Evaluation of the Effect of Harmonic and Interharmonic Distortions on Inverse Time Protective Relays

Gustavo D. M. Ferreira, João Ricardo M. S. de Souza, Alberto De Conti

Abstract—**Short-circuit conditions can significantly alter fault currents due to harmonic and interharmonic distortions from various sources, such as electric arcs in high-impedance faults. Additionally, the growing prevalence of nonlinear loads and inverter-based resources (IBRs) has intensified these distortions, potentially compromising the performance and reliability of protective relays. This paper evaluates the impact of such distortions in the operation of time-overcurrent relays considering the use of two different quantities as reference, namely the phasor amplitude and the root-mean-square (RMS) value of the monitored quantity. To perform this, simulations of digital inverse time-overcurrent relay were performed in MATLAB varying the distortion of the input current and evaluating the operation time for each situation. Tests in an actual protective relay were also performed, reproducing the same situation as the simulations. The results show that harmonic and interharmonic distortions can have a significant influence on the actuation time of the relay, which could, in turn, lead to selectivity problems, specially when equipments that use different quantities are used.**

Keywords—**Harmonic distortion; interharmonic distortion; inverse time overcurrent protection; selectivity.**

I. Introduction

During short-circuits, fault currents can be affected by many sources of distortions, such as the electric arc during high impedance faults [1]. Moreover, the ever growing deployment of nonlinear loads in electrical grids and the continuing expansion of renewable energy sources that make use power electronics converters, known as Inverter Based Resources (IBR), have been contributing to a rise in the distortion levels of current and voltage waveforms in electrical power systems Such distortions can be expressed as a summation of sinusoidal components that are called harmonics, when their frequencies are integer multiples of the fundamental frequency, and interhamonics when their frequencies are located between harmonic components [2]. A fundamental requirement for protective devices is that they must perform optimally under all conditions keeping the security and reliability. Since harmonic and interharmonic distortions can modify current waveforms significantly, it is important to evaluate to what extent they can affect the selectivity, sensitivity, and response speed of protection systems.

The literature extensively explores the effects of harmonic injection, both in general terms and specifically in the context of power system protection [3]. However, practical investigations involving actual relays remain limited, and there is a significant research gap regarding the differences between the use of the RMS and phasor current measurements in Intelligent Electronic Devices (IEDs), as well as the effects of interharmonics. In this context, the literature review presented in [3] lists some studies that evaluated the impact of harmonic distortions in protective relays that have been conducted since the decade of 1980. In 1985, Horton *et al.* [4] had already notably demonstrated that harmonic content in current and voltage waveforms has a significant effect on the operating point of relays. Furthermore, they developed an analytical model that can predict the operating points of relays based on the degree of harmonic distortion.

A study conducted by Fuller *et al.* [5] explored the effects of harmonics on various types of protective relays. Their research revealed that both static (solid-state) and electromechanical overcurrent relays were significantly affected by the presence of harmonic currents, particularly in terms of their pick-up values. Furthermore, the study examined the influence of non-sinusoidal voltages and currents on underfrequency and overcurrent relays. The results indicated that harmonic voltage and current amplitudes led to a notable degradation in the performance of underfrequency relays and caused time-delay issues in the operation of overcurrent relays. The instantaneous operating characteristics of overcurrent relays were, however, found to remain largely unaffected. Concerning solid-state relays, Girgis *et al.* [6] conducted a study on four different types of static relays, revealing that voltage distortions can significantly impact their performance. The findings highlight that such distortions may lead to delayed activation times or, in extreme cases, result in complete relay failure. Through computer simulations of a three-phase harmonic source, Rob *et al.* [7] proposed a simulation approach to examine harmonic effects. Their method was applied to assess the functionality of a ground directional overcurrent relay, focusing on its behavior in environments with significant waveform distortion. The experiments revealed that the performance of the relay becomes inconsistent, therefore losing reliability, when the current distortion reaches a total harmonic distortion level

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equal to or higher than 40%. Later, Donouher *et al.* [8] carried out experiments on an induction disk relay, finding that harmonics can significantly modify the relay's operating speed.

