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Laboratory-Based Investigation of Contactors Susceptibility to Short Duration Voltage Sags

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Abstract. Voltage sags pose substantial challenges in electrical systems, disrupting power supply and adversely impacting equipment. This paper outlines the issues arising from voltage sags, emphasizing their detrimental effects on electrical installations powered by relays and contactors. The study delves into the susceptibility of these critical components when faced with voltage fluctuations, exploring how sags influence their functionality. Additionally, the research presents experimental results from laboratory tests, focusing on contactors of different power exposed to voltage sags lasting less than one cycle. These assessments provide insights into the performance of contactors under short-duration voltage variations, offering valuable contributions to enhancing the reliability of electrical systems.

Key words. Short Duration Voltage Sags; Contactor; Susceptibility; Power quality; Voltage tolerance curve.

1. Introduction

Information regarding equipment susceptibility to voltage sags is crucial for preventing system production interruptions [1]. When equipment is powered by voltage sags, interruptions, malfunctions, undesired shutdowns, and even damage can occur. Finally, this can lead to apparent financial losses for consumers.

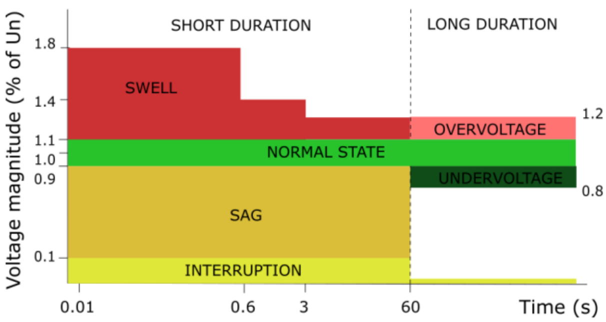

Fig. 1. Characteristic Parameters of Short and Long Duration Variations.

The magnitude and duration of voltage sags, as depicted in Fig. 1, are the primary characteristics that describe the power quality issue, but they are not the only ones. Other factors include symmetrical and unsymmetrical sag characteristics, phase shift angle, and the point on wave (POW) of sag initiation. Voltage sags typically result from short circuit faults in the power system, as well as from large motor starting and transformer energizing.

Several methods exist to assess equipment susceptibility to voltage variations [2]. One approach is through the use of power acceptability curves, such as those designed by the Computer Business Equipment Manufacturers Association (CBEMA). Another resource specifically tailored for voltage sags is the Semiconductor Equipment and Materials Institute (SEMI-F47) standard. Additionally, the IEEE P1668TM standard provides a recommended standard curve.

Understanding the susceptibility curve is essential to gauge an electrical device's resilience when voltage sags occur, determining whether the device maintains its operation or enters a malfunction/shutdown state. This information can be obtained through laboratory testing or from the manufacturer, who sometimes conducts internal tests but rarely makes the results available in their datasheet.

The CBEMA, an industry standard introduced in 1980 and referred to as the Power Acceptability Curve, has become a standard guideline in the industry for assessing the susceptibility of data processing equipment to short-duration voltage changes. This curve clarifies that equipment susceptibility to voltage changes is significantly influenced by the magnitude and duration of the voltage sag. In 1996, the CBEMA curve was redesigned and renamed ITIC (Information Technology Industry Council) and documented in IEEE Std. 1346, 1998. This curve is nearly identical to the old CBEMA, with the difference that it is more segmented to accommodate digitalization.

SEMI F47 was the first to recommend a specific susceptibility curve for voltage sags in semiconductors. The ITIC and SEMI F47 curves are plotted in Fig. 2.

Existing standards for testing equipment immunity to voltage sags primarily focus on verifying the minimum response of immunity requirements to them. Several popular standard equipment tolerance curves, typically used, include the Information Technology Industry Council (ITIC) curve, the SEMI F47 curve, and the IEC 6100-4-11 standard curve. Each point on the curve indicates for how long this equipment component can withstand certain voltage sags [3].

