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MINIATURE CIRCUIT BREAKER TIME-CURRENT CHARACTERISTIC FOR A NON-SINUSOIDAL CURRENT

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Abstract: The paper presents the outcome of miniature circuit breaker time-current curve measurements for a non-sinusoidal current. The measurements were conducted using a research stand being an isolated electrical installation, providing full control of both power supply and load. The achieved results indicate the current waveform impact on circuit breaker operation, specifically on its time-delay overcurrent element.

Keywords: non-sinusoidal current, time-current characteristic, miniature circuit breaker, time-overcurrent protection.

1. INTRODUCTION

The modern consumer is increasingly focused on electrical energy usage. Many devices and technical objects that are based on different kinds of energy transformation now have their electrical counterparts, e.g., heating or electromobility, which is gaining increasing participation in global electrical energy consumption.

Many of these operate in a different way compared to typical ones, a kind of “primal” electrical device. These differences are mostly influencing the shape of the drained current which, consequently, have some impact concerning the operation of the supply grid. The most important element of such a grid, from the consumer’s point of view, is the protective element, as it provides safety for both the electrical

infrastructure and its user. Such devices, essentially circuit breakers, are commonly used in typical electrical installations and are often referred to as general purpose. While they are suitable for the majority of conventional electrical energy receivers, one issue that is worth mentioning is their operation in conditions differing from the ideal case. Typical circuit breakers are non-electronic elements, which operate in terms of emitted energy from the flow of current. Taking into account that non-sinusoidal currents can be significantly different in terms of effectiveness parameters compared to sinusoidal currents, the operation of circuit breakers may also be influenced.

This problem was originally identified some time ago in “Wave Distortion on Consumer’s Interconnections Working Group” [1984], a paper presented in 1984 when power quality issues were not a global subject of interest, but were occurring in specific cases. However, the subject of sine-wave distortions potential impact on protective relays (both analogue and digital) was raised. The continuation of the considerations is referred to in Brozek [1990]. This work, originating from 1990, states the problem of harmonic distortion is a “relatively new issue”, although it was already alerting the scientific community.

Today, power quality is a widely known issue that is present in all low voltage distribution systems. The significant development of electronic equipment, based on dedicated power supplies, drivers, etc. has caused a wide consumption of current waveforms differing from the sinusoidal waveform. Thus, the number of scientific works raised on this topic has also increased, although the majority of these focus on industrial or more sophisticated solutions in terms of electrical energy distribution. For example, in Medina & Martinez-Cardenas [2005], the authors present the influence of harmonic distortion on digital systems operation. Such an issue has also been identified in the present study, and has been briefly described in Klebba et al. [2025b] and remains within the scope of deeper analyses.

Another example of a more industry-focused approach can be observed in Santos et al. [2013], where the authors describe the results achieved for testing capacitor bank protection systems operating with harmonic distortions. Such an aspect is vital, as reactive power compensation remains an important aspect of industrial plant management. Studies concerning sine-wave distortions have also been conducted in terms of more sophisticated aspects, as can be seen in Liu et al. [2021]. In this work, the authors focused on the breaking arc occurring during circuit breaker operation.

The aspect of harmonic distortions impacting specific protection systems is being constantly considered by researchers. However, there is another issue that needs to be taken into account in such conditions, being the different approach for impulse current recognition. While some authors state that impulse currents are still harmonic distortion of a specific type, others remain convinced that such cases should be described as discontinuous sinusoidal currents, which is another issue that is also the object of interest of the authors of this work [Klebba et al., 2025ac].

The presented work takes into consideration circuit breaker operation under impulse currents. Two different components of the same type were tested under the

same conditions to determine whether any influence of current distortion from a sine wave on their operation can be detected and, eventually, of what form. The studies have focused on the most basic measurements of time-current characteristics under non-sinusoidal current flow conditions.

2. MINIATURE CIRCUIT BREAKER

2.1. CONSTRUCTION & PRINCIPLE OF OPERATION

A miniature circuit breaker (MCB) is a typical protection unit for general purpose electrical grids. The type of apparatus is suitable for different types of electrical energy receivers, from simple electronic units to complicated multi-task systems. MCBs are also nowadays typically used in both flats and detached houses. Industrial apparatus has some differences comparing to MCBs; however, their general principle of operation remains the same.

The construction of a miniature circuit breaker is presented in a schematic form in Figure 1.