A study presented by Medina and Martinez-Cardenas [9] with digital relays indicated that the impact of non-sinusoidal waveforms on the operation of such devices is significantly reduced, and estimated it to be lower than 20%. Nevertheless, although harmonic distortion effects are relatively reduced in modern digital relays when compared to electromechanical and static relays, they are, notwithstanding, not negligible. In [10], Wannous and Toman explored the impact of harmonic distortion on digital protection relays, focusing on identifying the causes of false trips or failures to trip using a mathematical model in MATLAB Simulink. The study evaluated relay algorithms under abnormal conditions by testing the influence of high-value harmonics on fault detection and protection zones, investigating the effects of individual and combined harmonics, fault locations within distance protection zones, and the power factor on fault identification. Furthermore, the authors studied the relationship between tripping time and total harmonic distortion (THD) levels. The study highlights the limitations of digital relays, which primarily detect changes in fundamental current or voltage magnitudes, when operating with current phasors. It was concluded that overcurrent relays are less affected by low harmonic distortion, while distance relays may face reliability issues regarding fault location, particularly for the case of faults located near the limit of the zone of protection. In [11], Zamora *et al.* evaluated the effects of frequency variation and harmonic distortion in simulations and in a digital overcurrent relay. The study, which was based on the injection of different harmonic currents, compared phasor and RMS measurements. It was found that the error produced under different current THD levels, in the case of RMS calculation, increases with the THD. Interharmonics were, however, not considered in the article.

Although the effects of harmonics in power system protection have been investigated in detail in the past, the available literature is rather scarce with regard to the effects of interharmonics on the operation of protective relays. This is in clear contrast with the emergence of distributed generation, which increases the relevance of interharmonic effects and poses challenges to protection systems. This is because commonly used energy sources, such as solar and wind power, are connected to the grid through power converters, which, particularly during short-circuit events, lead to the injection of interharmonic components into the grid [12]. In [13], Wang and Bollen investigated the impact of interharmonics on the performance of protective relays. The study involved power quality measurements conducted in a controlled laboratory environment, revealing the presence of 182 Hz and 282 Hz components in both voltage and current signals. Utilizing a digital model of an overcurrent relay, the authors investigated the effects of these interharmonics on the relay's filtering mechanisms and operational response. The findings indicate that interharmonics can alter the relay's setting thresholds and sensitivity, potentially undermining its security and reliability during prolonged disturbances. However, the study did not include experiments with an actual relay.

This article aims to investigate the influence of harmonic and interharmonic distortion on the operation of digital time overcurrent relays, considering the differences between phasor and RMS current calculations and the processing of these components by the Fourier and RMS filters of an actual digital relay. To do this, this study presents a comprehensive study that integrates practical experimentation and computational simulation to assess the performance of an inverse time overcurrent function based on an actual feeder protective relay under the influence of harmonic and interharmonic distortion. In the experiments performed in the laboratory, the relay's response to distortions with varying frequencies and amplitudes was meticulously evaluated in a controlled laboratory setting to ensure precision and reproducibility. Meanwhile, identical scenarios were modeled and simulated using MATLAB Simulink, allowing for a detailed comparison between empirical data and theoretical predictions. This dual approach aims to uncover nuanced insights into the relay's sensitivity, accuracy, and overall effectiveness in detecting and addressing harmonic and interharmonic distortions.

The rest of this paper is organized as follows. Section II presents the basic concepts and formulations used along the study. Section III presents the test structure and the simulation used in the analysis. Section IV presents and discusses the results obtained. Finally, section V presents the conclusions.

II. Inverse Time Overcurrent Protection Function

Despite of its simplicity, the inverse time overcurrent principle is one of the most used in protection systems, being the base of the functioning of fuses, thermomagnetic circuit breakers, automatic reclosers and time-overcurrent (TOC) relay functions used to protect many equipments such as feeders, transformers, capacitor banks, reactors, and harmonic filters. The widespread use of this technique is motivated by two main reasons. The first one is the fact that, in many situations, the selectivity of protection systems composed by inverse time overcurrent devices could be easily achieved by the coordination of their time-current curves. The second reason is the possibility of ensuring that the thermal and dynamic supportability limit of the protected equipment is not exceeded, since these limits are usually expressed as inverse time curves as well.

Basically, a TOC function operates by monitoring the current in a system and triggering a response when it exceeds a predefined threshold. Its key feature is the time delay, which is inversely proportional to the magnitude of the current. This means that smaller overcurrents result in longer delays, whereas larger currents result in faster tripping actions. This functionality ensures a coordinated response to faults, allowing downstream devices to operate first and isolate the issue locally, thereby maintaining stability of the system. Therefore, TOC relays are widely used for coordination in radial systems, ensuring efficient fault clearance while minimizing unnecessary disruptions.