SEMI F47 is the standard for voltage sag immunity for electronic equipment used in the semiconductor industry, developed by SEMI, a global association representing the semiconductor manufacturing industry. This standard was updated in 2006 to its latest version: SEMI F47-0706.
In Fig. 2, the previously described curves are overlaid. These curves can be used for both single-phase and three-phase equipment without distinction.

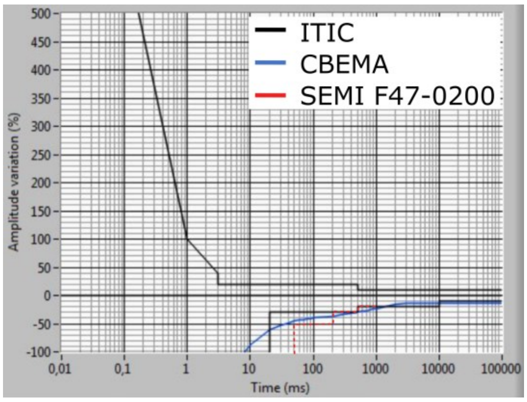

Fig. 2: Curve ITIC, SEMI F47 and CMEBA.

Instead, voltage sag immunity curves 2 and 3 (IEC 61000-4-11 and IEC 61000-4-34) are standards that provide specifications for the immunity of electrical and electronic equipment during voltage sag events based on specific equipment requirements and operating conditions [4]. Specifically, IEC 61000-4-11 (Curve 2) is commonly used for devices that do not require high reliability during prolonged voltage sags. For example, it is suitable for electronic consumer devices or household appliances. The IEC 61000-4-34 standard (Curve 3) is more stringent and is suitable for equipment requiring high reliability during prolonged voltage sag events. It is often used in industrial and commercial environments for critical equipment.
The IEEE P1668TM 2014 recommends immunity testing for three-phase equipment categorized as type I, type II, and type III, based on the magnitude of phase voltage sag. The document provides clear and specific guidelines for conducting ride-through tests on voltage sags and short interruptions on electrical and electronic equipment connected to low-voltage power systems, ensuring that such equipment can operate reliably even under non-ideal power supply conditions. Susceptibility curves are depicted in Fig. 3.

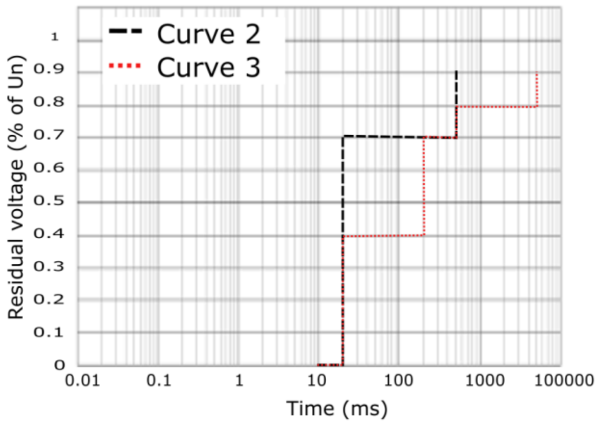

Fig. 3: Immunity curve 2 and curve 3 according toIEC61000-4-11 and IEC 61000-4-34.

Voltage sags typically do not cause damage to equipment, but they can easily disrupt the operation of sensitive equipment [5]. The AC contactor allows the electrical connection of an electromagnetic device when the electromagnetic coil is connected to a voltage source [6]. Current flows through the coil, creating a magnetic field that pushes the spring to close the contacts; the magnetic force generated is influenced by the voltage. When the supply voltage decreases or is interrupted, the spring returns the contact to the open position. Contactors require a high current to close the contacts, unlike the lower current under normal operating conditions. Additionally, contactors are known to be susceptible to voltage sags. A contactor de-energizes when the intensity of the magnetic field becomes lower than the spring pressure, which tries to move the core away from the armature [3].
According to EN 60947-1 (CEI 17-44), a contactor is defined as: "*A mechanical switching device having only one position of rest, operated otherwise than by hand, capable of making, carrying and breaking currents under normal circuit conditions including operating overload conditions*."
For the standards, the rated control circuit voltage and rated frequency, if any, are the values on which the operating and temperature-rise characteristics of the control circuit are based. The electromagnetic and electro-pneumatic equipment shall close with any control supply voltage between 85% and 110% of its rated value (*Us*) and an ambient air temperature between –5 °C and +40 °C. These limits apply to DC or AC as appropriate. For electromagnetic and electro-pneumatic equipment, the drop-out voltage shall not be higher than 75% of the rated control supply voltage (*Us*) nor lower than 20% of *Us* in the case of a.c. at rated frequency or 10% of *Us* in the case of DC[7].
Electric contactors are electromechanical devices widely used in industrial processes [8]. Their most common industrial application is the control of electric motors, preventing sudden restarts upon voltage restoration [7].
The electric motor receives power from the grid through the contactor. During a voltage sag, the contactor may deactivate, disrupting the connection between it and the motor creating a motor stopping [9].
In a typical start-stop diagram of a three-phase asynchronous motor, as depicted in Fig. 4, for example, a holding circuit device is employed to keep the contactor closed even after releasing the start button.

