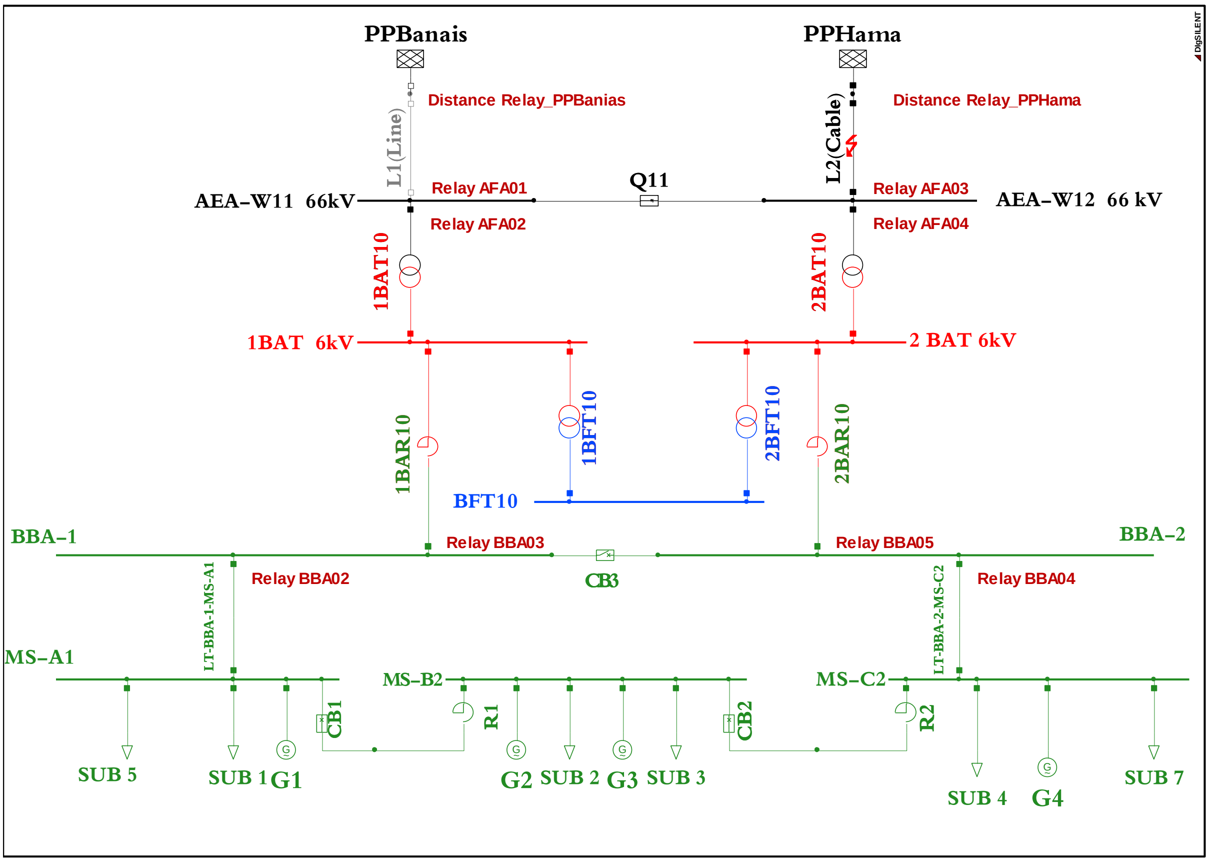

Fig. 4. 2. Three-phase fault at the distance 3.32 Km from Distance Relay_PPHama

The siemens SIPORTEC device model 7SA6125 (numerical distance relay) is used to simulate the Distance Relay_PPHama and Distance Relay_AFA03.
it is noticed from figure 4.3, that the arrow is located in the fourth impedance zone, the parameters of the fault are: fault impedance z1=0.271pri.ohm and time delay time =0.94s, this response is compatible with Distance_PPHama relay settings.

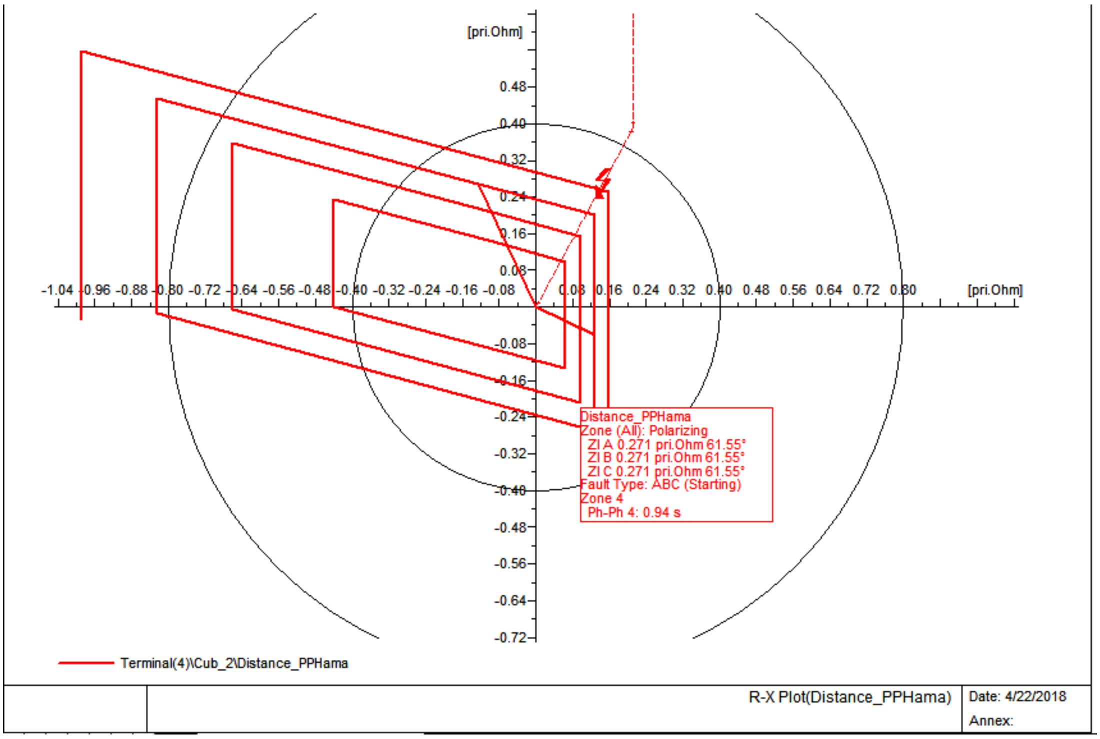

Fig. 4. 3. Characteristic of R-X plot of Distance_PPHama Relay

it is noticed from figure 4.4, that the fault is located in the second impedance zone, the parameters of the fault are: fault impedance z1=0.174pri.ohm and time delay time =0.44s, this response is compatible with Distance_AFA03 Relay settings

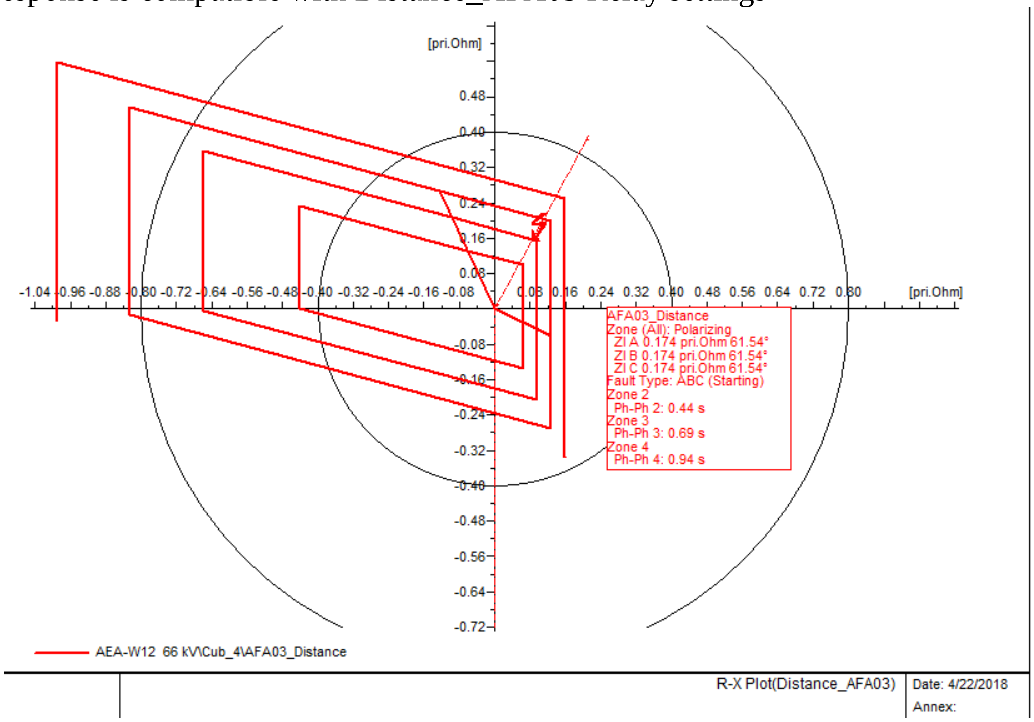

Fig. 4. 4. Characteristic of R-X plot of Distance_AFA03 Relay

Figure 4.5, shows that over current relay AFA03 will operate at current I=1223 A and time delay t=3.289 S.

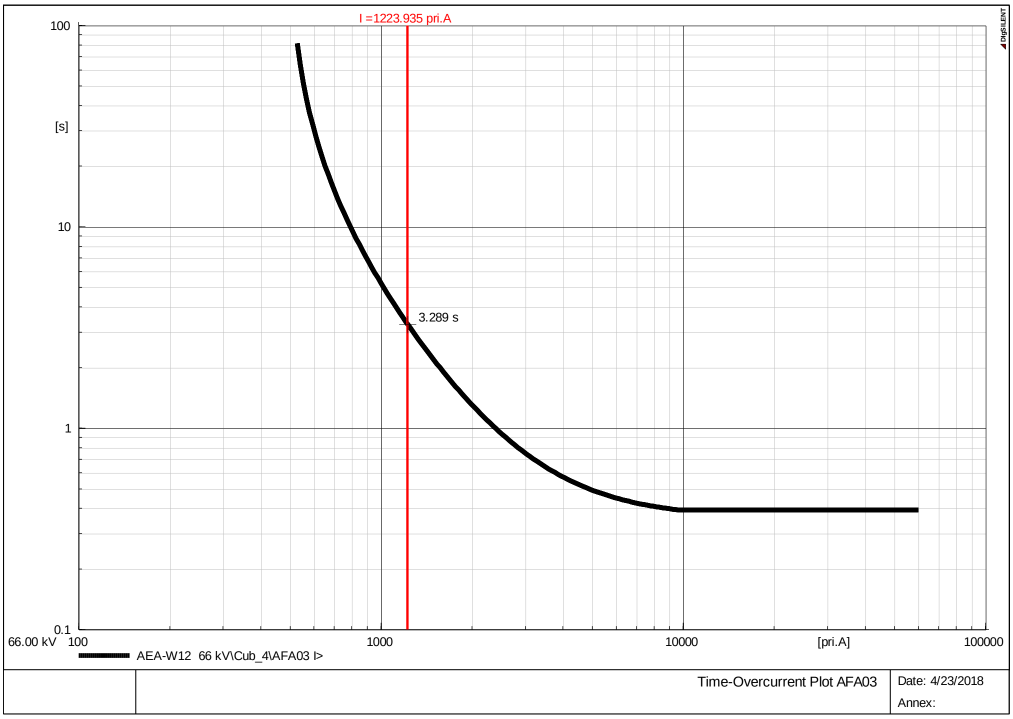

Fig. 4. 5. Time overcurrent Relay_ AFA03 plot

Figure 4.6, shows that over current relay AFA02 will operate at current I=584 A and time delay t=7.265 S.

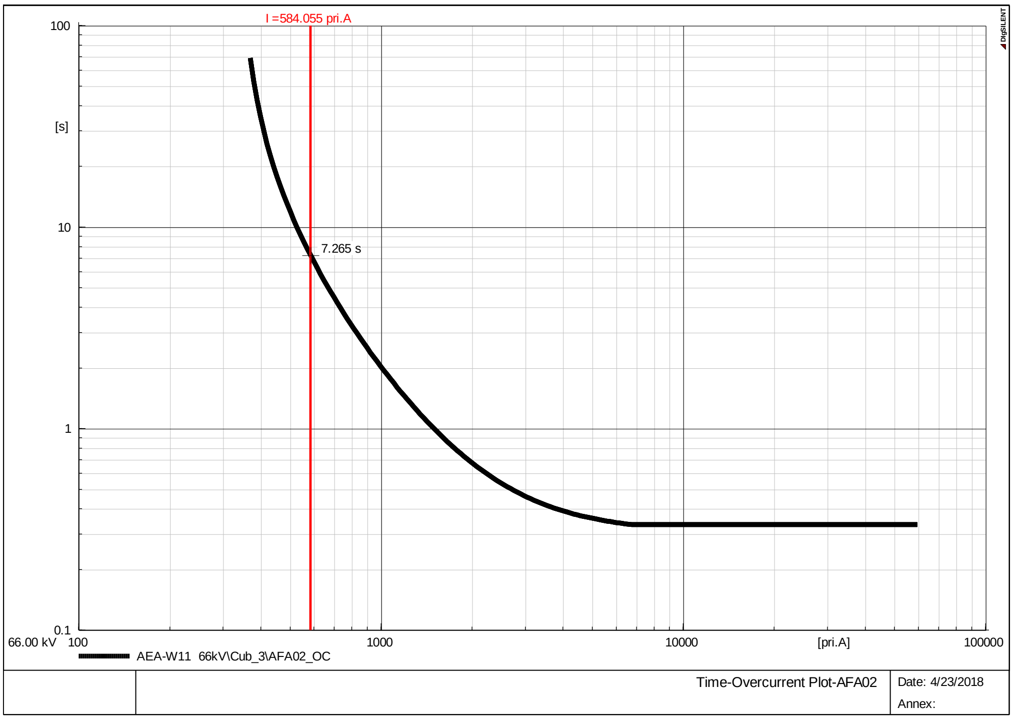

Fig. 4. 6. Time overcurrent Relay_ AFA02 plot

Figure 4.7, shows that over current relay BBA03 will operate at current I=6422 A and time delay t=5.880 S.