Time-overcurrent relays use varied inverse curve characteristics, in accord with the necessities of the

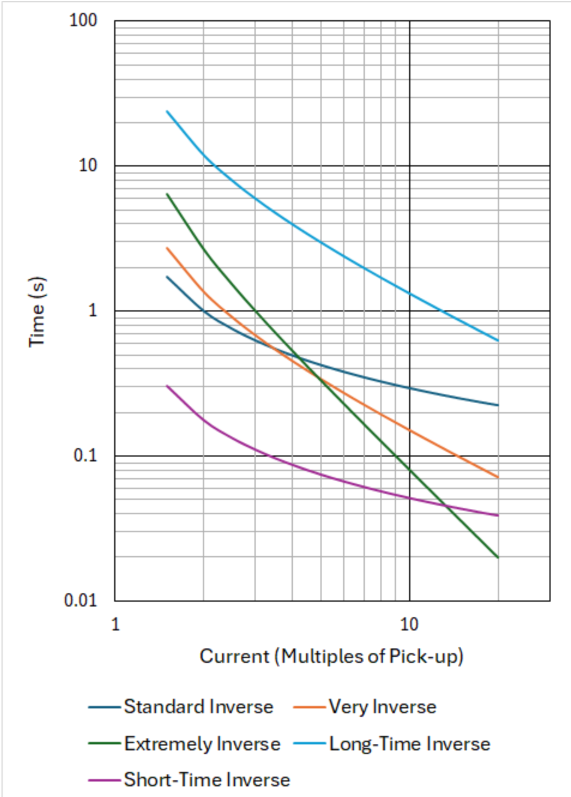

Fig. 1. Example of overcurrent curves - IEC standard curves considering a time dial set in 0.1.

protection system. These time-current curves define the relationship between the magnitude of the overcurrent and the operating time of the relay. The most common curves are the standard inverse (SI), very inverse (VI) and extremely inverse (EI). The SI curve allows for a slower curve, making it specially suitable for moderate time relays, with stable faults. In turn, the VI curve has faster tripping characteristics, making it suitable for high-current faults and longer delays for lower overcurrents, such as feeders with high fault levels. Finally, the EI curve is designed for systems where high fault currents demand rapid isolation, such as transformers and some motors. As an example, Fig. 1 shows IEC standard 60255-151 [14] overcurrent curves considering a time dial set in 0.1.

Many IEDs offer the option to calculate either the RMS current or the phasor current and use both in their TOC functions. It is therefore expected that the operating time will vary depending on the chosen calculation method in the presence of distortions. The phasor current calculation tends to attenuate most of the harmonic content, as it relies on a full-cycle Fourier filter within the IED. This filter suppresses components at frequencies other than the fundamental, thereby retaining only the fundamental component (in this case, 60 Hz) in the phasor representation. Conversely, the RMS calculation, described in (1), where $i(t)$ is the instantaneous current value and T is the period of the fundamental component, accounts for all harmonic components that characterize the current waveform. Hence, it is expected to be more sensitive to the presence of harmonics.

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i(t)^2\,dt} \tag{1}$$

The RMS value calculated with (1) encompasses harmonics, interharmonics, DC components, and other distortions, along with the fundamental frequency values. The true RMS value reflects the thermal effects of the current and is widely used for monitoring and thermal-related protection functions. This value, often referred to as the "effective value" of the current, is particularly critical in systems where the dissipated power needs to be calculated, as it directly represents the thermal impact and energy consumption. In fact, as highlighted by Zamora *et al.* [11], the value of the RMS current is expected to increase with the THD. This is apparent if one calculates (1) in steady-state conditions, in which case

$$I_{RMS} = \sqrt{\sum_{i=0}^{n} I_i^2} \tag{2}$$

where I_i is the magnitude of the i-th harmonic component of $i(t)$.

III. Test Description

A. Experiment

To evaluate the effect of harmonic and interharmonic distortions on an actual protective relay, an experiment was conducted in the laboratory using a Multilin 850 feeder digital relay and a Euro SMS Quasar protection relay test system as shown in Fig. 2. A sinusoidal current of 5 A, devoid of any significant distortions (i.e., consisting solely of the fundamental 60 Hz component), was injected in the relay. Both RMS and Phasor calculation methods were utilized to process the current, and the results were systematically recorded. The time-overcurrent protection function (ANSI 51) was configured using a pick-up current of 1 A and three different curves, namely the normally inverse, the very inverse, and the extremely inverse IEC standard curves shown in Fig. 1. The relay operating times were documented for each configuration.