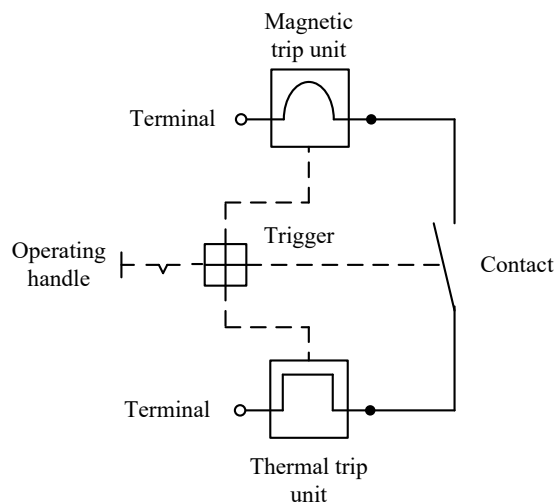


Figure 1. Miniature circuit breaker schematic

Source: [Szulborski et al., 2021].

The main components of an MCB are two triggers – an overload trigger and a short-circuit trigger. Their names simultaneously describe their purpose. An overload trigger is in fact a metallic badge that becomes plastic with increasing temperature. A temperature increase within the badge is related to heat losses emitted by a conductor, caused by a current flow, according to the formula:

$$\Delta P = \int_V J \cdot dV = J^2 \cdot \rho \cdot l \cdot S = I^2 \cdot R$$

where: ΔP – heat losses, J – current density, V – volume, ρ – resistivity, l – length, S – surface, I – current, R – resistance.

A temperature increase that exceeds the badge's yield strength causes its strain due to the contact being eventually opened and the current flow interrupted. The operation of this electromechanical element is strongly time-dependent, thus it is known as a delayed segment.

A short-circuit trigger is an element based on electromagnetic phenomena. It is made as a coil which has the purpose to strongly multiply the magnetic field generated by a current flow. The general principle of operation is comparable to an overload trigger – the stronger the field, the lower the time of activation. However, since a short-circuit is far more energetic compared to an overload, the trigger's time of activation must be as short as possible, which is the effect provided by the electromagnetic coil. The generated magnetic field of a specific value generates enough strength to open the MCB's contact and, consequently, interrupt the current flow [Szulborski et al., 2021].

3. TIME-CURRENT CHARACTERISTIC

Each MCB, in terms of its operation, is described with a time-current characteristic. It is in fact a function that matches a specific time of activation at a specific nominal current multiplicity. In other words, the higher the current exceedance over the nominal value, the shorter the time of its flow through the apparatus. Nowadays, MCBs have many different characteristics, e.g., general purpose, mostly domestic applications (B), industrial applications with a risk of higher inrush currents (C) and industrial applications where inrush currents are typically present (D). The letter symbol of the characteristic describes the type of short-circuit trigger, determining the range of currents that activate the trigger, e.g., from $3 \cdot I_n$ to $5 \cdot I_n$ for the B-type characteristic.

The time-current curve of the overload trigger, as mentioned before, is related to the amperage value and is common for all types of characteristics, differing only by the MCB's nominal current. Similarly to a short-circuit trigger time-current curve, it is described with a range of currents that activate the trigger, typically from $1.13 \cdot I_n$ to $1.45 \cdot I_n$ [Polski Komitet Normalizacyjny, 2019].

The whole time-current characteristic is a combination of both triggers time-current curves (see Figure 2).

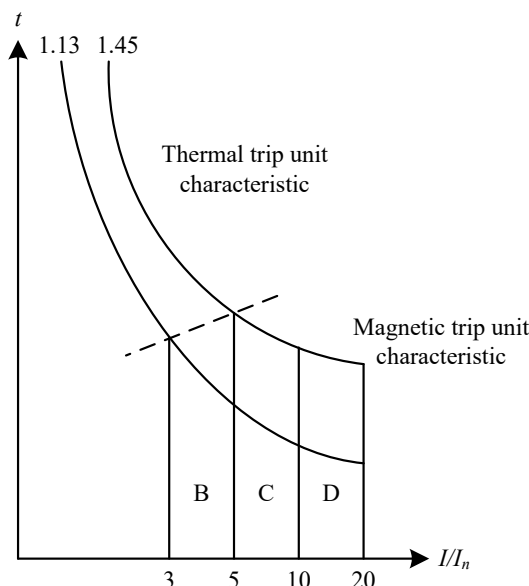


Figure 2. Miniature circuit breaker time-current characteristic

Source: [Schneider Electric, 2024/2025].

As can be seen, the area of activation for the overload trigger is common for all characteristics, while visible differences occur in the short-circuit trigger area of activation. The presented characteristics are representative of all MCBs available on the market, as their operation is strictly specified in the technical norms.

4. RESEARCH METHODOLOGY

All measurements were conducted using a dedicated research workbench (see Figure 3).

Two MCBs were tested during the research work. Both of them were dedicated for use in typical applications and widely available for purchase in the market. Each protection unit has an immediate segment, purposed for a short-circuit switch-off, and a delayed segment for overload switch off.