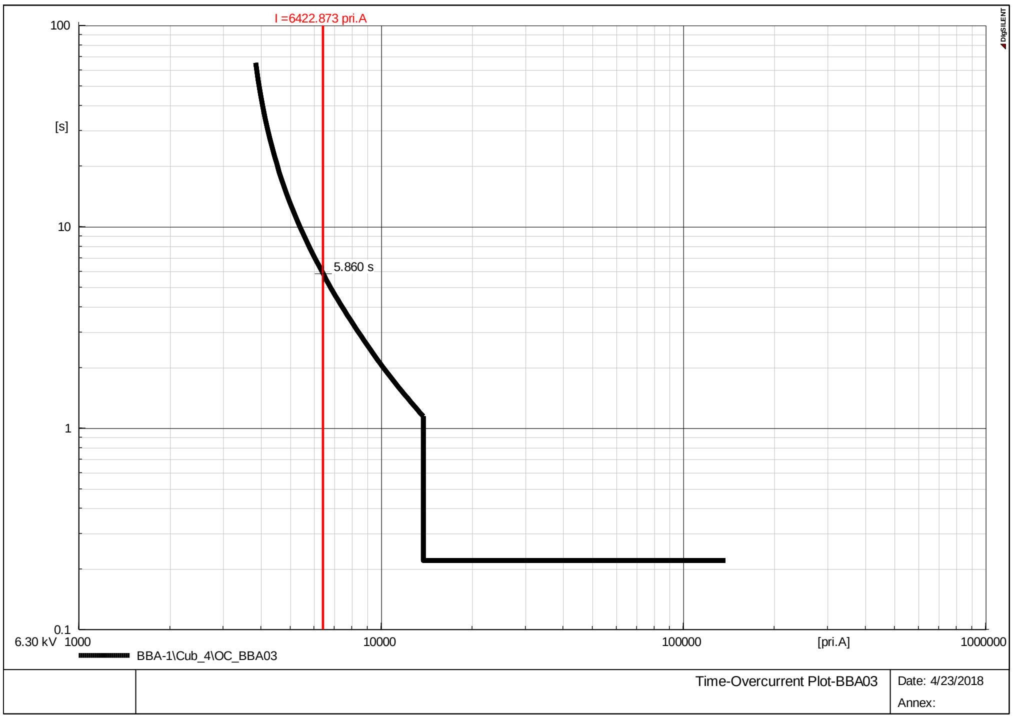

Fig. 4. 7. Time overcurrent Relay_ BBA03 plot

Figure 4.8, shows that over current relay BBA02 will operate at current I=6422 A and time delay t=2.930 S.

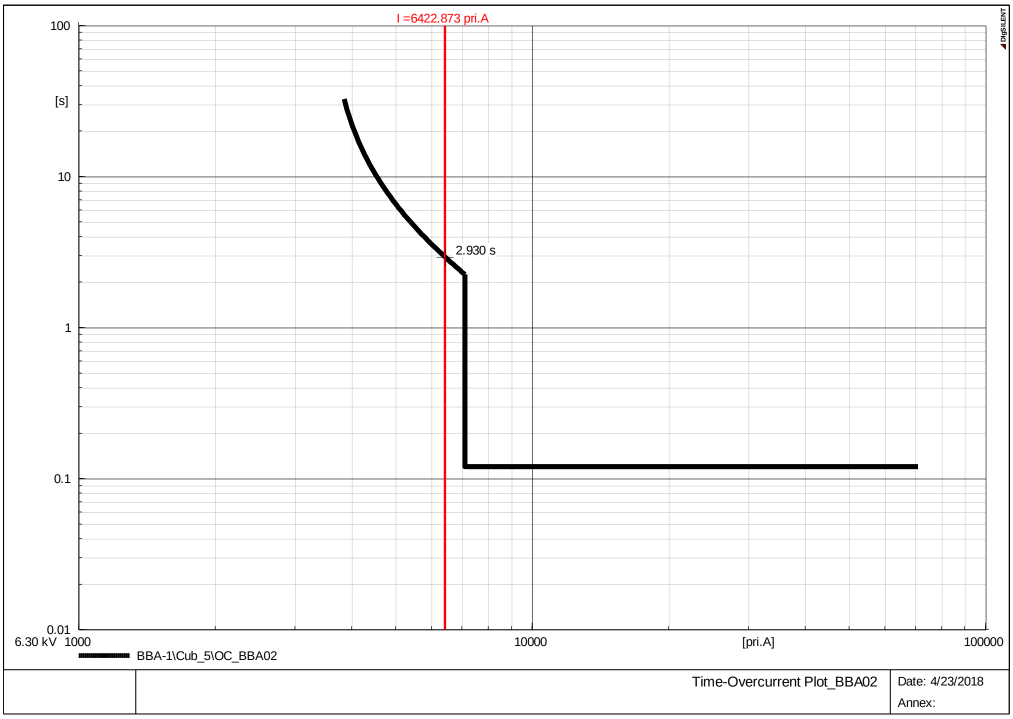

Fig. 4. 8. Time overcurrent Relay_ BBA02 plot

In this case, we can see that the distance_AFA03 Relay Siemens 7SA6125 will operate and isolate the fault because it has the smallest delay time.

4.3. CONCLUSION

- protection settings have been calculated and tested by performing faults in all parts of the electrical power system.
- After careful knowledge of the performance of the protection relaying system and its behavior under the effect of various faults, we can make a careful study of the impact of poor power quality on the protection system by comparing the results in both cases.

CHAPTER 5. THE EFFECT OF POOR POWER QUALITY ON DIGITAL RELAYS

5.1. INTRODUCTION

the effect of harmonics and current transformer saturation on distance relays and overcurrent relay have been investigated in this chapter. this study will be done by using a computer simulation program DigSILENT power factory 15.1 (PF).
the effect of current transformer saturation on differential relays will be done by using electrical power system has three ends. This study will be done by using EMTP-ATP software.
A practical solution had suggested and tested by using EMTP-ATP, the practical solution is done by adding a metal oxide varistor element to the secondary side of the current transformer.

5. 2. THE EFFECT OF HARMONICS ON DIGITAL RELAYS PERFORMANCE

To study the effect of harmonics on distance relays of cable line(L2) in figure 5. 1, we will do modeling of harmonic sources.
In DigSILENT, harmonic sources can be either current or voltage sources [95]. To generate harmonics, we will use the following sources for this purpose [95]:
-General loads like SUB 7, SUB 3 and SUB 5 will be modeled as harmonic current sources.
-Voltage sources.
-External grid like PPHama or PPBanias will be modeled as harmonic voltage sources, in this case the spectral of harmonic injections for the voltage sources are directly entered on the page of the element itself via harmonic/power quality/ harmonics voltage table.

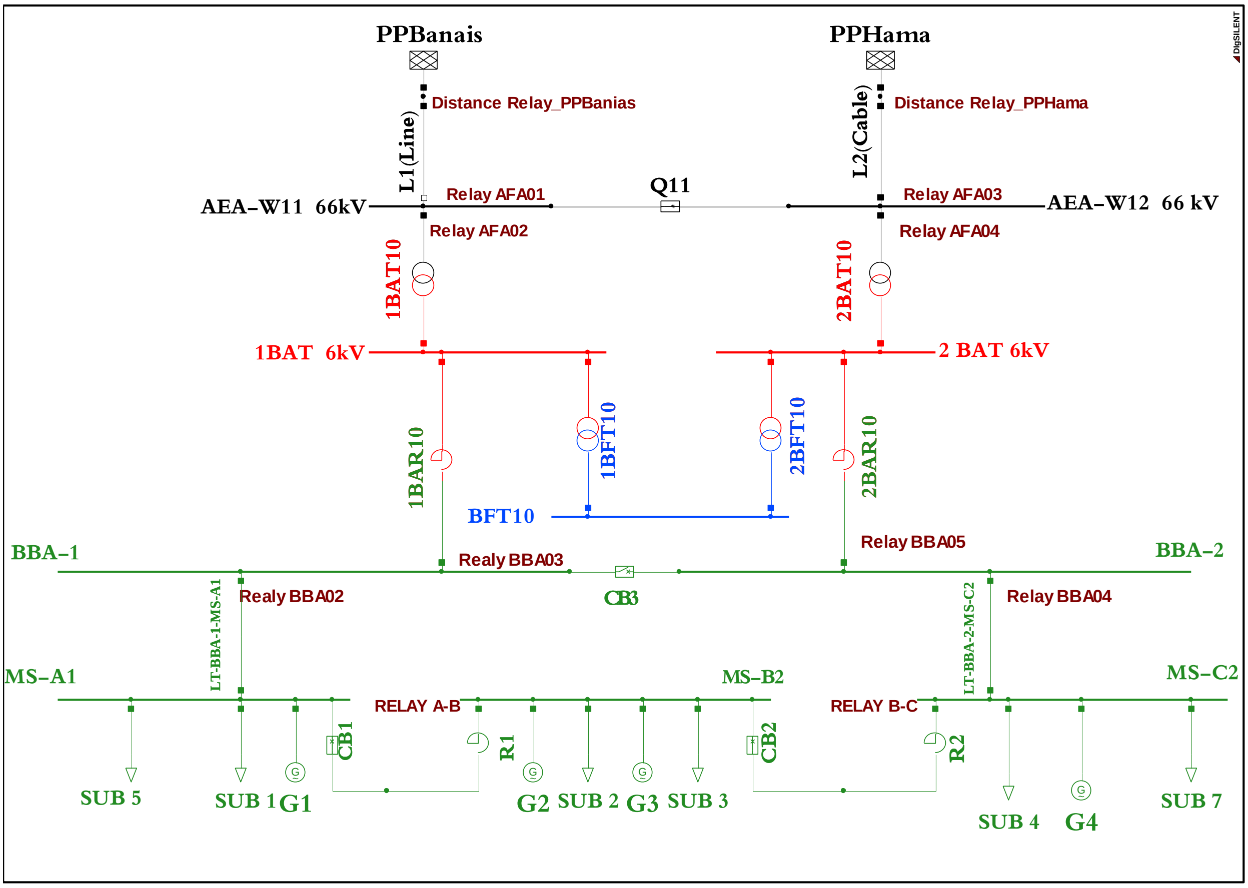

Fig. 5. 1. Single line diagram of the electrical power system

After executing harmonic load flow for all frequencies, we see that distance Realy_PPHama will act in the first zone and send a trip signal to the circuit breaker to isolate the fault as shown in figure 5.2, in fact we do not have any fault but the flow of harmonics in the electrical power system causes this wrong behavior of distance relay.

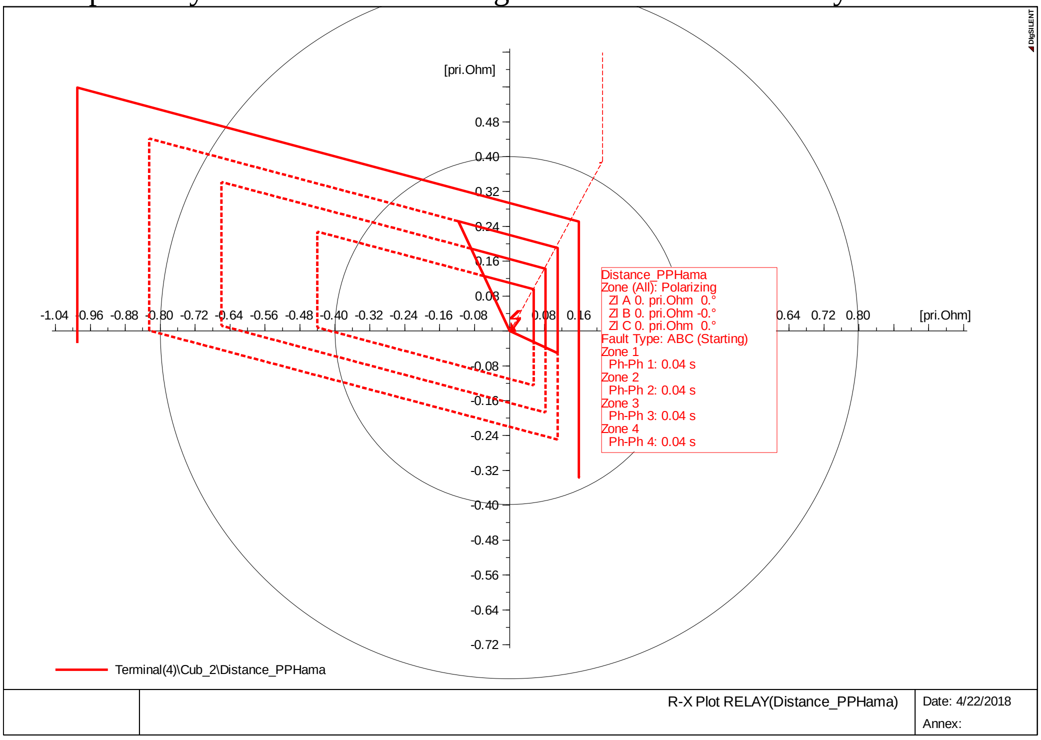

Fig. 5. 2. Characteristic of R-X plot of Distance_PPHama

From figure 5.3, it is noticed that the distance relay_ AFA03 of cable line acts as if the fault is located in zone 1 and send alarm signal to the circuit breaker, by other words, the figure 5.3 shows that the relay may report a wrong fault location in the presence of the harmonic distortion. It can be noticed that the distance relay acts incorrectly. The presence of harmonics leads to incorrect current / voltage measurements and therefore errors in calculating the fundamental quantities.