The experiment was repeated by injecting a composite current into the relay, comprising the 60 Hz fundamental component and an additional 70 Hz component with a magnitude of 1 A. The procedure was further extended by injecting currents that combined the 60 Hz fundamental component with harmonic components incrementally increased by 10 Hz (20 Hz, 30 Hz, 40 Hz etc.), up to 240 Hz (the fifth harmonic). Each harmonic component had a fixed magnitude of 1 A. The relay's operating times for both RMS and phasor measurements were carefully recorded for each test case.

To examine the relay's response to higher distortion magnitudes, the tests were repeated with harmonic components increased to 2 A, while maintaining the same procedure for measurement and documentation. This systematic approach ensured a comprehensive evaluation of the relay's performance

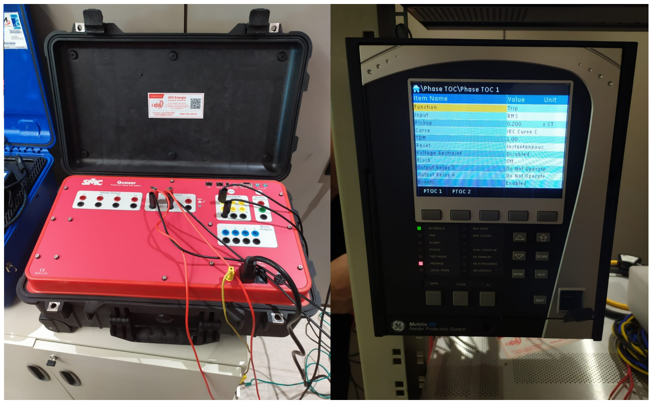

Fig. 2. Experimental setup consisting of a secondary injection test set and a feeder protection relay

under varying harmonic conditions. Therefore, since the fundamental component magnitude is 5 A, the tests with 1 A distortion present THD of 20%, while the tests with 2 A distortion present a THD of 40%. According to Bhandia *et al.* [1], while the distortion measured in a network operating under normal conditions is approximately 2% for a pure sine wave, this level can surpass 30% under fault conditions. Therefore, in the experiment thus conducted, tests were made with THD values ranging from 0 to 40%. Such values represent, respectively, the network operating without distortion, and during the most severe distortion condition during a fault, as well as at intermediate levels.

B. Simulation

The same tests were also performed in a time overcurrent relay model implemented on Matlab according to the procedure presented in [15] and the results were systematically recorded in order to be compared with the results obtained in the practical experiment.

According to the relay's technical manual [16], the DFT uses one fundamental frequency cycle of samples to calculate a phasor quantity. On the other hand, the RMS (root mean square) values are calculated from one fundamental frequency cycle of samples prior to filtering. The implemented relay model uses the same procedure using 64 points per cycle.

IV. Results

The experimental results are summarized in Tables I and II, which present the relationship between the frequency of the injected harmonic component and the respective times of operation of the relay for the normally inverse, very inverse, and extremely inverse protection curves. Specifically, Table I lists the results obtained for harmonic currents with a magnitude of 1 A, while Table II provides the corresponding results for harmonic currents with a magnitude of 2 A. Thus, these tables highlight the influence of harmonic magnitude and frequency on the relay's response times.

The results presented in Tables I and II are shown in the plots of Fig. 3 and Fig. 4 together with the simulation results. The actuation times obtained in the experiments and in the simulations are similar, indicating that the implemented model is coherent with the actual relay.