MCBs were simultaneously put in the common part of the three-phase electrical grid, powered by a programmable power supply, while the current flow in the grid was forced by a three-phase electronic load. Such a solution provided the possibility of setting identical parameters in terms of supply voltage and loading for both protection devices at the same time, along with no interaction with the electrical environment, providing no interference with the research stand during the tests. The tested units were both of the B2 1P type:

- ic60N B2 1P by Schneider Electric – “MCB A”,
- Ex9BN B2 1P by Noark – “MCB B”.

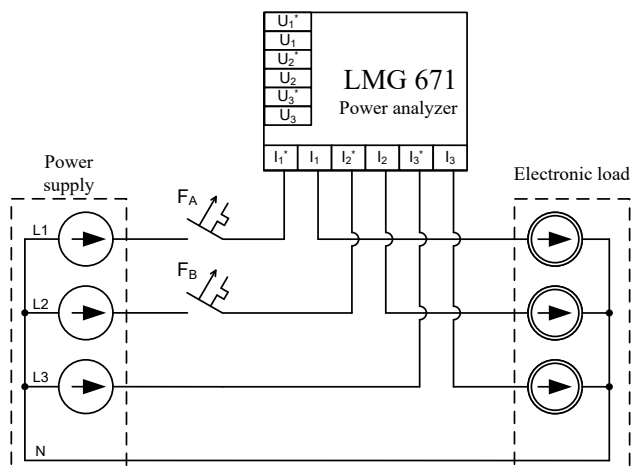


Figure 3. Research stand schematic

Source: own study.

Both units were operated at a 400/230 V voltage and 50 Hz frequency. Using two different MCBs was intended to evaluate the reaction of the two apparatus to the current distortion. During the tests, typical measurement of the MCB's time-current characteristic was conducted. The range of currents was from $1.25 \cdot I_n$ to $5 \cdot I_n$. For currents greater or equal to 8.5 A, the supply voltage was limited to 180 V due to the electronic loads power limitation. Such an action did not influence the MCBs' operation in any way. Each series of measurements consisted of three identical measurements, conducted for the same initial MCB temperature, providing identical test conditions and, consequently, outcome reliability. The assumption of three measurements for each current level was a compromise between result adequacy and avoiding excessive MCB contact wear due to frequent opening and closing, which would significantly impact their operation.

Each measurement began with setting the current setpoint at a specific level, followed by measuring the lapse of time from the current flow initiation to the apparatus activation causing the current flow interruption. All measurements were observed using a Zes Zimmer LMG671 precise power analyzer equipped with a recording function. The analyzer recorder amperage values in the test system (see Figure 1) with two levels of recording period was 10 ms for a nominal current multiplicity greater or equal to 3 and a 20 ms period for a nominal current multiplicity of less than 3. The recording period extension was caused by an expected increase of the recording timespan, which could result in the exceeding analyzer's storage.

The MCB's time of activation for a specific current level was calculated using the formula:

$$t_i = N_i \cdot T_i$$

where: t_i – MCB's time of activation in the i -th test, N_i – number of recorded measurements with a non-zero current flow in the i -th test, T_i – recording period in the i -th test (10 ms or 20 ms).

Due to the tests being conducted under controlled conditions, with separation from the external grid and an identical initial temperature, the only identified factor influencing the measurement accuracy was the imperfection of the power analyzer and measurement method. Thus, the type B uncertainty was assumed for all the tests. According to the specified recording period, the assumed error caused by the recorder was equal to the recording period (counterparting the analyzer's resolution), ± 10 ms and ± 20 ms respectively, and specified with a rectangular distribution. Consequently, two values of type B uncertainty were obtained:

$$u_{B10}(t) = \frac{\Delta t_{10}}{\sqrt{3}} = \frac{10}{\sqrt{3}} = 5.774 \text{ ms}$$

$$u_{B20}(t) = \frac{\Delta t_{20}}{\sqrt{3}} = \frac{20}{\sqrt{3}} = 11.547 \text{ ms}$$

The algorithm of each measurement series for the specified MCB nominal current multiplicity is presented in Figure 4.