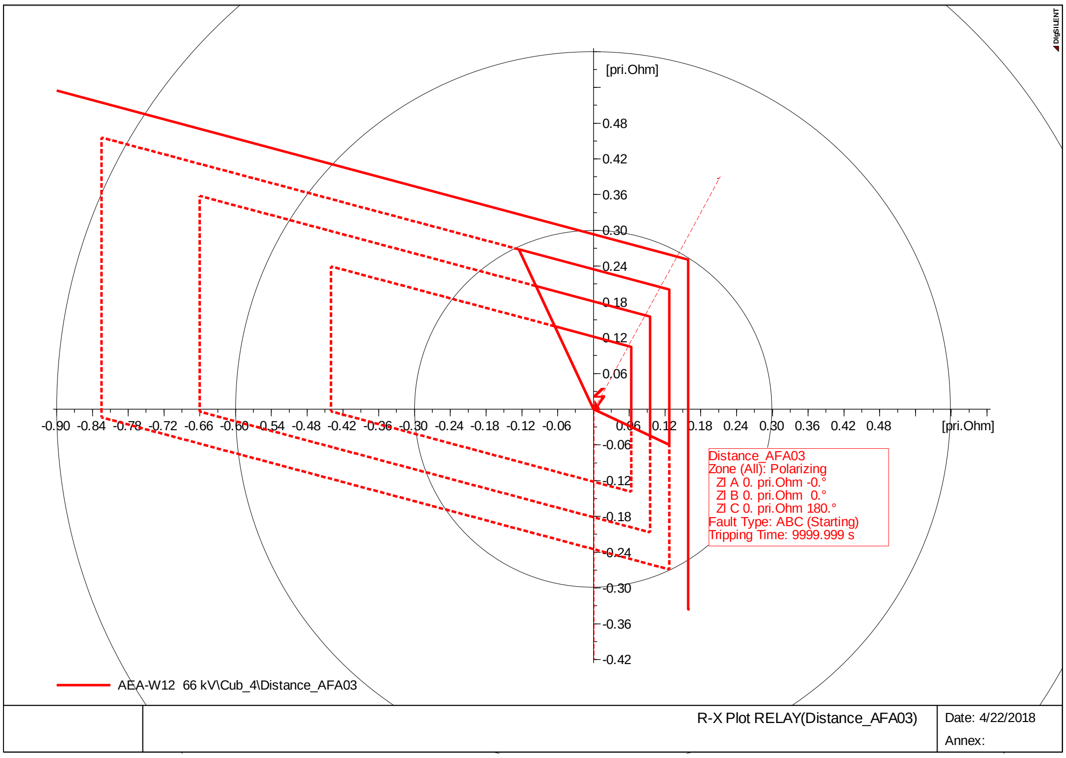

Fig. 5. 3. Characteristic of R-X plot of Distance_AFA03 Relay

5.2.1. The Effect of Harmonic and Saturation of Power Transformer on The Response of Overcurrent Relays

In general, the nonlinearities of the power transformer core are considered as a major source of harmonics. For example, this nonlinearity may cause to increase the magnitude of inrush current from 10 to 15 times the rated current, thus results in high level of harmonics which damages the insulation [149], [150].

We will do power flow calculation in DigSILENT and analyze the response of digital relays.

-figure 5.4 and figure 5.5, display the magnetization curves of power transformer 1BAT10 and 2BAT10 after modification of current values versus voltage values, to verify the effect of core transformer saturation on the response of digital relays.

From the two next figures, I can see that we use the same magnetization curve for the both transformers 1BAT10 and 2BAT10.

In general, when the saturation of core transformer happens, the transformer will consume a high current to maintain the level of voltage into acceptable limits.

In the saturation region of magnetization curve, it is seen that a small increase of excitation voltage will cause a high increase of current values.

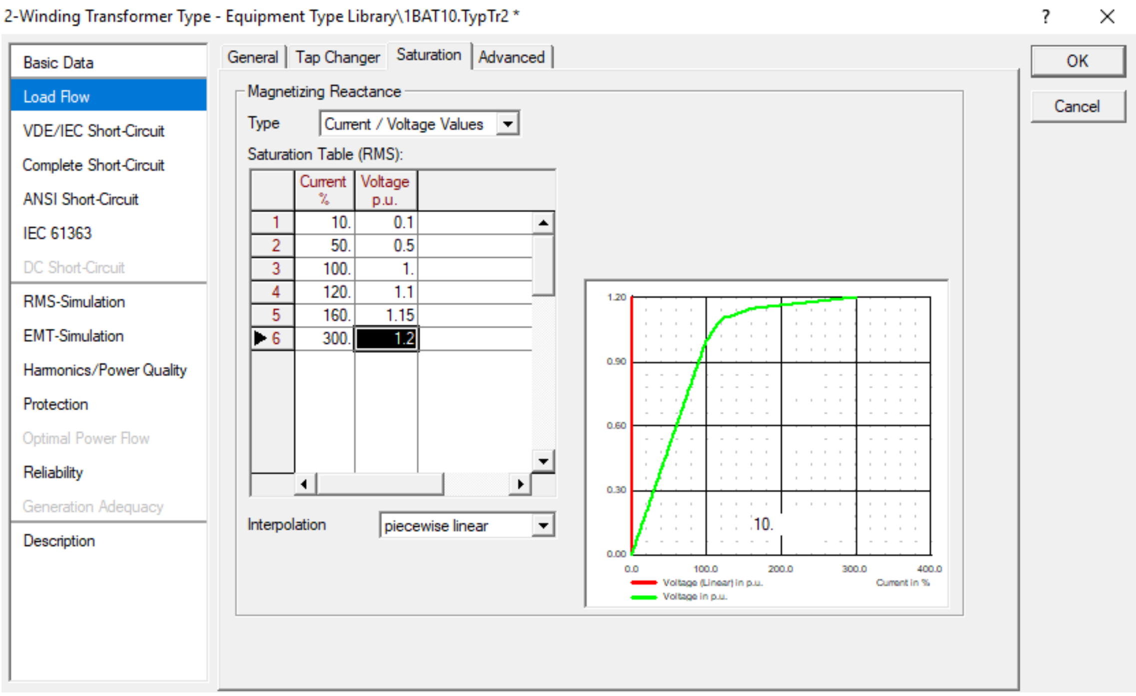

Fig. 5. 4. Magnetization curve of 1BAT 10

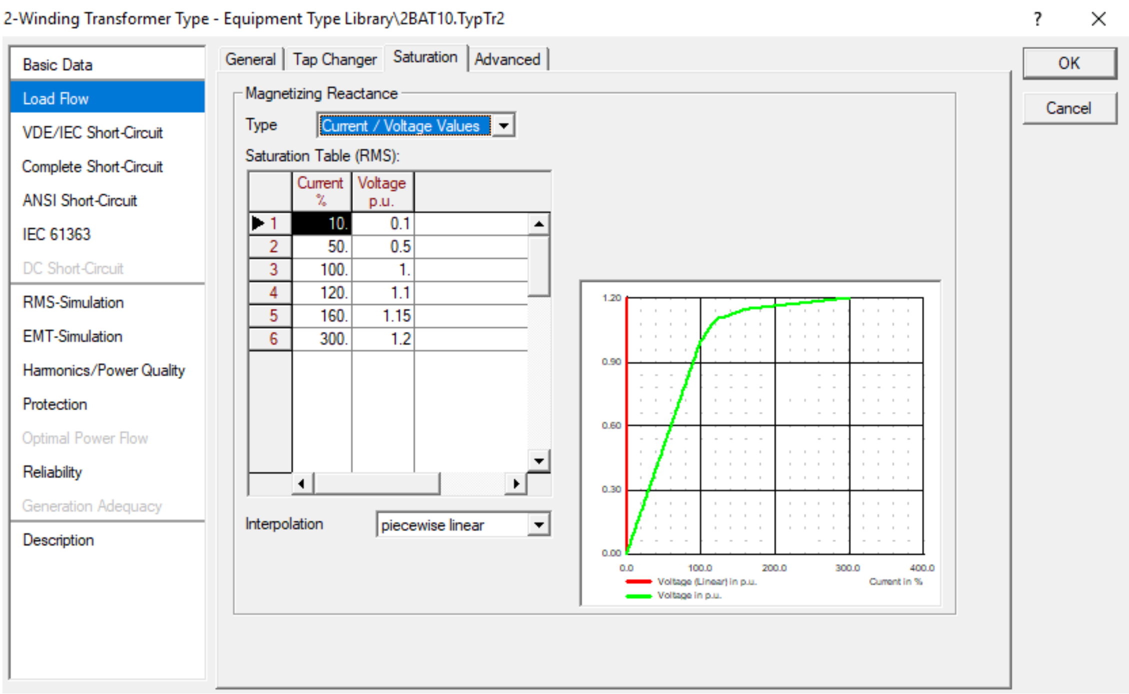

Fig. 5. 5. Magnetization curve of 2BAT 10

From the simulation results shown in the figure 5.6 and figure 5.7, the time and current tripping values have changed as follows:

- AFA03: I=867A & t= 7.665S.

-AFA02: I=429.83 A & t= 22.813 S.

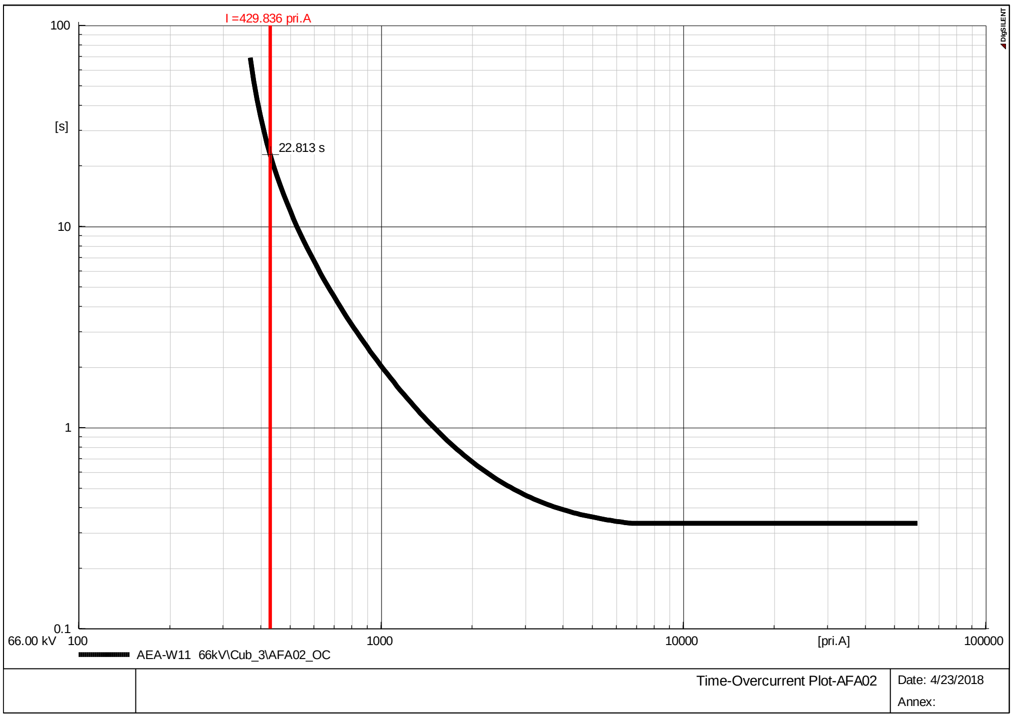

Fig. 5. 6. Time overcurrent plot _ AFA02

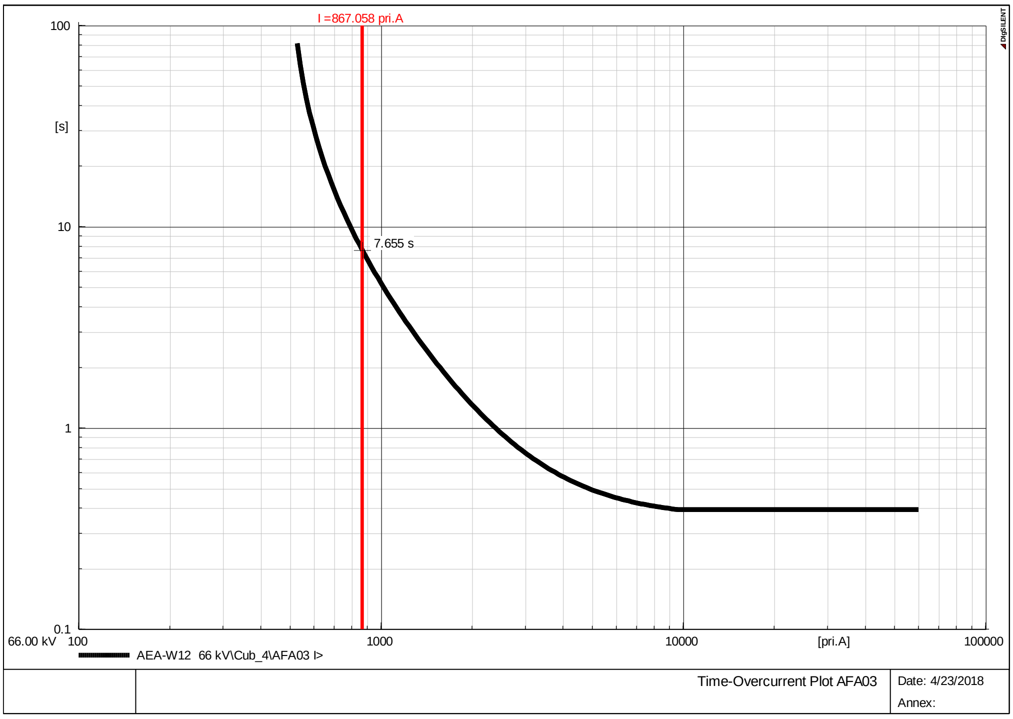

Fig. 5. 7. Time overcurrent plot _ AFA03

-From figures 5.8, 5.9, 5.10 and 5.11, it can be seen that by increasing the value of knee point voltage of magnetization curve of power transformers we will avoid the wrong response of overcurrent relays which are located at the high voltage side of this transformers.