TABLE I
Relay Operating Times for 1A Distortion With Different Frequencies

Distortion Frequency (Hz)	**Tripping Time (s)**					
	Normally Inverse		**Very Inverse**		**Extremely Inverse**	
	RMS	**Phasor**	**RMS**	**Phasor**	**RMS**	**Phasor**
0	4.31	4.32	3.41	3.41	3.37	3.38
70	4.31	4.31	3.36	3.37	3.23	3.21
80	4.30	4.31	3.35	3.36	3.23	3.21
90	4.28	4.32	3.34	3.38	3.23	3.24
100	4.26	4.31	3.32	3.40	3.23	3.30
110	4.26	4.32	3.32	3.41	3.23	3.35
120	4.26	4.32	3.32	3.42	3.23	3.37
130	4.26	4.31	3.32	3.41	3.23	3.36
140	4.26	4.31	3.32	3.40	3.23	3.35
150	4.26	4.31	3.32	3.40	3.23	3.34
160	4.26	4.32	3.32	3.40	3.23	3.35
170	4.26	4.31	3.32	3.40	3.23	3.36
180	4.26	4.32	3.32	3.42	3.23	3.37
190	4.26	4.31	3.32	3.40	3.23	3.36
200	4.26	4.32	3.32	3.40	3.23	3.35
210	4.26	4.31	3.32	3.40	3.23	3.35
220	4.26	4.32	3.32	3.41	3.23	3.36
230	4.26	4.32	3.32	3.41	3.23	3.37
240	4.26	4.32	3.32	3.41	3.23	3.37

TABLE II
Relay Operating Times for 2A Distortion With Different Frequencies

Distortion Frequency (Hz)	**Tripping Time (s)**					
	Normally Inverse		**Very Inverse**		**Extremely Inverse**	
	RMS	**Phasor**	**RMS**	**Phasor**	**RMS**	**Phasor**
0	4.31	4.32	3.41	3.41	3.37	3.38
70	4.29	4.31	3.23	3.24	2.90	2.81
80	4.24	4.31	3.19	3.22	2.88	2.83
90	4.20	4.31	3.15	3.26	2.89	2.95
100	4.16	4.30	3.15	3.30	2.88	3.10
110	4.13	4.31	3.12	3.39	2.87	3.31
120	4.12	4.32	3.11	3.40	2.89	3.37
130	4.12	4.32	3.10	3.40	2.88	3.33
140	4.13	4.30	3.10	3.36	2.89	3.28
150	4.13	4.31	3.10	3.37	2.89	3.24
160	4.12	4.31	3.10	3.38	2.88	3.29
170	4.11	4.31	3.11	3.40	2.89	3.34
180	4.11	4.30	3.11	3.40	2.89	3.37
190	4.12	4.32	3.10	3.40	2.89	3.36
200	4.11	4.31	3.10	3.40	2.89	3.32
210	4.13	4.32	3.10	3.39	2.89	3.30
220	4.12	4.33	3.10	3.39	2.89	3.33
230	4.12	4.32	3.10	3.40	2.89	3.36
240	4.12	4.32	3.10	3.40	2.89	3.37

The first four periods of the current signals used in the simulations for all considered distortion frequencies for 1 A and 2 A of amplitude are shown in Figs. 5 and 6, respectively. The plots in these figures also show the phasor amplitudes and RMS values evaluated for each current signal. In all cases it is possible to verify that both evaluated quantities

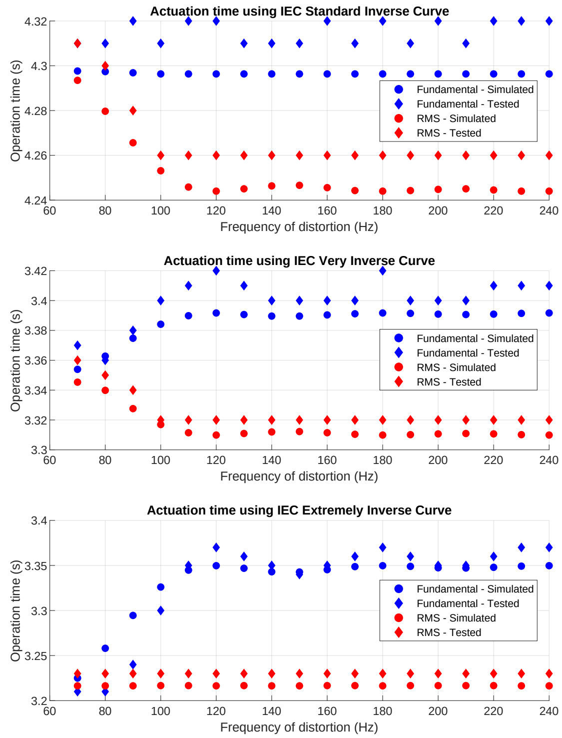

Fig. 3. Actuation times obtained in tests and simulations for all evaluated frequencies of distortion considering a distortion of 20% (1 A)