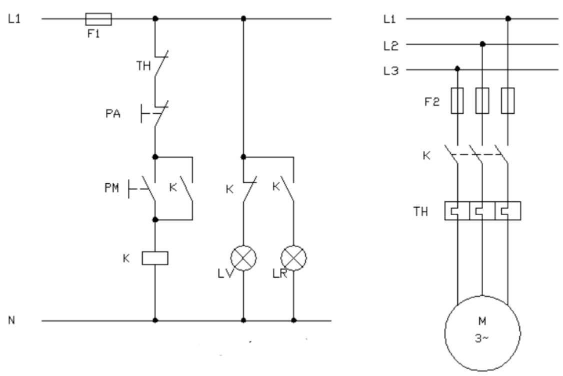

Fig. 4. Typical diagram for start-stop control of a three-phase asynchronous motor with contactor and holding circuit.

This ensures continuous motor operation even after releasing the button. However, if there is an interruption or a voltage drop while the contactor is in the holding mode (closed), the holding circuit device may fail to keep the contactor closed. As a result, this causes a disruption in the motor's power circuit and its subsequent shutdown.

This paper aims to investigate the behavior of contactors during short-duration voltage sags. Tests have been conducted on various types of contactors, exploring different characteristics of voltage sags, including magnitude, duration, and waveform point. Section 2 describes the adopted test system with the contactors model for their evaluation. Section 3 discusses the obtained experimental results under several conditions. Finally, Section 4 concludes the paper.

2. Test system

Three voltage-sensitive contactors were tested against voltage sags: i) ABB A185-30 ,ii) DANFOSS CI 12, and iii) OMRON MY4IN Contactor (Fig. 5).

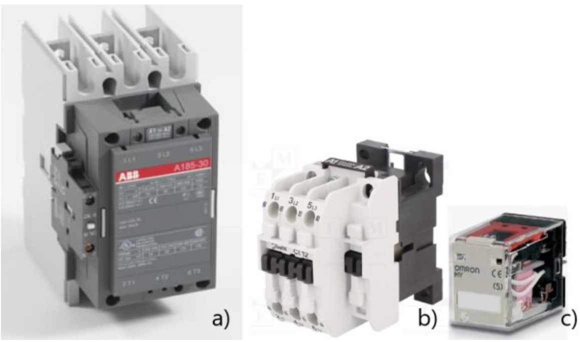

Fig. 5. a) Contactor ABB A185-30; b) Contactor DANFOSS CI 12 ; c) Contactor OMRON MY4IN

The specifications of these contactors, sourced from different manufacturers and with varying current ratings are summarized in Table I. C1 and C2 are 3-phase contactors [10], while C3 is a monostable relay mounted on a DIN rail socket.