The wrong response of overcurrent relay happens because of saturation of power transformer and harmonics sources in power system.

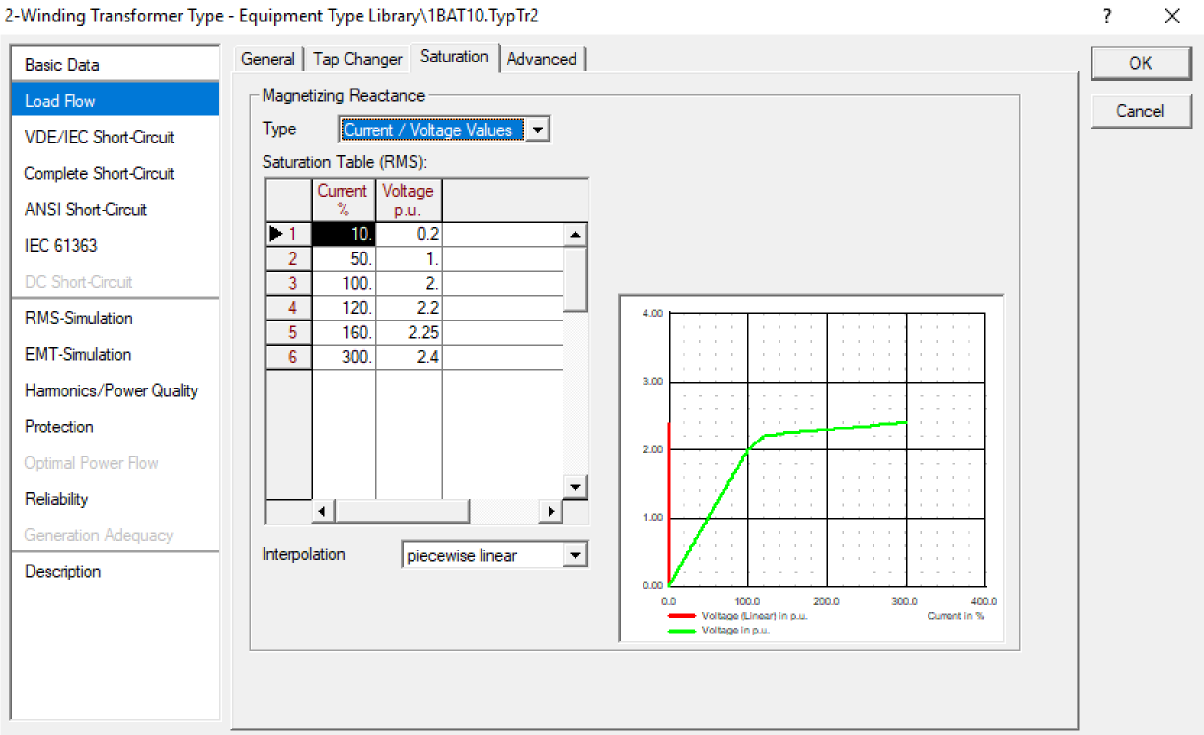

Fig. 5. 8. Magnetization curve of 1BAT 10

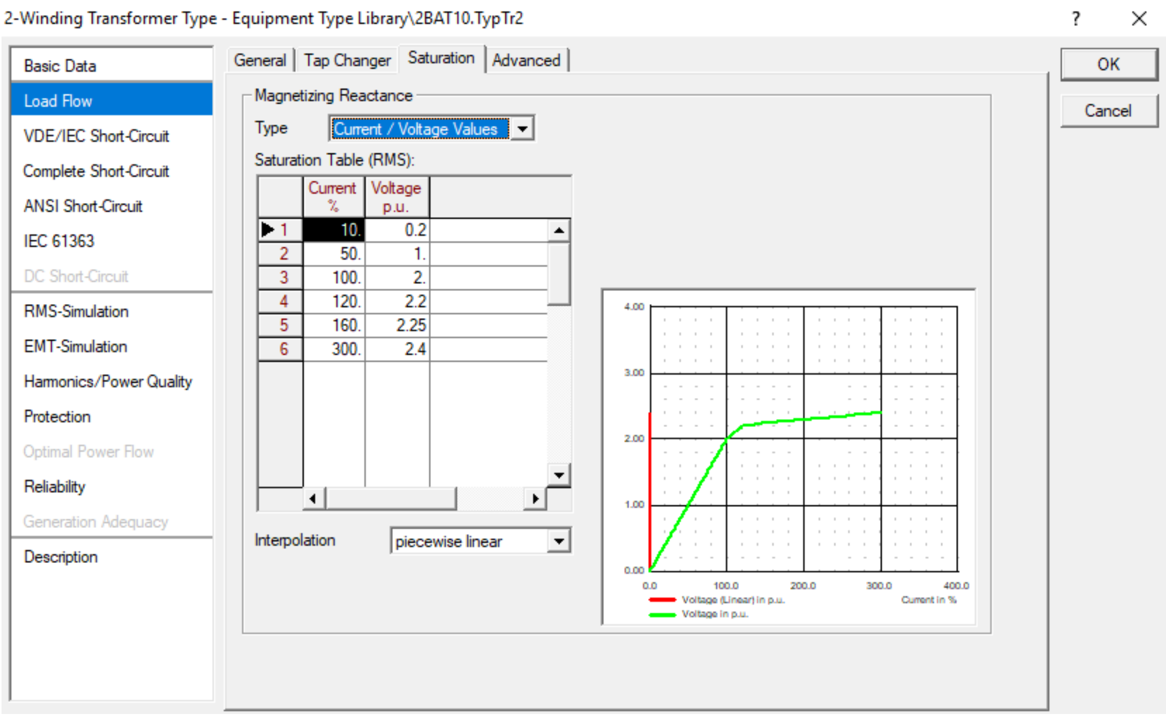

Fig. 5. 8. Magnetization curve of 2BAT 10

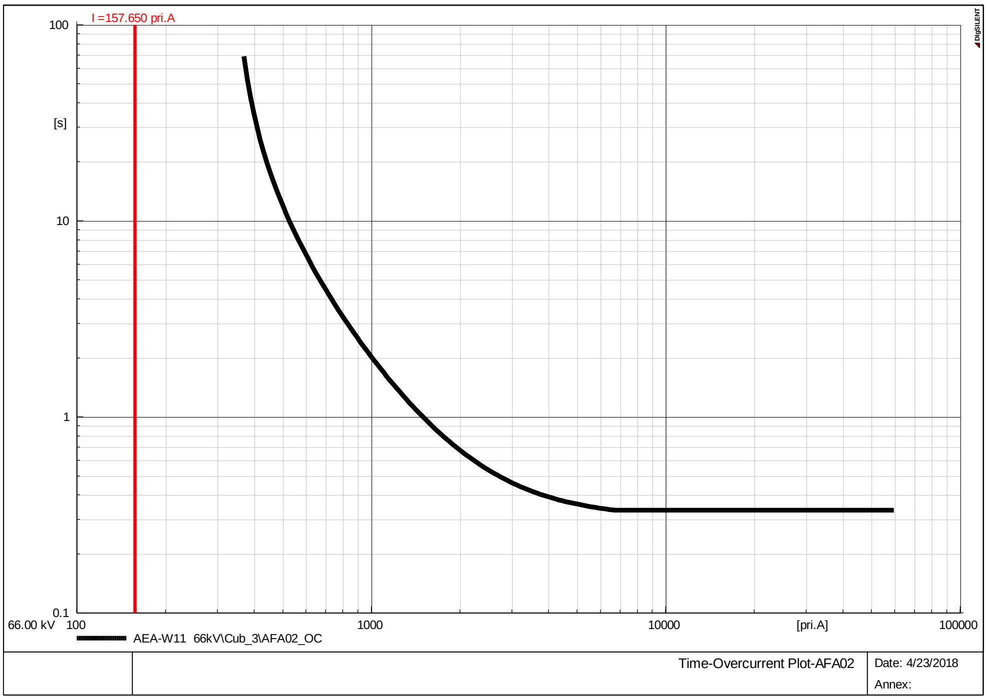

Fig. 5. 9. Time overcurrent plot _ AFA02

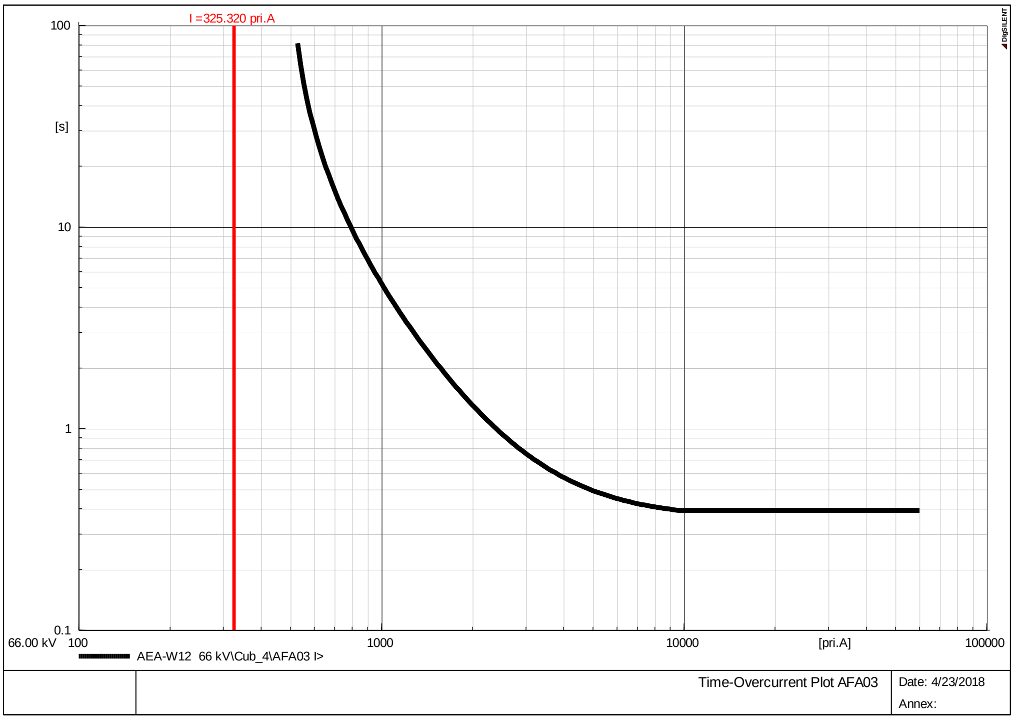

Fig. 5. 10. Time overcurrent plot _ AFA03

5.3. IMPROVEMENT OF DIFFERENTIAL PROTECTION PERFORMANCE BY EXTERNAL FAULTS ASSOCIATED WITH A CURRENT TRANSFORMER SATURATION

5.3.1. INTRODUCTION

The addition of a non-linear (MOV) component improves the stability of differential protection when the fault occurs outside the protection zone associated with saturation in a current transformer.

This component (MOV) has a non-linear characteristic between voltage and current, At a voltage equal to or greater than the threshold voltage, a large current passes through the MOV element, which improves the stability of the current transformer and return its work point from the nonlinear region to the linear area on the magnetization curve with a nano-time delay [155], [156], Thus avoiding saturation of the current transformer. This solution was verified through a computer simulation by using EMTP-ATP.

The proposed solution is simple and can be used in differential protection systems of different generations.

5.3.2. TEST OF RELAY DIFFERENTIAL PROTECTION PERFORMANCE UNDER THE EFFECT OF SATURATION BY USING EMTP-ATP PROGRAM

Fig. 5.12, shows a power system which is modeled by using the EMTP-ATP program consisting of a Bus Bar of three ends which is protected by using differential protection.