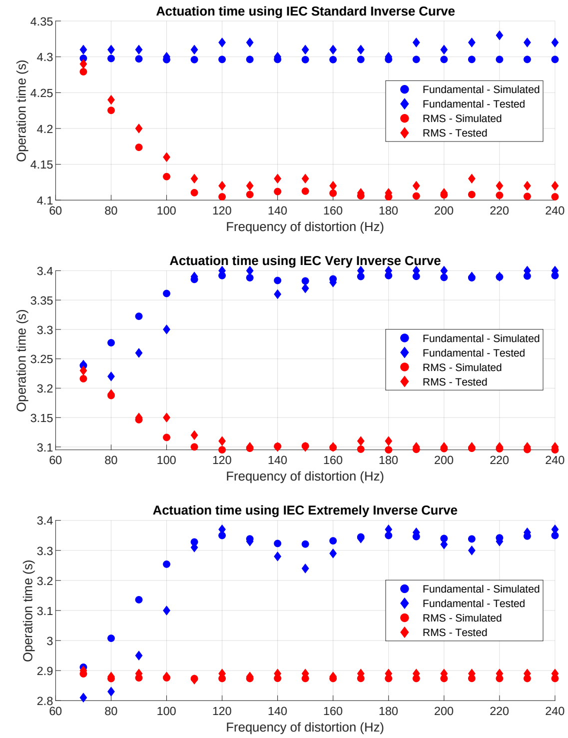

Fig. 4. Actuation times obtained in tests and simulations for all evaluated frequencies of distortion considering a distortion of 40% (2 A)

presents minor differences for a given component of distortion. An analysis of the obtained results reveals that, although the effects are less pronounced when compared to those observed in experiments with electromechanical relays presented on the technical literature, harmonic distortion can have an impact on the sensitivity and operation of digital relays. It is observed that despite the minor difference between the phasor and RMS amplitudes, the operation time can be significantly affected by the interharmonic distortion content. In fact, according to the results presented in Table I, for a 20% THD the difference between the operation time obtained by using phasor and RMS signals can reach 40 ms, 100 ms and 140 ms for the normally inverse, very inverse and extremely inverse curves, respectively. Similarly, as displayed in Table II, for a distortion signal of 40% this difference could reach 200 ms, 290 ms and 480 ms. Since the coordination interval usually adopted in coordination studies is between 200 ms and 400 ms, the obtained results show that the use of devices which use different quantities can result in selectivity problems in presence of distortions, specially when more inverse curves are used

The operation time obtained for the RMS currents remained approximately constant as the frequency of the injected harmonic or interharmonic component varied, as expected. This behavior is attributed to the RMS calculation method, which does not employ any filtering to suppress components other than the fundamental frequency. Conversely, the phasor calculation successfully attenuates harmonic components, albeit with varying effectiveness depending on the frequency and magnitude of the injected distortion current. Notably, interharmonic components were significantly less attenuated than harmonic ones. For this reasons, the difference between the operation time obtained by using phasor and RMS signals usually reaches highest values in harmonic frequencies of distortion (120 Hz, 180 Hz and 240 Hz).

V. Conclusions

This paper presents an evaluation of the effect of harmonic and interharmonic distortions on inverse time overcurrent relays. Special attention was given to the difference obtained in operation times when different quantities, i.e. phasor or RMS values, are used by the TOC function. The results obtained suggest that selectivity problems may occur when different quantities are used. Thus, a discussion arises regarding the most suitable method — RMS or phasor calculation — for specific applications. The phasor calculation facilitates the coordination procedure, since short-circuit analysis programs are usually based on phasor quantities. In contrast, the RMS value accurately reflects the actual stress imposed on equipment considering thermal and dynamic effects, enabling more precise diagnostics to determine operating curves relative to the withstand capabilities of the equipment. It consists, therefore, in a trade-off situation, requiring careful evaluation of priorities in each case. In any case, according to the results