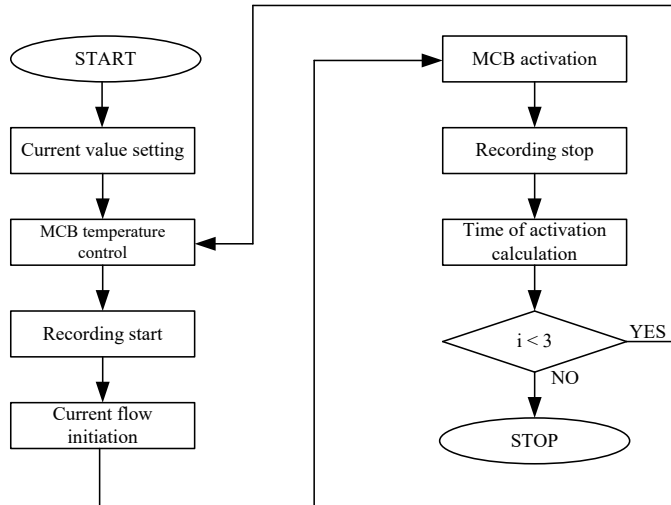


Figure 4. Algorithm of the measurement series for a specified current

Source: own study.

Three different tests of the time-current characteristic were conducted in total, for three current wave shapes, determined by the PF set on the electronic load: $PF = 1$, $PF = 0.75$ and $PF = 0.5$. A decrease in PF value caused a more impulsive character of the load current with a simultaneous constant RMS value. Consequently, the amplitude and timespan of the impulse were variable (see Figures 5 and 6).

A slight visible current distortion at the beginning of the current's positive and negative half-wave for $PF = 1$ results from the principle of operation of the electronic loads. This is in fact an analogue of an alternating current controller and its presence does not affect the obtained outcome compared to the ideal sine wave shape.

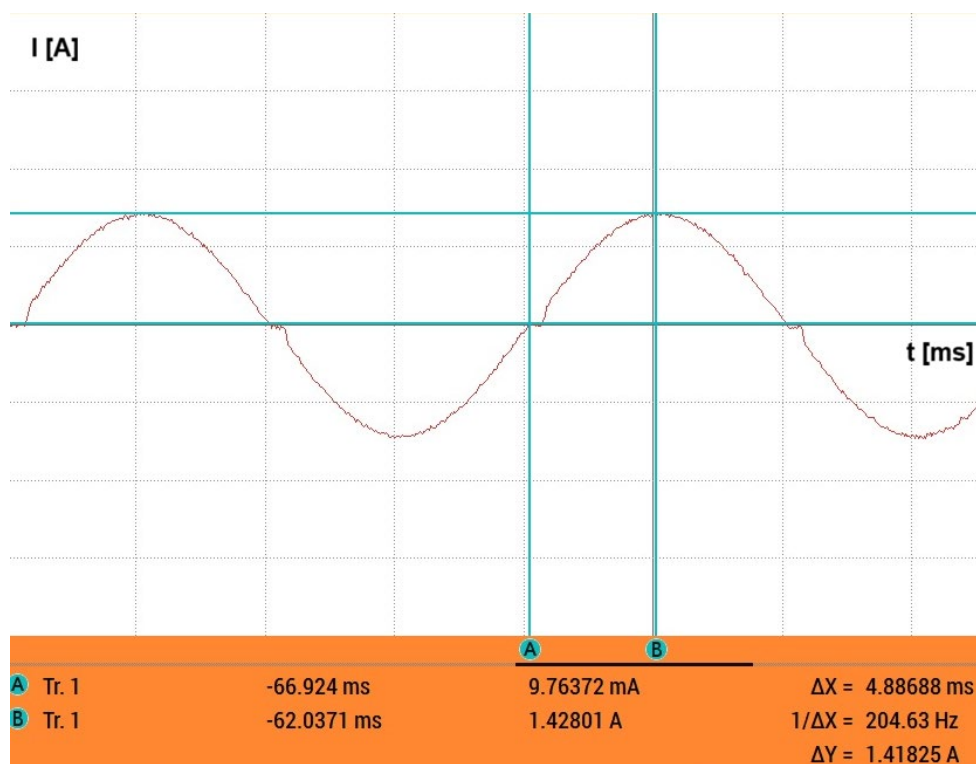


Figure 5. Current wave shape for $PF = 1$ and $IRMS = 1$ A

Source: own study.