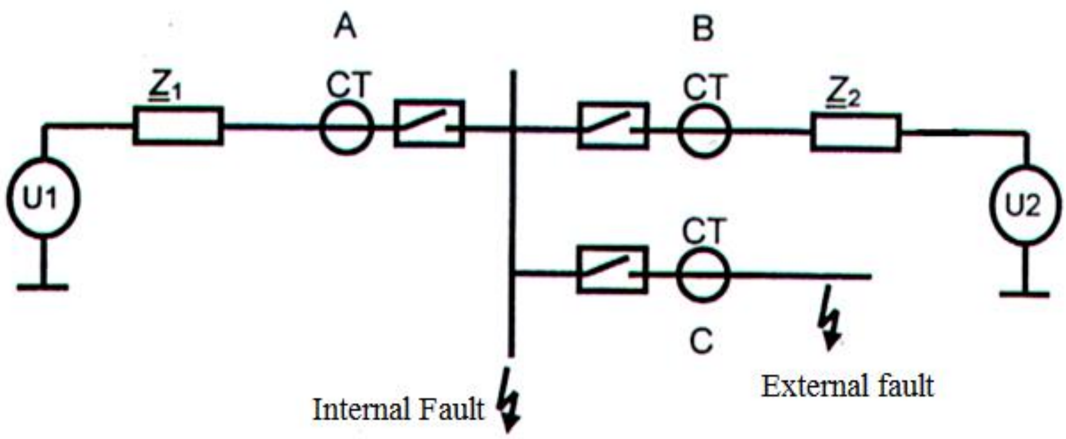

Fig. 5. 11. The power system which is tested in the EMTP-ATP program

5.3.2.1. One-phase-to-ground short circuit (1l-g) inside the protected zone and the presence of MOV element

Fig. 5.13, shows the representation of the power system in the EMTP-ATP program, while Fig. 5.14, Fig. 5.15 and Fig. 5.16, shows the phase currents in the relay.

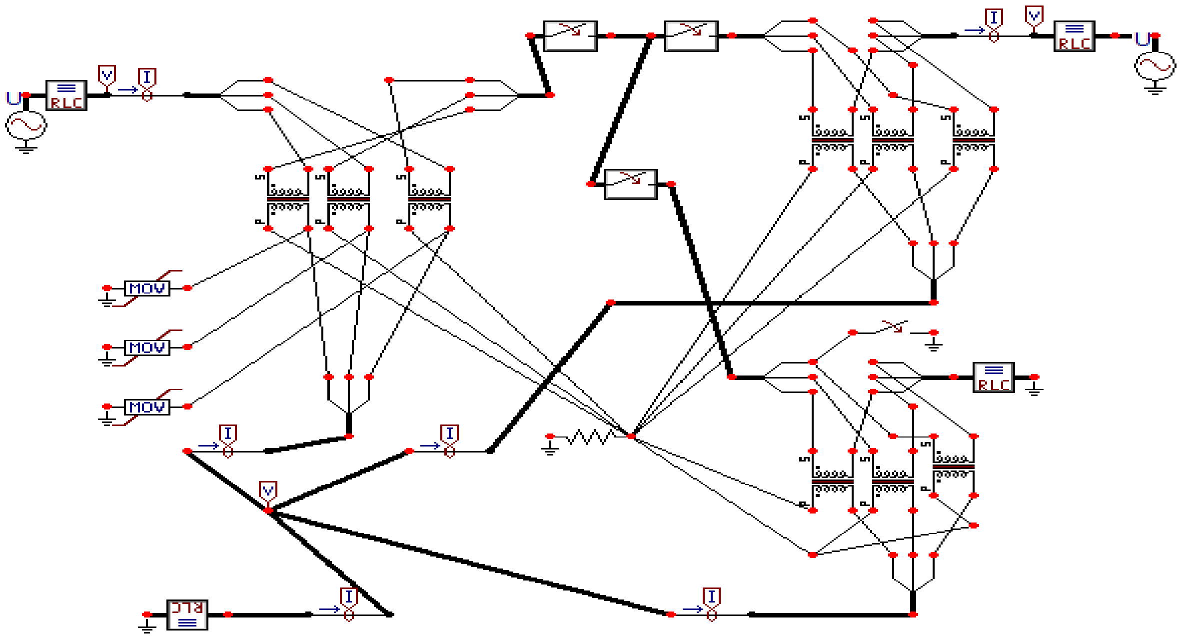

Fig. 5. 12. Representation of the power system in the case of internal fault by using EMTP-ATP

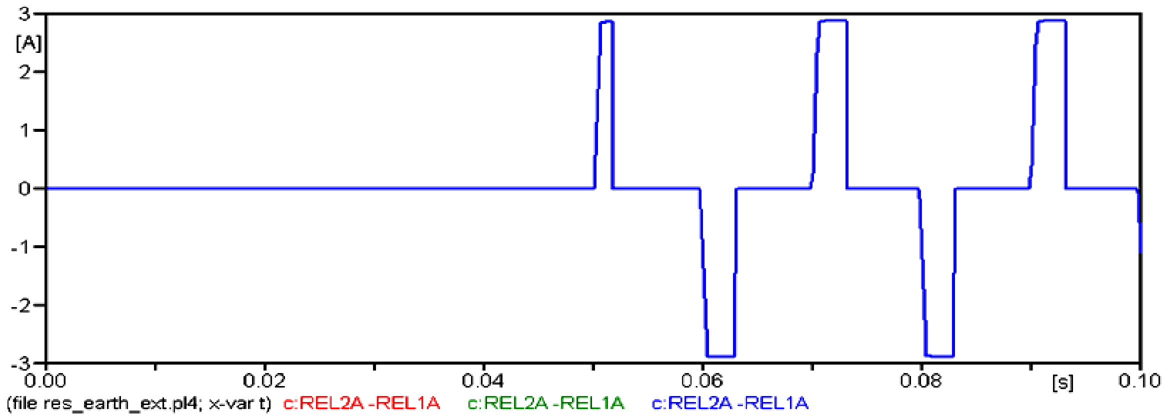

Fig. 5. 13. The differential current, passing in the phase (A)

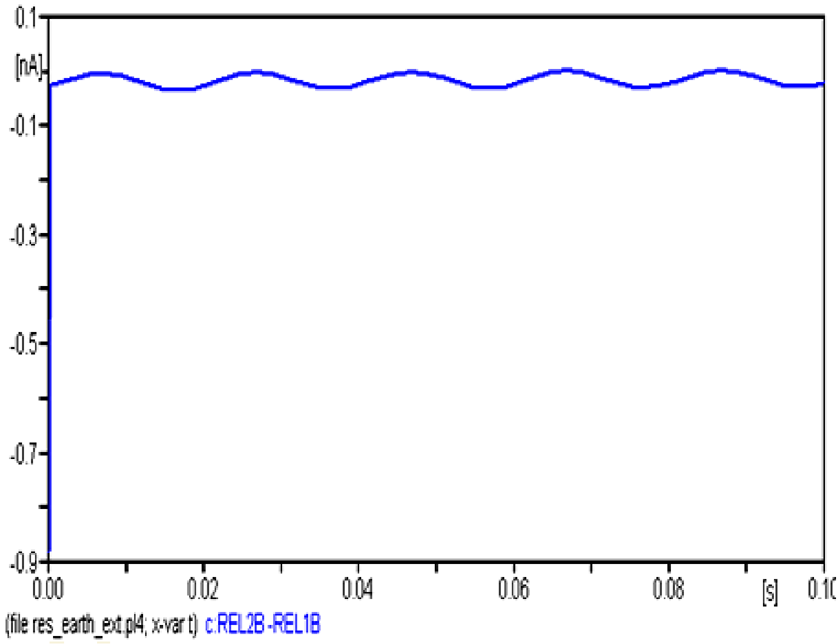

Fig. 5. 14. The differential current, passing in the phase (B)

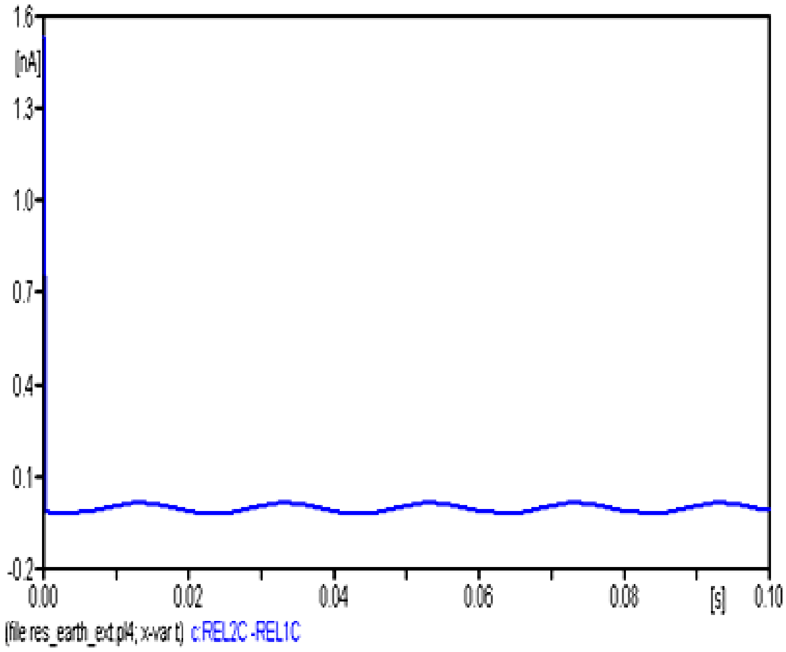

Fig. 5. 15. The differential current, passing in the phase (C)

We notice from the previous three figures, that the differential current of phase A of the relay is greater than the rated operating threshold value of the differential protection, which leads to the work of protection and direct tripping of the fault, i.e., differential protection works correctly here.

5.3.2.2. A Fault Condition Outside the Protection Zone Without Using the MOV Element

Fig. 5.17, shows the representation of the power system without using of the MOV element in the EMTP-ATP program, while Fig. 5.18, Fig. 5.19, and Fig. 5.20, show the phase currents in the relay.

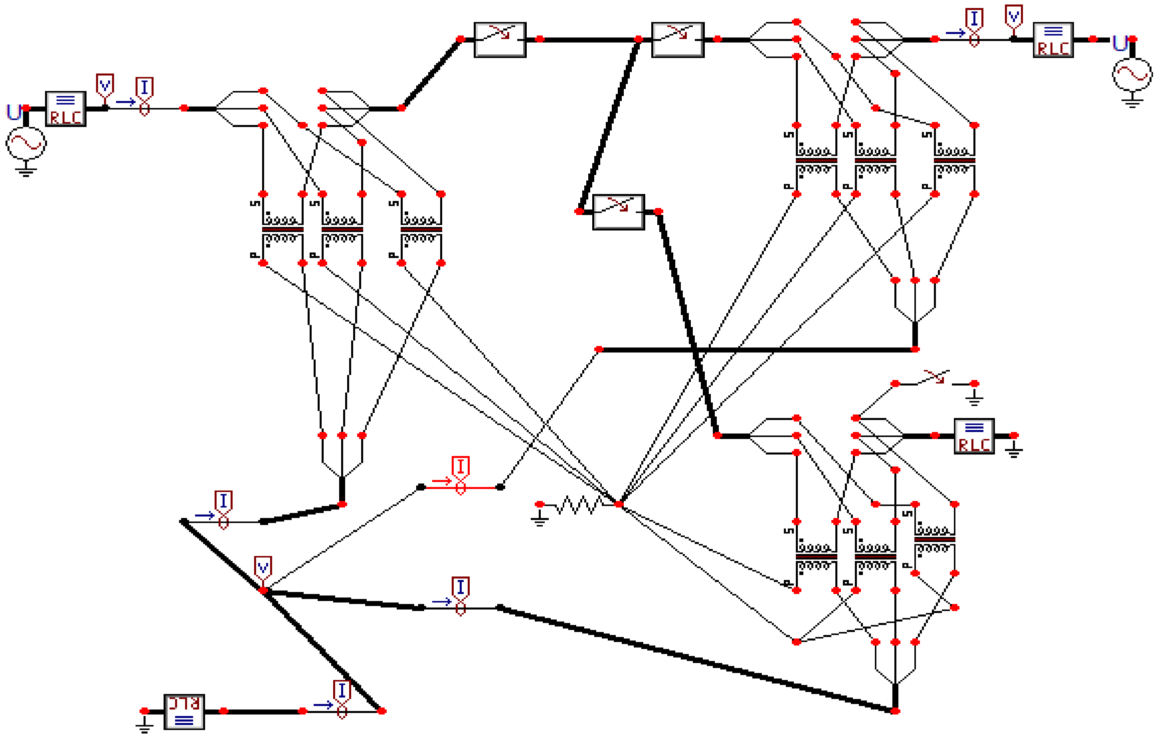

Fig. 5. 16. Representation of the power system in the case of an external fault

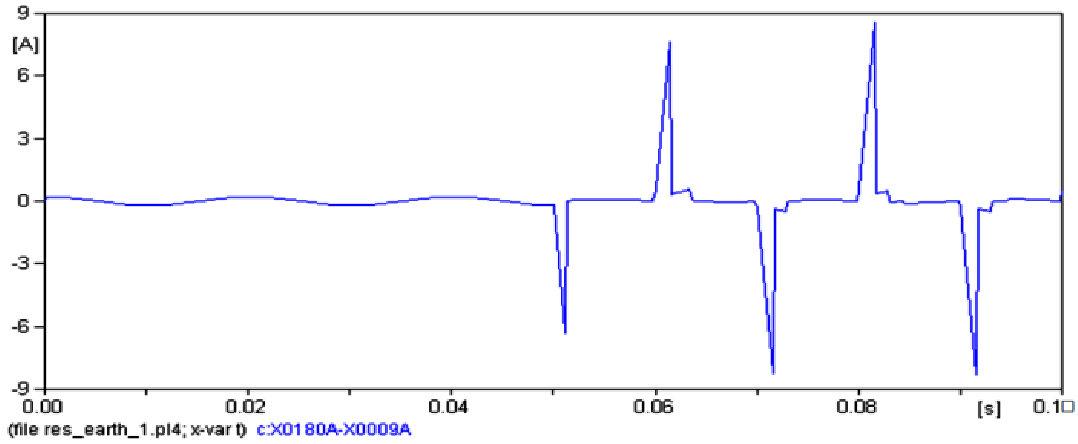

Fig. 5. 17. The differential current, passing in the phase (A)