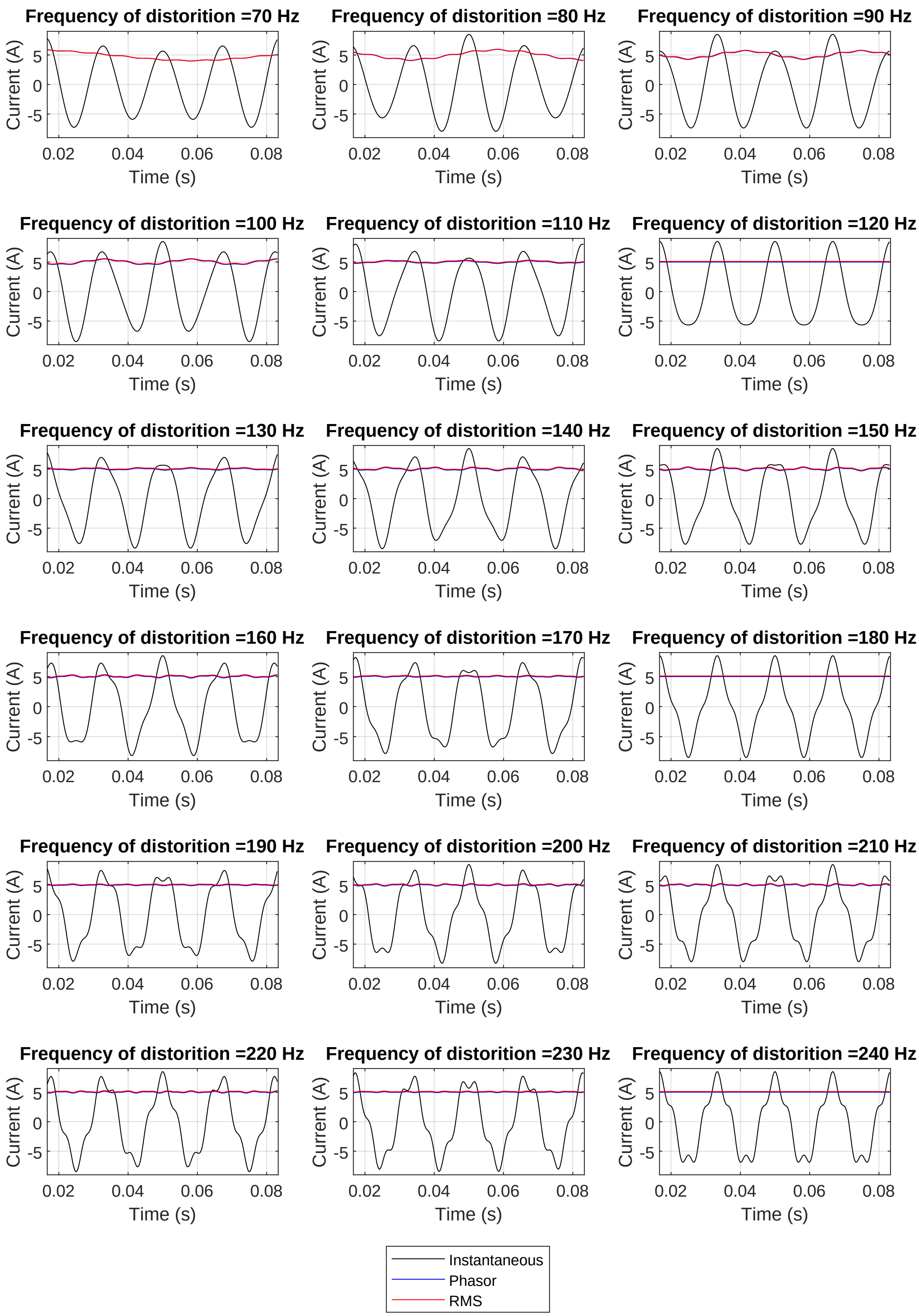

Fig. 5. Current signals used in the simulations for all evaluated frequencies of distortion considering a distortion of 20% (1 A)