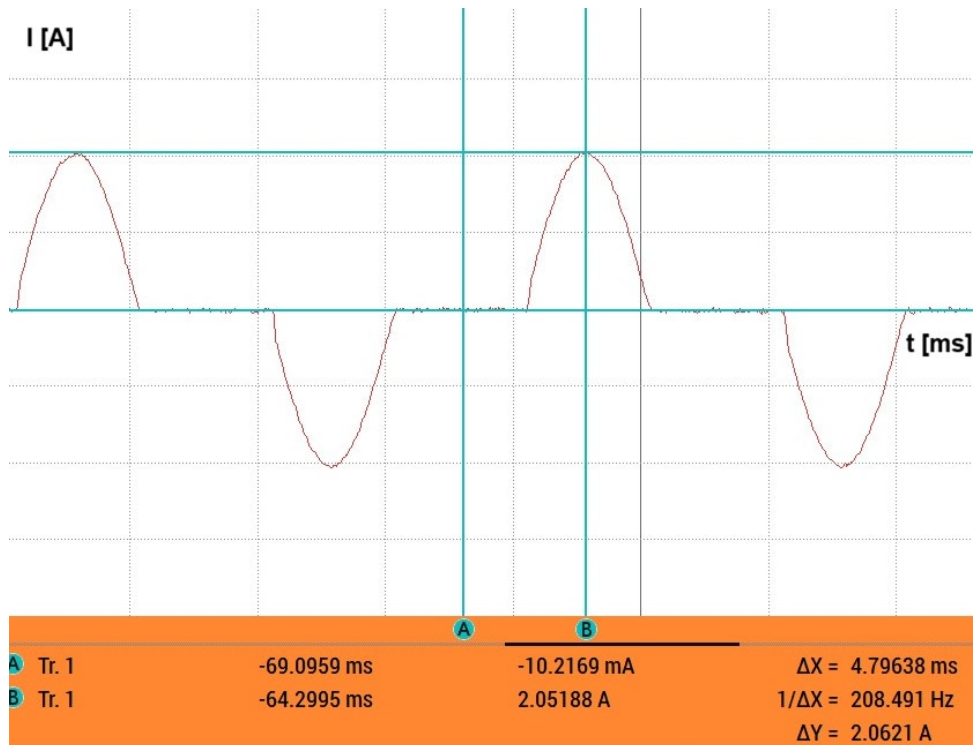


Figure 6. Current wave shape for PF = 0.6 and $I_{RMS} = 1 \text{ A}$

Source: own study.

Table 1. Current wave crest factor, CF, depending on the electronic load's power factor (PF)

PF [-]	1	0.9	0.8	0.75	0.7	0.6	0.5
CF [-]	1.43	1.72	1.82	1.92	1.95	2.05	2.25

Source: own study.

Setting different values of the power factor on the electronic load caused current wave crest factor, CF, changes (see Table 1).

5. RESULTS

The results obtained from the tests, being averaged times of activation for different nominal current multiplicities, are presented in Table 2. The results that deviated significantly from the general trend were identified as spurious errors and omitted during the average value calculation.

Table 2. Averaged times of MCB activation depending on the power factor (PF)

$I/I_n [-]$	$t_{av} [s]$					
	MCB A			MCB B		
	PF = 1	PF = 0.75	PF = 0.5	PF = 1	PF = 0.75	PF = 0.5
1.25	846.81	566.23	756.44	146.02	86.31	79.32
1.45	101.04	95.23	99.34	44.77	44.47	40.66
1.50	76.11	83.83	78.13	172.91	44.47	39.75
1.75	39.49	42.05	37.55	27.77	29.86	25.56
2.00	24.21	26.13	26.90	20.31	21.78	20.75
2.25	17.91	18.93	19.06	16.71	17.23	19.97
2.50	13.67	15.53	15.31	12.76	15.11	17.63
2.75	11.17	12.64	9.49	12.08	15.20	12.55
3.00	7.40	8.35	1.78	8.91	0.13	0.14
3.25	6.13	0.66	0.41	7.63	0.06	0.06
3.50	0.18	0.15	0.23	7.33	0.05	0.05
3.75	0.07	0.05	0.07	0.05	0.05	0.03
4.00	0.06	0.05	0.05	0.05	0.06	0.05
4.25	0.04	0.04	0.04	0.07	0.03	0.03
4.50	0.04	0.04	0.04	0.35	0.05	0.03
4.75	0.02	0.03	0.04	0.06	0.05	0.04
5.00	0.03	0.03	0.03	0.04	0.03	0.03

Source: own study.

Measured characteristics for both protection devices are presented in Figures 7 and 8.

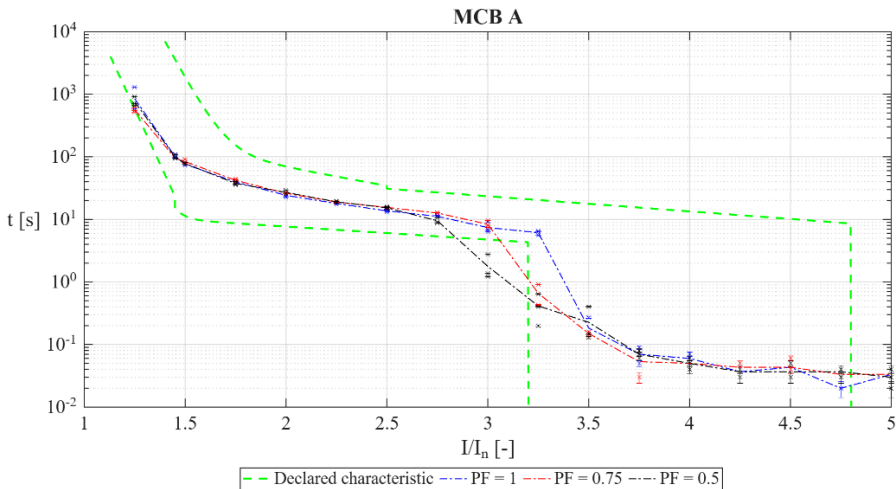


Figure 7. MCB A's time-current characteristic depending on the power factor (PF)

Source: own study, based on [Schneider Electric, 2024/2025].