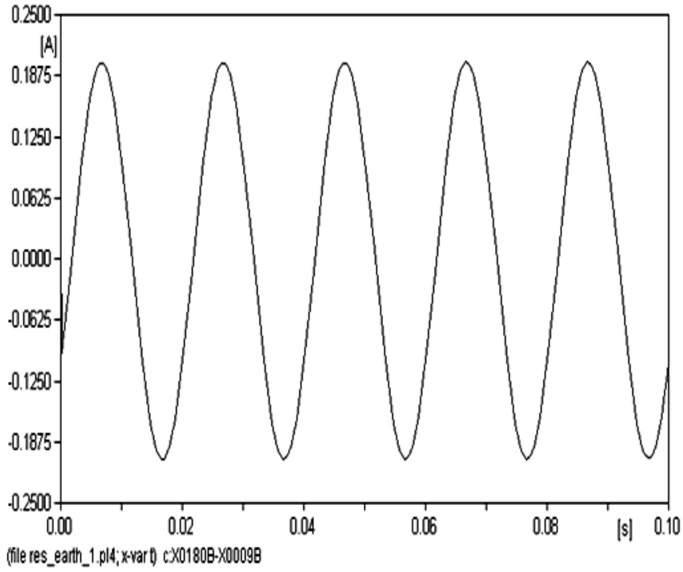

Fig. 5. 18. The differential current, passing in the phase (B)

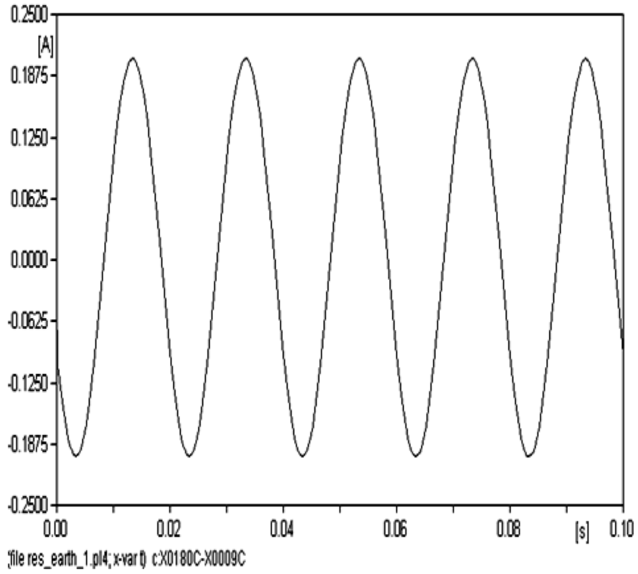

Fig. 5. 19. The differential current, passing in the phase (C)

We notice from the previous figures, that in the condition of a fault at the phase A of value 18 kA and outside of the protection zone, leads to saturation of the current transformers on this phase and thus passing a current of value 8.5A in the differential protection relay of the phase A which is greater than the operational value of the differential relay, Which leads to the work of this protection wrongly.

5.3.2.3. A Fault Condition Outside the Protection Zone with The Use of The MOV Element

Fig. 5.21, shows the representation of the power system using the MOV element in the EMTP-ATP program, while Fig. 5.22, Fig. 5.23, and Fig. 5.24, show the phase currents in the relay.

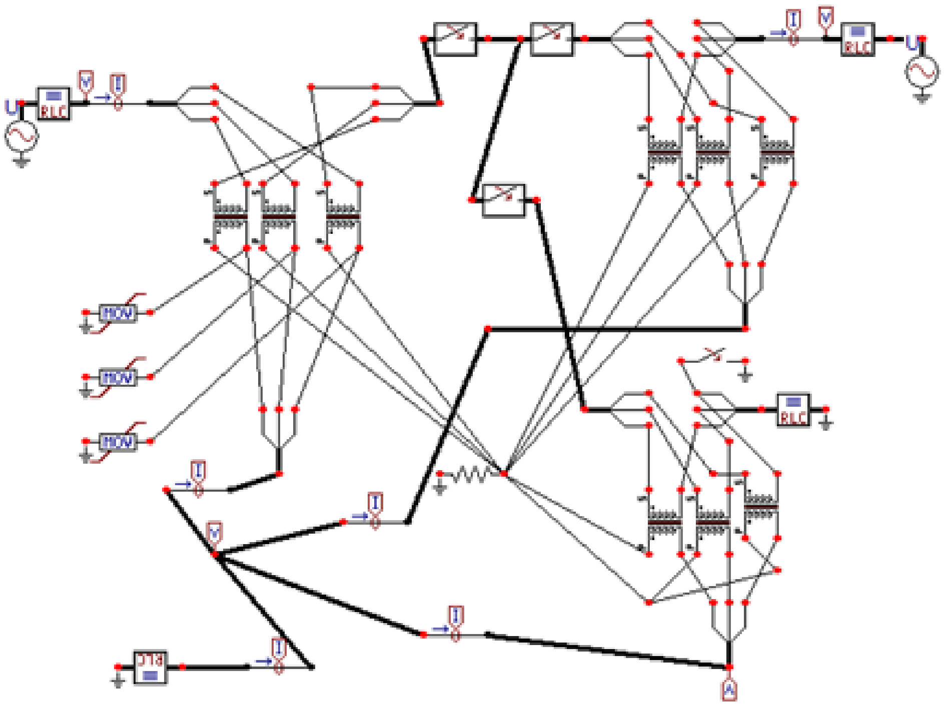

Fig. 5. 20. Representation of the power system in the case of an external fault

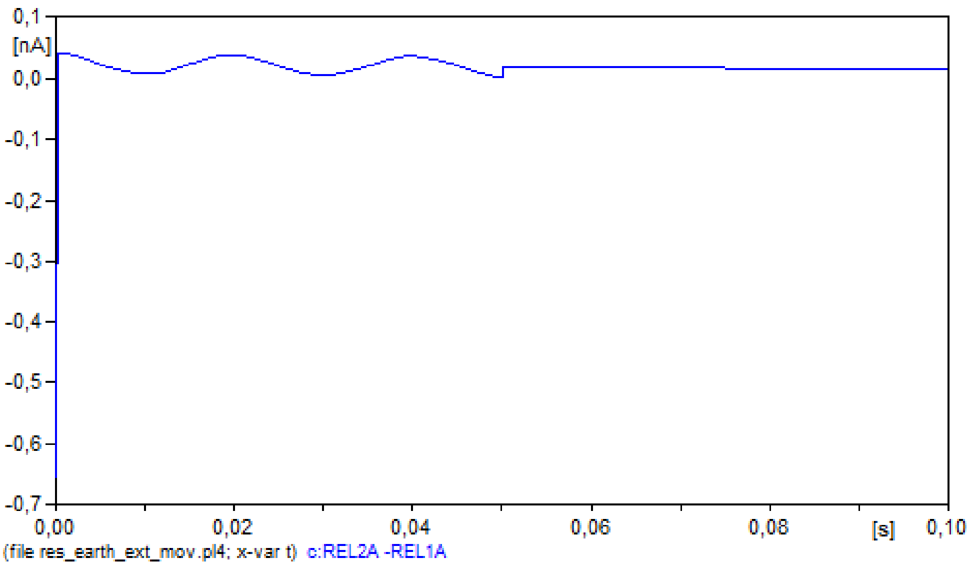

Fig. 5. 21. The differential current, passing in the phase (A)

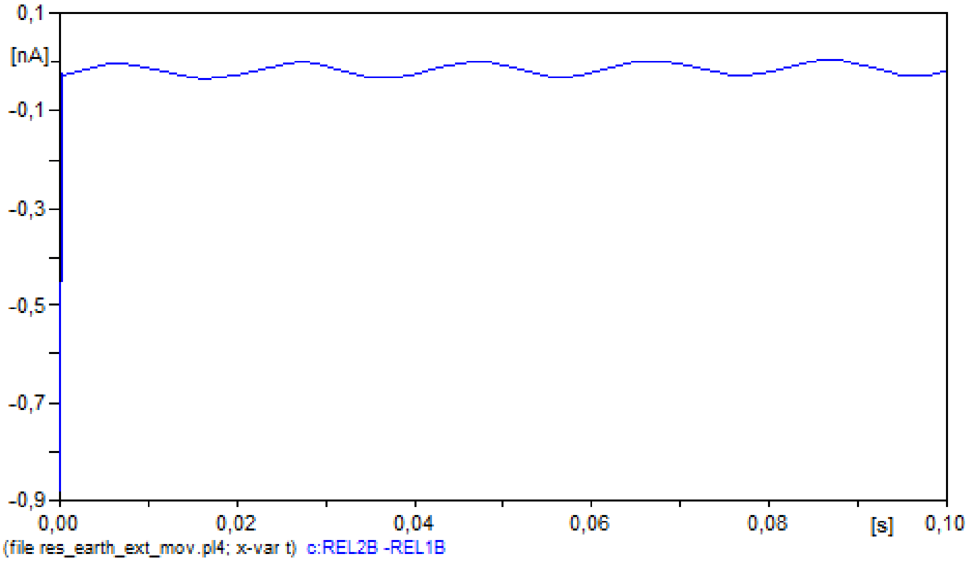

Fig. 5. 22. The differential current, passing in the phase (B)

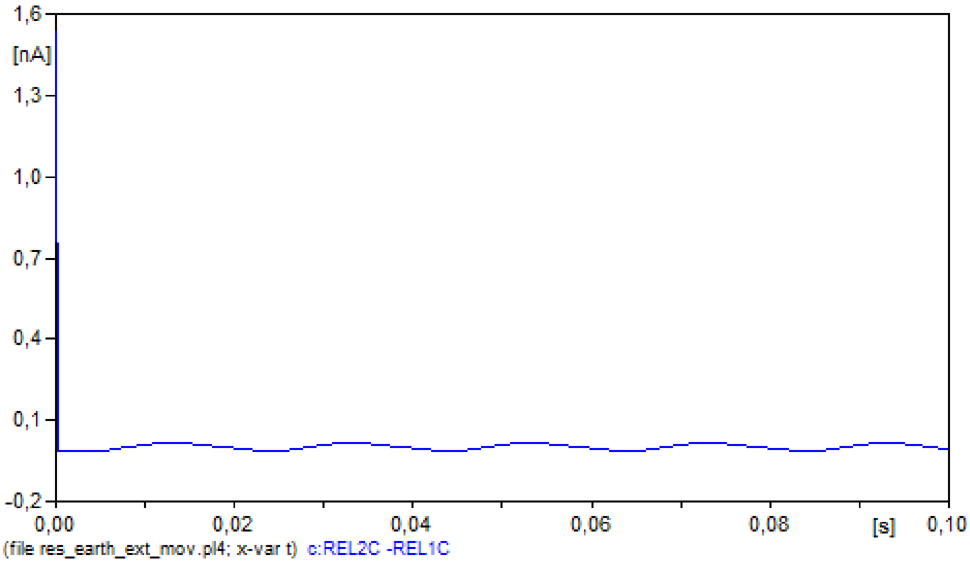

Fig. 5. 23. The differential current, passing in the phase (C)

Fig. 5.22, shows that by using the MOV element, the correction of the performance of current transformers on the affected phase is done, thus avoiding the effect of saturation and thus keeping the protection device stable.

5.4. Conclusion

- The existence harmonics in the grid must be analyzed accurately to find the best solutions that avoid these effects on the performance of distance relays and over current relays.
- The magnetization curve of the power transformer must be selected well to take into account technical and economic considerations.

- Differential protection performance can be improved, when a fault occurs outside the protection zone associated with saturation in the current transformer, by using the non-linear element (MOV).

- This practical solution was tested and validated using EMTP-ATP.

-The suggested solution is simple and can be adopted for all generations of differential relays and also for the future generations of relays.

CHAPTER 6. ADVANCED ALGORITHM FOR DETECTING AND CORRECTING SECONDARY CURRENTS OF THE CURRENT RANSFORMER

6.1. INTRODUCTION

Protection systems require reproduction of the primary current on the secondary side of the current transformer exactly according to the ratio of the transformer.

We found that the saturation of the current transformer leads to the wrong operation of the differential protection in case of faults outside the protection zone. In addition, the saturation of the current transformer leads to the failure of overcurrent relays. Saturation also leads to errors in the impedance calculation of the distance protection relays [161].