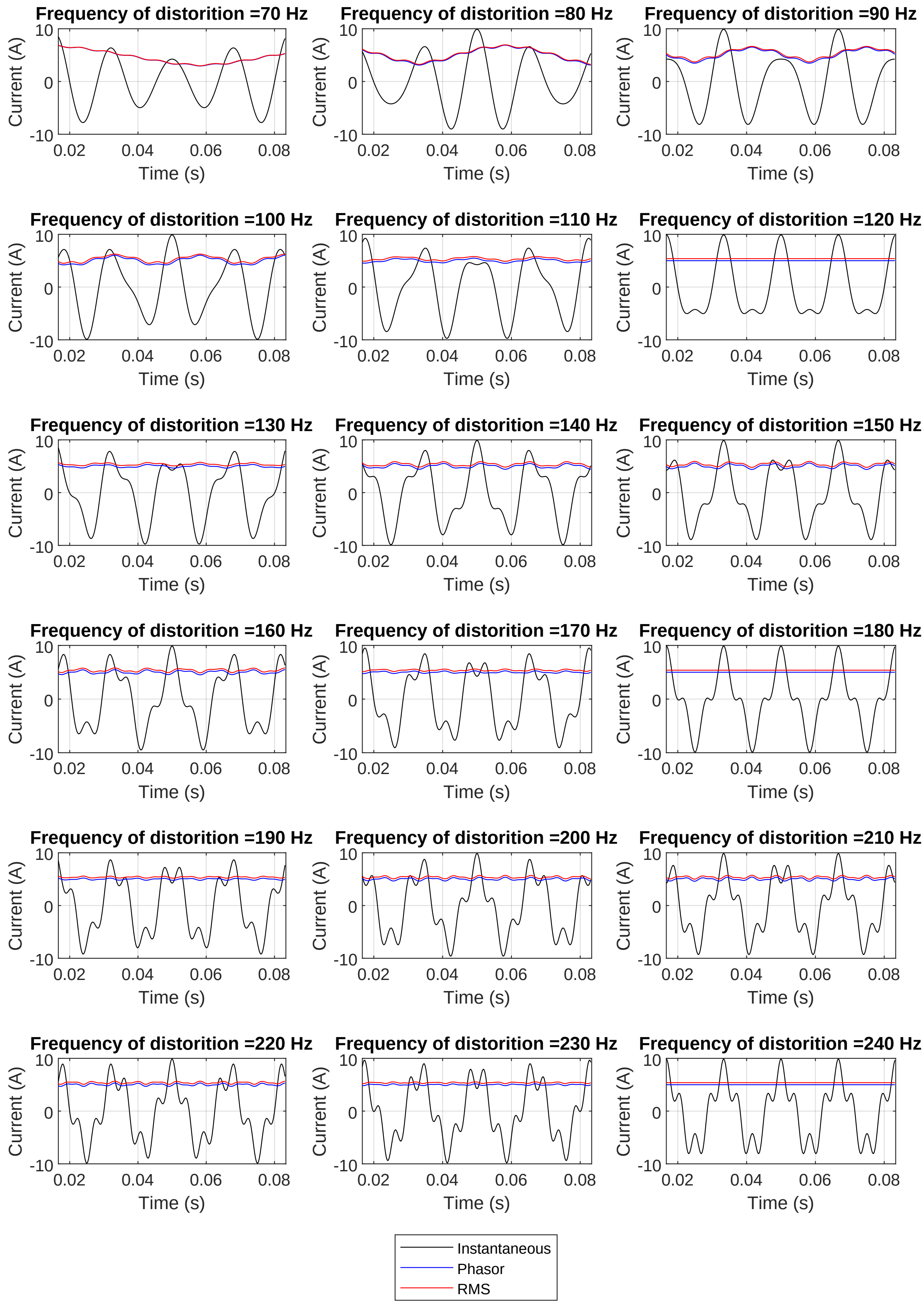

Fig. 6. Current signals used in the simulations for all evaluated frequencies of distortion considering a distortion of 40% (2 A)

presented in this study, the use of devices that use different quantities in the same protection system is not recommended. So, if electromechanical relays, fuses or, even, thermomagnetic circuit breakers are used in the same protection system, the use of RMS currents is more suitable.

- The presence of harmonic or interhamonic distortions can have a significant impact on the response time of inverse time overcurrent protection functions;
- According to the current quantity used, i.e. phasor or RMS values, this impact can be very different;
- The differences in the actuation times when different quantities are used are higher in the presence of harmonic distortions than in the presence of interharmonics. This is expected because the harmonic components are filtered out by the phasor estimation filter (Fourier), whereas the RMS filter does not remove any frequency component;
- If equipment that use different quantities are adopted, the user must pay special attention to the coordination time interval between their curves in order to avoid selectivity problems.

This situation could be particularly concerning because the presence of harmonic distortions in power systems tends to be more frequent than that of interharmonics. However, its influence is naturally attenuated by the presence of harmonic filters or transformer delta windings, which can block triplen harmonics.

It is important to point out that sub-cycle protection algorithms such as those based on traveling-wave approaches could be used to obtain instantaneous and selective protection in scenarios with high harmonic and interharmonic distortions. However, this paper focuses on traditional protective algorithms that are still widely used because of their low cost and simplicity.

VI. Acknowledgment

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