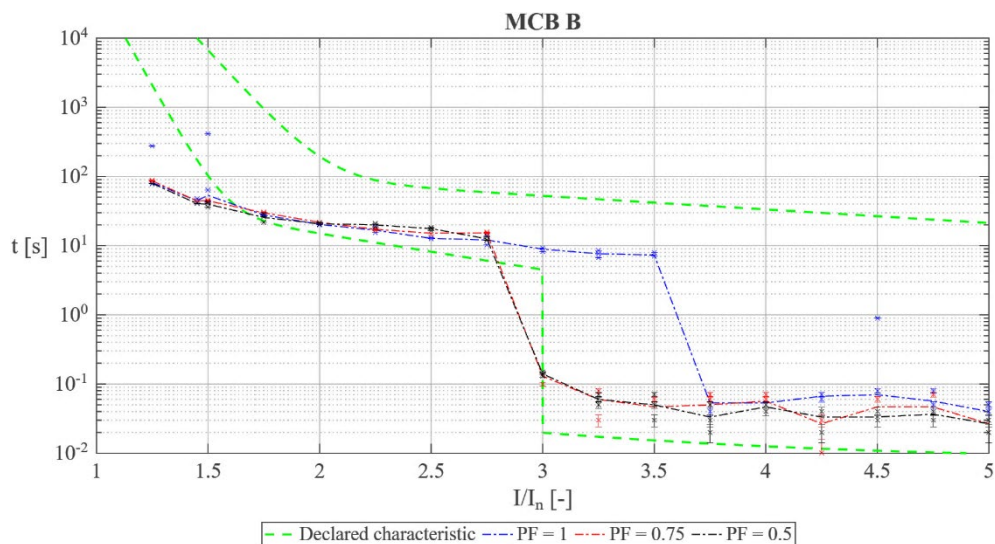


Figure 8. MCB B's time-current characteristic depending on the power factor (PF)

Source: own study, based on [Noark, 2025].

The shapes of the characteristics indicate that the tested MCBs do not lose their performance properties under current distortion conditions. However, some differences in terms of their operation can be noticed, especially in the 'transition zone' between the immediate and the delayed segment characteristics.

The crest factor (CF) increase results in operation for a nominal current multiplicity between 3.0 and 3.5 with an immediate segment characteristic. This implies that the current's amplitude increase causes a short-circuit trigger activation, leading to overcurrent trigger operation.

During the tests, another effect of current distortion was noted. The CF increase led to a significant acoustic effect, being a specific sound indicating that of an activated short-circuit trigger coil for the decreasing current multiplicities. Unfortunately, such a phenomenon was not measured due to the lack of suitable measuring tools.

As a supplement to the measured time-current characteristics, the measurements of the time of activation were conducted for three particularly important current multiplicities: 1.45, 3.00 and 5.00 for PF values of 1.0, 0.9, 0.8, 0.75, 0.7, 0.6, and 0.5. All other conditions remained unchanged compared to the previously carried out tests. The main assumption was to verify the parameters describing MCBs operation with current flow of the same RMS value with different CF values.

Table 3 presents the achieved averaged times of activation from current flow initiation to the MCBs activation for current multiplicities of 1.45, 3.00 and 5.00.

Table 3. Averaged measured times of activation depending on current's power factor (PF) and crest factor (CF)

PF [-]	CF [-]	t_{AV} [s]					
–		MCB A			MCB B		
		$I/I_n = 1.45$	$I/I_n = 3$	$I/I_n = 5$	$I/I_n = 1.45$	$I/I_n = 3$	$I/I_n = 5$
1	1.43	101.04	7.40	0.033	44.77	8.91	0.040
0.9	1.72	95.86	10.17	0.047	44.96	0.11	0.033
0.8	1.82	94.93	10.03	0.040	44.70	0.12	0.047
0.75	1.92	95.23	8.35	0.033	44.47	0.13	0.027
0.7	1.95	94.08	7.11	0.033	43.89	0.14	0.040
0.6	2.05	93.60	1.78	0.033	45.25	0.13	0.037
0.5	2.25	99.34	4.37	0.030	40.66	0.14	0.027

Source: own study.