The saturation of current transformers may disturb the work of protection systems if an appropriate detection and correction algorithm does not apply. This requires the development of detection and correction algorithms that can be programmed into modern digital protection devices to avoid the effect of saturation.

6.2. METHOD DESCRIPTION

The algorithm is carried out according to the following steps:

- determination saturation’s start points, as shown in figure 6.1.
- determination saturation’s end points, figure 6.1.
- calculation the estimated values of samples in the saturated section based on the unsaturated section of the secondary current waveform.
- Calculation of the fundamental and dc components based on the unsaturated section of the secondary current waveform.
- primary current reconstruction.

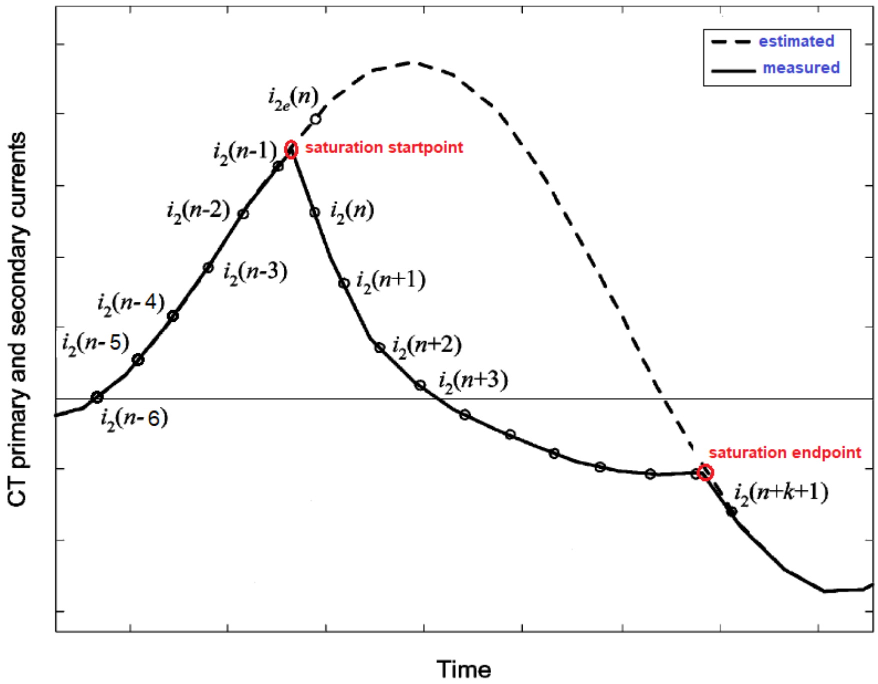

Fig. 6. 1. Real measured values and estimated values s of CT’ secondary currents

6.3. FORMATION A MATHEMATICAL MODEL of THE SINUSOIDAL WAVE ACCORDING to NEWTON'S BACKWARD DIFFERENCE INTERPOLATION

The value of the first derivative of two consecutive samples can be considered approximately of equal value [164]:

$$\frac{\nabla\, i(n)}{T_S} \approx \frac{\nabla\, i(n-1)}{T_S} \qquad (6.1)$$

$$\frac{[i(n) - i(n-1)]}{T_s} \approx \frac{[i(n-1) - i(n-2)]}{T_s}$$

T_S: sampling period.

$$i(n) \approx 2 * i(n-1) - i(n-2) \qquad (6.2)$$

This is the estimated value of the secondary current sample based on two consecutive previous samples (the first derivative method).

- **The second derivative method (second difference function)**:

The value of the second derivative of two consecutive samples can be considered approximately of equal value [164]:

$$\frac{\nabla^2 i(n)}{T_S} = \frac{\nabla^2 i(n-1)}{T_S} \qquad (6.3)$$

$$i(n) = 3 * i(n-1) - 3 * i(n-2) + i(n-3) \qquad (6.4)$$

- **The third derivative method (third difference function):**

The value of the third derivative of two consecutive samples can be considered approximately of equal value [164]:

$$\frac{\nabla^3\, i(n)}{T_S} = \frac{\nabla^3\, i(n-1)}{T_S} \qquad (6.5)$$

$$i(n) \approx 4 * i(n-1) - 6 * i(n-2) + 4 * i(n-3) - i(n-4) \qquad (6.6)$$

- **the fourth derivative method (fourth difference function)**:

The value of the fourth derivative of two consecutive samples can be considered approximately of equal value [164]:

$$\frac{\nabla^4\, i(n)}{T_S} = \frac{\nabla^4\, i(n-1)}{T_S} \qquad (6.7)$$

$$i(n) = 5 * i(n-1) - 10 * i(n-2) + 10 * i(n-3) - 5 * i(n-4) + i(n-5) \qquad (6.8)$$

- **The fifth derivative method:**

The value of the fourth derivative of two consecutive samples can be considered approximately of equal value [164]:

$$\frac{\nabla^5\, i(n)}{T_S} = \frac{\nabla^5\, i(n-1)}{T_S} \qquad (6.9)$$

$$i(n) = 6 * i(n-1) - 15 * i(n-2) + 20 * i(n-3) - 15 * i(n-4) + 6 * i(n-5) - i(n-6) \qquad (6.10)$$

6.4. ERROR OF THE ESTIMATION METHOD

the estimation error of the used method is calculated by the following formula [172]:

$$erro = \frac{|\text{estimated magnitude} - \text{actual magnitude}|}{\text{actual magnitude}} \times 100 \qquad (6.11)$$

let us suppose that the sampling period is equal to 1ms (20 samples per cycle), and the primary current is given by the equation:

$$i_1 = e^{-25*t} + cos(\omega t) \qquad (6.12)$$

Figure 7.2 shows the primary current and the estimated current by using the first derivative and the error resulting from the estimation method.

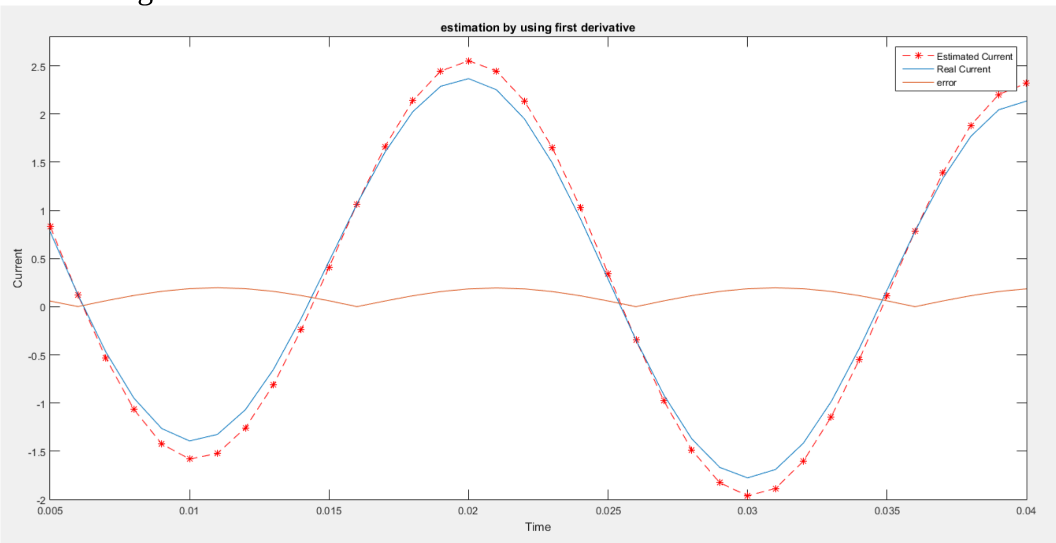

Fig. 6. 2. Estimation by using 1st derivative

Figure 6.3 shows the primary current and the estimated current by using the second derivative and the error resulting from the estimation method.

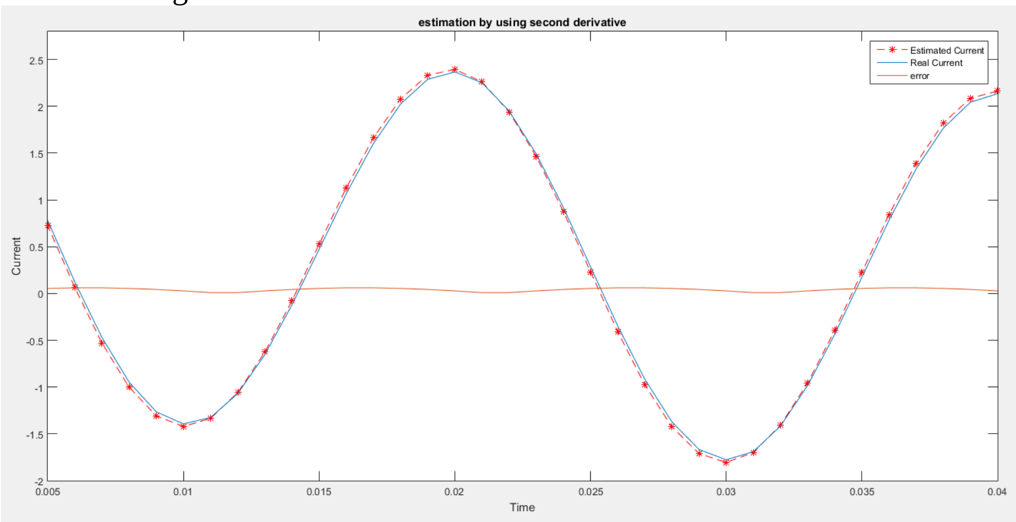

Fig. 6. 3. Estimation by using 2st derivative

Figure 6.4 shows the primary current and the estimated current by using the third derivative and the error resulting from the estimation method.

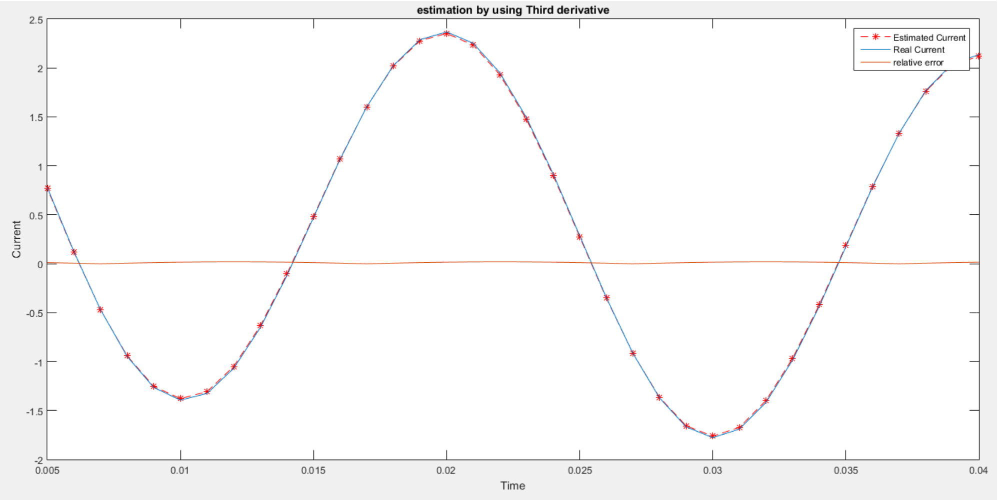

Fig. 6. 4. Estimation by using 3[st] derivative

Figure 6.5 shows the primary current and the estimated current by using the fourth derivative and the error resulting from the estimation method.

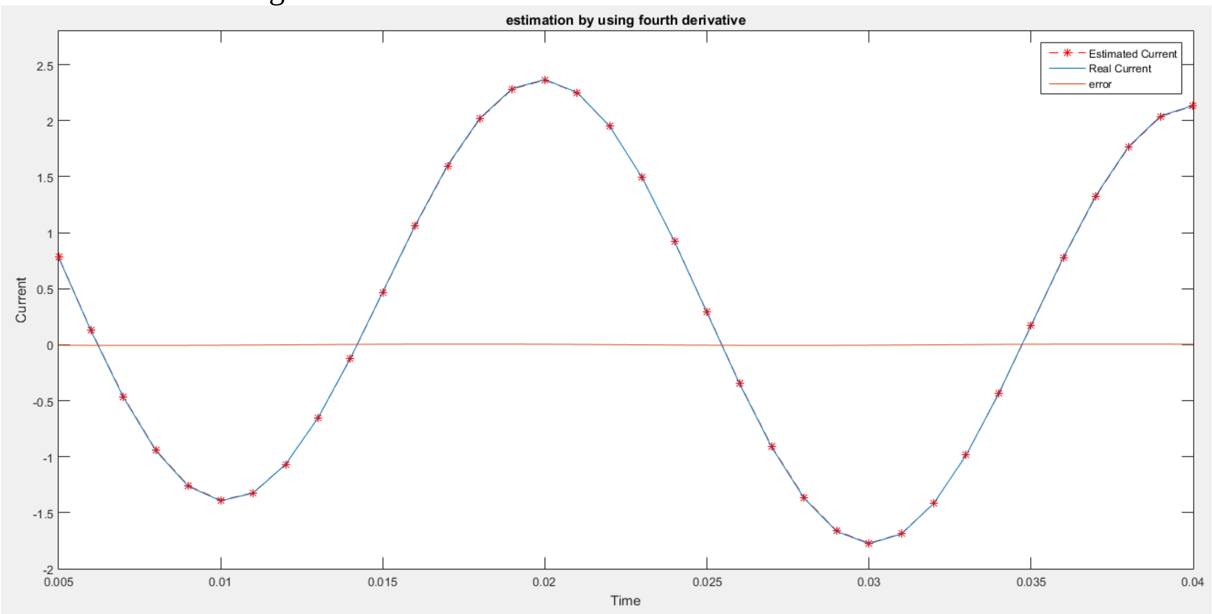

Fig. 6. 5. Estimation by using 4[st] derivative

The estimated current using the fifth derivative is as shown in figure 6.6.