Table I: Electrical Characteristics of the 3 Contactors under Test

	C1	C2	C3
Manufactured name	ABB	DANFOSS	OMRON
Model	A185-30	CI 12	MY4IN
Rated voltage (V)	690	690	250
Rated Current (A)	185 (AC-3)	12 (AC-3)	5
Frequaency [Hz]	50/60	50	50/60
Coil voltage (Vac)	220-230	220-230	220/240
Coil current (mA)	(Coil consumption at 50 Hz: 35 VA)	---	5.2/6.2 (at 50Hz) 4.3/5.0 (at 60Hz)
Number of poles	3	3	4
Mechanical endurance	5 millions		50,000 operations

For C1 [11], according to the datasheet: "Operating coil limits: (according to IEC 60947-4-1) 0.85 x Uc Min. ... 1.1 x Uc Max. (at θ ≤ 70 °C)"

For C3 [12], according to the datasheet, the relay will operate if 80% or higher of the rated voltage is applied. To ensure release, use a value that is lower than the specified 30% minimum for AC.

The scheme of the testing system is shown in Fig. 6; the power quality phenomena were generated by the TRANSIENT-2000, a device available in the electrical engineering laboratory at the University of L'Aquila. This device accurately simulates transients originating from various interference sources, including indirect lightning in electronic systems, human body electrostatic discharges, switched inductance (Burst), power supply interruptions, and variations. The testing system comprises the EMC-partner Transient 2000 transient test system generator, which supplies power to the electromagnetic coil of the contactor via a 230V, 50Hz outlet. Additionally, a resistance, powered by a 3V DC power supply, is connected to the movable contact of the Equipment Under Test (EUT). Using an oscilloscope, measurements are taken for the output voltage of the TRANSIENT-2000, the voltage on the movable contact, and the trigger signal of the power quality phenomenon induced by the transient 2000.

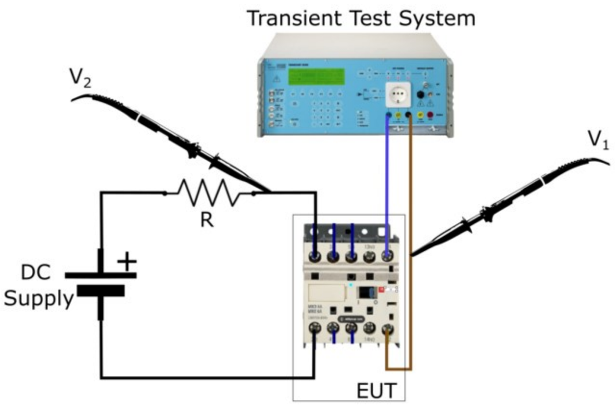

Fig. 6. Principle diagram of the testing system

The settings for the reproduced voltage sag were introduced via the instrument's display by modifying:

- DIP Level, indicating the residual percentage voltage of the voltage sag: which we set to 5 levels of 0% (interruption), 20%, 40%, 60%, and 80% of the nominal voltage.
- DIP Mode: "Less than 1 period", to determine the duration of the event as less than one cycle.
- DIP Power Synchronization (main 2), a setting used to define both the start and end POW (point on waveform) of the event. For a deep investigation, the first DIP begin and first DIP end is increased with steps of 30 degrees, i.e., 0°-30°, 0°-60°, 0°-90°,...0°-360°, 30°-60°,...30°-360°, 60°-90°, and so on, totaling 390 tests for each contactor.

3. Result

The test was conducted considering various magnitudes of voltage sag, durations, and phase angles of the voltage