The data from Table 3 are also graphically shown in Figures 9–11.

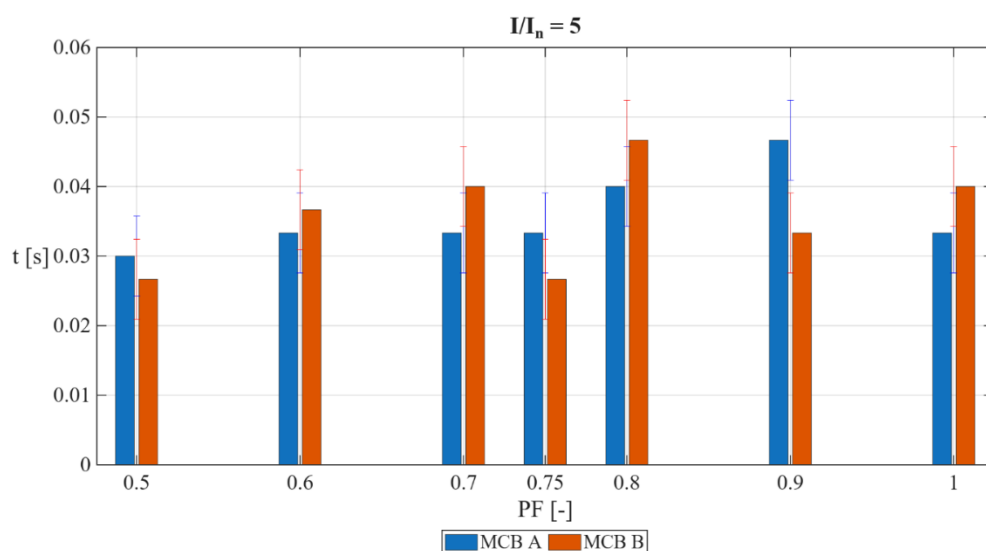


Figure 9. Averaged measured times of activation for nominal current multiplicity $I/I_n = 5$ depending on current distortion

Source: own study.

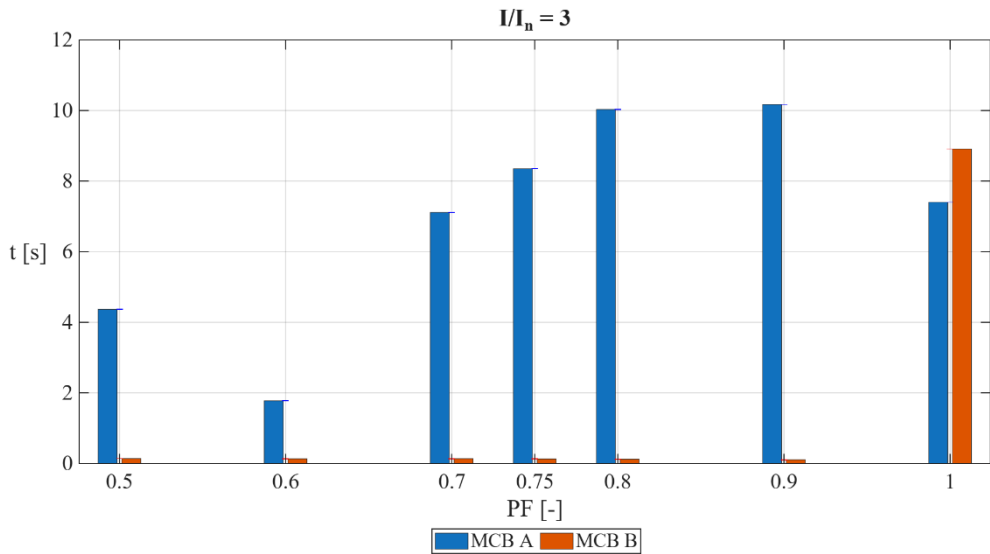


Figure 10. Averaged measured times of activation for nominal current multiplicity $I/I_n = 3$ depending on current distortion

Source: own study.