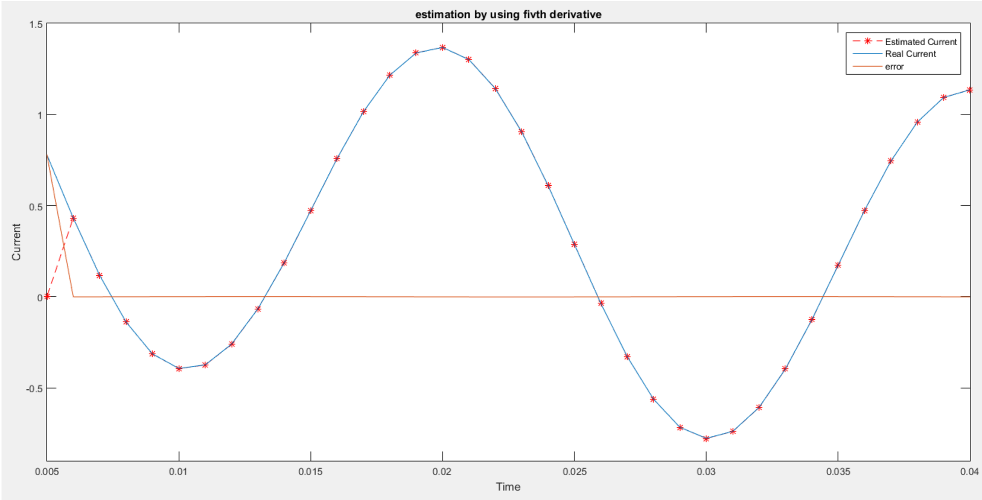

Fig. 6. 6. Estimation by using 5st derivative

By comparing the accuracy of the previous estimation methods, the higher the order of estimation, the greater the precision.

6.5. DETECTION OF CT SATURATION START

The saturation is detected when the absolute value of the the estimated value of the secondary current sample based on the first or second or three or fourth derivative method are larger than the threshold value [173], [174], [172], [175], [176], [163].

The Feature of $\nabla^4\, i(n)$

The criteria for detecting CT saturation is given by the following equation

$$|\nabla^4\, i(n)| > Th \qquad (6.13)$$

The proposed threshold for first derivative is given by the following equation

$$T_h = k\sqrt{2I_{fmax}\left[2\sin\left(\frac{\pi}{N}\right)\right]^4} \qquad (6.14)$$

6.6. DETERMINATION of CT SATURATION END

supposing that the saturation's start happened midway between the samples (n-1) and (n) according to figure 6.1, If equation (6.15) is satisfied, the first sample of the new unsaturated part is n + k + 1 [171]:

$$sign\left[\frac{i_2(n-1)}{8} + \frac{i_{2e}(n)}{8} + \frac{3 * i_2(n)}{4} + i_2(n+1) + \ldots.. + i_2(n+k)\right] \neq sign\left[\frac{i_2(n-1)}{8} + \frac{i_{2e}(n)}{8} + \frac{3 * i_2(n)}{4} + i_2(n+1) + \ldots.. + i_2(n+k) + i_2(n+k+1)\right] \qquad (6.15)$$

6.7. RECONSTRUCTION OF THE CORRECTED CURRENT (PRIMARY CURRENT)

The general formula of the corrected current is given by the following equation [177], [152], [178]:

$$i_C(n+h) = (I_0 * e^{-2*\tau}) * e^{-(h+2)*\tau} - I_1 * cos[\gamma + (h+2) * \varepsilon] \qquad (6.16)$$

This current is calculated for the changing value h between zero (for the first sample of the saturated part) and k (the last sample of the saturated part).

Where:
I_0: amplitude of DC component
τ: DC time constant
I_1: amplitude of fundamental frequency
The amplitude of the fundemental frequency compononet is given by formula

$$I_1 = \sqrt{\left(\frac{i_p(n-2) - i_p(n-3)}{2 * sin\left(\frac{\varepsilon}{2}\right)}\right)^2 + \left(\frac{i_p(n-2) + i_p(n-3)}{2 * cos\left(\frac{\varepsilon}{2}\right)}\right)^2} \quad (6.17)$$

6.8. VERIFICATION OF THE PROPOSED ALGORITHM

By applying the proposed algorithm on a fault wave downloaded from EMTP-ATP program, we obtained the corrected current in figure 6.7 which represents the output of Matlab program.

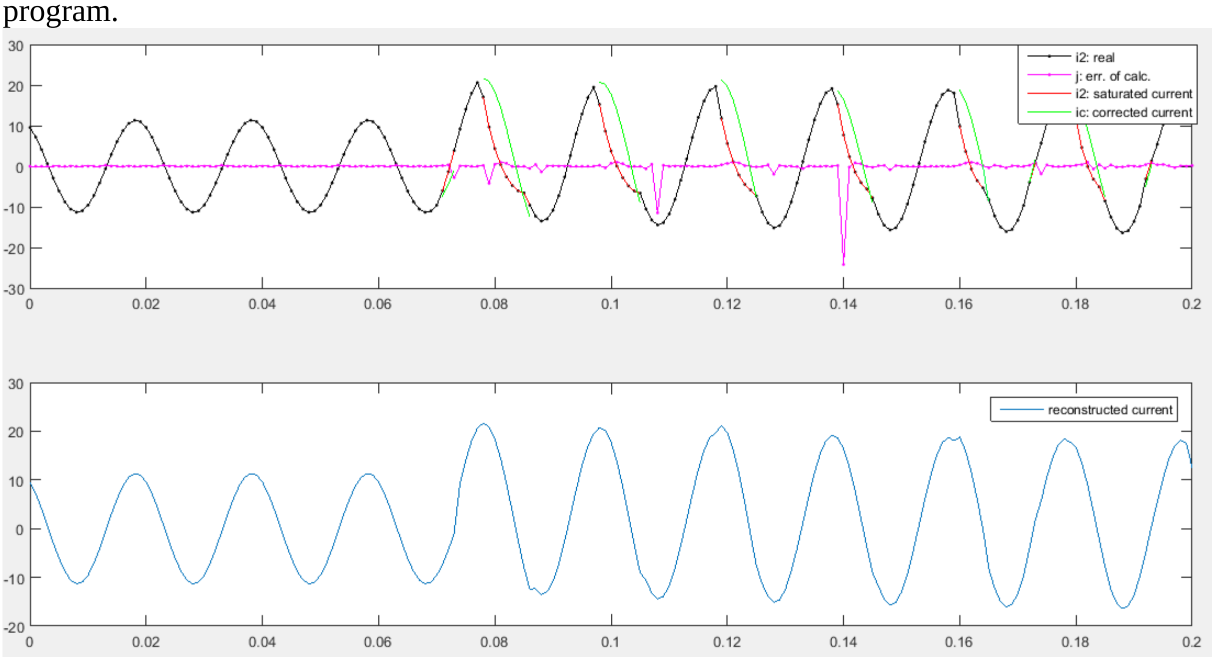

Fig. 6. 7. Corrected Current by using the proposed algorithm

6.9. EFFECTIVENESS OF THE PROPOSED ALGORITHM

Figures 6.9 and 6.10 show the effectiveness of the algorithm developed in correcting the distortion of a secondary current during the saturation period. From MATLAB's output, we have obtained excellent results by applying the proposed algorithm which we have created and written m-file using MATLAB. The algorithm is successful and effective in correcting the secondary wave distortion of the current transformer due to its magnetic saturation.
This method depends on the fixed value of the fourth derivative and gives good accuracy by using five samples of the unsaturated part. after testing of this method in correcting many recorded fault waves, we have discovered that This method has a good performance of different protection type.

CHAPTER 7. CONCLUCTIONS

7. 1. ORIGINAL CONTRIBUTIONS

Poor power quality can affect the performance of digital relays in stable and transient conditions. This can cause damage to some elements of the power system and sometimes lead to general blackout.

Measurement algorithms can be considered as a critical element in the performance of digital protection relays. Their main task is to estimate the fundamental frequency component of the input signals (current and voltage).

The speed and accuracy of the measurement algorithms have an important role in achieving the protection relays their functions.

The digital Fourier filter is considered as the most widely used among measurement algorithms in the field of protection applications.

In faults conditions, its performance changes according to the presence of unwanted signals in the input signal. These unwanted signals mix with the fundamental frequency component to give distorted input signals.

This research work analysis the impact of power quality problems on digital relays' performance in networks of different voltage levels; low, medium and high.

A well-known phenomenon that has dominated the efforts of many previous, current and future research, namely the saturation of current transformers and their impact on the performance of protection relays.

In this research, the effect of secondary waveforms saturation of the current transformer was studied on different types of relays. For this reason, an algorithm was developed to detect and correct the secondary current of the current transformer and thus correct the performance of the relays that receive the input signals from these current transformers.

the main contributions for the thesis are summarized below.

Chapter 1 presents a simple and clear presentation of power quality concept, as well as that it lists the various disturbances that occur in electrical networks and what are the causes of their occurrence and what their effects on the elements of the power system.

The theoretical side of the power quality concept was linked to the practical side by executing a set of measurements at Baragan Photovoltaic farm by using Fluke Test Set, these measurements were compared with the international standards for deciding Whether these values within the acceptable limits or no.

These measurements, which may last up to a few weeks or more, show the importance of the display, monitoring and recording systems of the power system, especially in detection of many electrical disturbances, in addition to find appropriate solutions to these problems.

Chapter 2 provides a detailed study of both hardware and software of digital relays. The following is a summary of the important study provided by this chapter, which can be used in future research:

1- Reconstruction of the original signal correctly depends on the sampling rate, so that the selection of sampling rate fs is very important for the correct decision of digital relays. the effect of sampling rate (fs) on the reconstructed signal is tested by using MATLAB. simulation results show that whenever the sampling rate is higher, the accuracy will be better, but not very high to avoid the high burden for the digital processing.
2- Many of the components of the relay should be carefully studied during the design stages, the components that have been highlighted in this chapter are anti-aliasing filter, sample-hold circuit, multiplexer and analog-to-digital converter.

3- The performance of many digital filters has investigated in this chapter, this verification was based on a new methodology which is the use of various input signals representing the various disturbances types from multiple sources. Some of these signals were taken from the output of the modeling programs as EMTP-ATP program and others were downloaded from fault recorders of the power plant of Banias Refinery. The Fourier filter full-cycle had proved a good efficient in dealing with different cases compared with the other filters but it was found that there is a need for additional algorithms to improve the total performance of the digital relay.

Chapter 3 represents a part of the Syrian network. This system consists from a set of electrical loads of various voltages for a Romanian oil refinery in the Syrian Banias city and these loads are feed through four generators operating in parallel and connected through three Bus Bars systems and tow feeders coming from the Syrian grid.

This chapter presents power flow and short circuit calculations for all components of this network for different operation scenarios. This study offers a new vision of the importance of the operational maneuvers and their impact on minimum and maximum values of short circuit currents and thus safety of equipment and personnel.

Chapter 4 shows the need to test the protection relays in normal fault cases to verify their reliability and readiness to work correctly in the abnormal fault cases.

abnormal fault cases include cases in which the current and voltage wave contain high ratios of harmonics and severe distortions.

Chapter 5 presents a set of practical and theoretical results that cannot be overridden and can be used to design any power system and its protection system, these results can be summarized as follows:

- all sources of current and voltage harmonics must be taken in account during designing and investment any power system.
- The magnetization curve of the iron core of the power transformer must be carefully selected, so that the presence of harmonics in the network does not effect on its behavior seriously and consequently reflects this effect on the protective relays which may send signal trip to CB to isolate this transformer from the grid, although there is no real fault. The disconnecting of this power transformer may be having serious reflections on the overall power system.

  This research has presented a clear methodology for selecting the magnetizing curve of power transformer accurately that takes into account the designing and economic considerations.
- this chapter has proposed a practical solution to avoid the act of differential protection outside the protected zone under the effect of current transformer saturation.

  This practical proposal leads to many future researches that study the possibility of expanding the use of nonlinear elements in the field of protection applications.
- The research has proposed an advanced algorithm for detecting and correcting the distortion of secondary currents of the current transformers due to the magnetic saturation of the current transformer. This algorithm characterizes by better accuracy compared to many of the algorithms used for the same purpose.

  The performance of this algorithm was verified by applying real current waves downloaded from fault recorders and waves taken from the EMTP-ATP program.

7.2. FUTURE WORKS

- ✓ the effect of poor power quality on digital relays which not investigated in this thesis such as flicker and Interruption will be done in the future works.
- ✓ To benefit from the research results, especially the use of the non-linear component MOV to improve the performance of the differential protection relays in the electrical system, I will try to use these results in the future researches to develop the usage of this element in other relays types.
- ✓ I want to find the various possibilities to limit the effect of the propagation of disturbances through the system and from one voltage level to another on the performance of protection relays.
- ✓ One of the future Work will be on developing the algorithm proposed in this thesis to become a more integrated and multi-functional algorithm, for example, with an additional algorithm to block harmonics that may affect the performance of the digital relay.

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