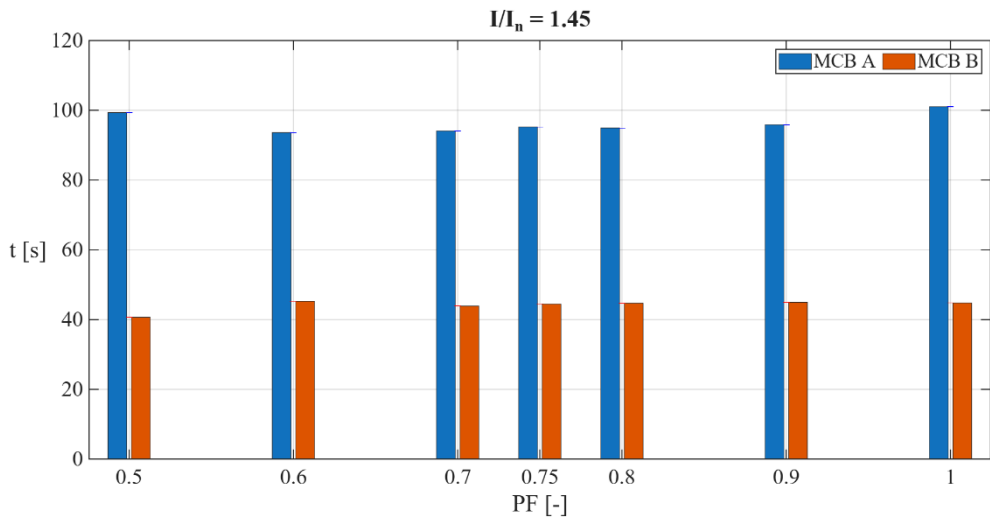


Figure 11. Averaged measured times of activation for nominal current multiplicity $I/I_n = 1.45$ depending on current distortion

Source: own study.

The obtained results prove the previous observations. Measurements conducted for the current multiplicity, $I/I_n = 5$, indicate a shortening of the time of activation along with the current distortion increase for both MCBs. However, it should be noted that the current setpoint caused the operation of the immediate segment, so the measured time is in fact the timespan of contact opening.

The most significant differences as far as the time of activation is concerned were observed for current multiplicity, $I/I_n = 3$. Along with this, some significant differences in terms of both the apparatus behavior are visible. The time of MCB B activation was sharply shortened for $CF = 1.72$ ($PF = 0.9$) and remained very short for all further analyzed values.

As far as MCB A is concerned, the reaction to current distortion at the current multiplicity, $I/I_n = 3$, is also visible; however, its form is different. At first, the time of operation extended up to about 2 seconds (for $PF = 0.9$ and $PF = 0.8$), and after that it shortened until the minimum value was under 2 seconds ($PF = 0.6$), followed by another extension to above 4 seconds.

The impact of current distortion was also noticeable for current multiplicity, $I/I_n = 1.45$, and was comparable to the previously described case as far as changes to the tendency was concerned. In the case of MCB A, the shortest noted time of activation occurred for $PF = 0.6$ and was about 93.6 seconds; however, the longest time of activation was noted for $PF = 1$ and was about 101.04 seconds. Thus, the difference was about 7.5 seconds, which largely exceeds the calculated measurement uncertainty.

In the case of MCB B, the shortest measured time of activation occurred for $PF = 0.5$ and was about 40.66 seconds, and the longest time of activation occurred for $PF = 0.6$, at about 45.25 seconds. The difference between the minimum and the maximum was about 5 seconds.

6. CONCLUSIONS

The outcome of the tests indicates that MCBs show some differences in operation in the case of non-sinusoidal current flow. The noted differences did not cause any deterioration in their effectiveness as far as the comparison to the manufacturer's characteristics is concerned. It should be noted, however, that for the current multiplicities 1.25, 1.45 and 1.5, MCB B indicated a deviation from the declared characteristic for all analyzed current shapes, including the sine wave ($PF = 1$). MCB A operated within an area shaped by the declared characteristic for the whole range of the analyzed currents; however, for current multiplicity $I/I_n = 1.25$, its closeness to its limitations is visible.

The most important conclusion is that the time of activation change for current multiplicity $I/I_n = 3$, which is in fact a kind of transient zone between the delayed and the immediate segments. The achieved results indicate that increasing the amplitude, being an instantaneous value, caused the activation of the short-circuit trigger for

current multiplicities that did not show such behavior as far as the sine wave is concerned. An additional factor proving this thesis is noted in the acoustic effect, which is distinctive for short-circuit trigger operation, that was present for lower current multiplicities for increasing current distortion.

The observed trend is also indicated by the results obtained for specific current multiplicity values, for which the range of PF values was widened. The acoustic effect mentioned above was also present. The observed deviation in terms of the time of activation tendency changes for $PF = 0.6$ and $PF = 0.5$ indicates that there is a specific multiplicity value, below which the impact of current distortion is no longer visible.

The search for this, leading simultaneously to either confirmation or denial of this thesis, is a determinant for further studies, which should focus on this specific range of current multiplicities. Additionally, an approach for measuring the acoustic effect of current distortion as a confirmation of current distortions triggering the immediate segment of the MCB should be taken. All of the above conclusions indicate that this issue, while appearing to be a basic one, can lead to an interesting outcome for further analyses with simultaneous demonstrating of other paths for possible tests.

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