waveform's onset [13]. To assign a numerical value to the sag, the recommended usage is sag at "X%", which means the line voltage is reduced to X% of its normal value. If the voltage sag is due to a short circuit, the sag duration is primarily determined by the fault clearing time. The onset point of the sag is the phase angle of the fundamental voltage waveform at which the voltage drop begins [14].
Three contactors from different manufacturers were used, and the waveforms of the coil input voltage and the voltage across the movable contacts were recorded to verify contact opening. From the tests, it was found that not all voltage sags result in contact opening, and often the contact remains closed even though the movable coil has moved due to the spring: in this case, the contactor emits a very annoying noise due to the movable contact reaching the end stop. The contactors have been tested with several dip beginning angles with increasing width in steps of 30.
In Table II, the test results for contactors C1, C2, and C3 with dip beginning angles of 0°, 30°, and 60° are shown. Cases where contact opening occurred are highlighted in red, while cases with no openings are highlighted in green. Cases where contact opening did not occur but a ticking noise was audible are highlighted in yellow for mild ticking and orange for strong ticking.
In Tables III and IV, the test results for contactors C1, C2, and C3, respectively, with dip begin angles of 90°, 120°, 150°, 180°, 210°, and 240°, 270°, 300°, 330° are shown. In the tests with dip beginning at 0°, for contactor C1, it is observed that contact interruption rarely occurs except for cases 0-330° and 0-360° with a residual voltage of 40%. For contactor C2, contact interruption is rare except for the case coinciding with the 20ms (0-360°) and 40% level. In the case of contactor C3, contact opening occurs with 0% DIP in the 0°-90° and 0°-120° cases, and with residual voltages of 20% and 40% if the sag duration exceeds 120°. As evident from the table, contactor C3 does not emit ticking noises due to its small-sized spring, whereas contactor C1 is the loudest during voltage sags. Contactor C3 also opens for the majority of tests. In fact, out of 390 tests for each contactor, C1 opened 42 times (10.8%), C2 23 times (5.9%), and C3 115 times (29.5%).
Contactor C3 is more sensitive to sags with a dip beginning at 60°, as it opens the contact for Vr=0% and Vr=20% sags lasting at least 60°, while for Vr=40% sags lasting at least 120°. Conversely, contactors C1 and C2 are more sensitive to sags with a dip beginning at 90°.
The waveform of the coil voltage and on the contact when contactor C1 is subjected to a voltage drop of 40% for a duration of 15 ms (0°-270°) is shown in Fig. 7.

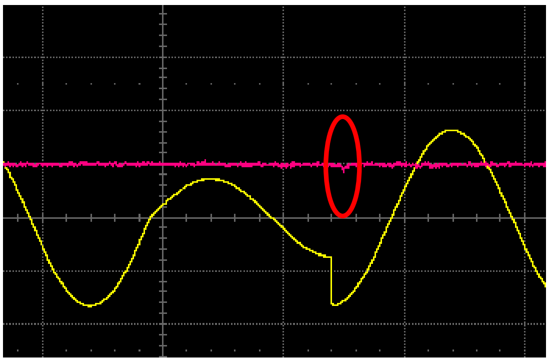

Fig. 7. Test contactor C2, Vr=40%, 0°-270°

Table II: Test with DIP begin: 0°, 30°, 60°

	Voltage residual [% Vn]														
	C1					C2					C3				
Duration	0%	20%	40%	60%	80%	0%	20%	40%	60%	80%	0%	20%	40%	60%	80%
0°-30°	green	green	green	green	green	green	green	green	green	green	green	green	green	green	green
0°-60°	green	green	green	green	green	green	green	green	green	green	green	green	green	green	green
0°-90°	orange	orange	yellow	green	green	orange	yellow	green	green	green	red	green	green	green	green
0°-120°	yellow	orange	orange	orange	green	green	orange	orange	green	green	red	red	red	green	green
0°-150°	yellow	orange	orange	orange	green	green	green	orange	green	green	green	red	red	green	green
0°-180°	yellow	orange	orange	green	green	green	green	orange	yellow	green	green	red	red	green	green
0°-210°	yellow	yellow	orange	orange	green	green	green	orange	yellow	green	green	red	red	green	green
0°-240°	yellow	yellow	orange	orange	green	green	green	orange	yellow	green	green	red	red	green	green
0°-270°	yellow	yellow	orange	orange	green	green	green	orange	yellow	green	green	red	red	green	green
0°-300°	green	green	orange	orange	green	green	green	orange	yellow	green	green	red	red	green	green
0°-330°	green	green	red	orange	green	green	green	orange	yellow	green	green	red	red	green	green
0°-360°	green	green	red	orange	green	green	green	red	orange	green	green	red	red	green	green
30°-60°	green	green	green	green	green	green	green	green	green	green	green	green	green	green	green
30°-90°	yellow	yellow	orange	orange	green	orange	green	green	green	green	green	green	green	green	green
30°-120°	yellow	orange	orange	yellow	green	green	orange	orange	green	green	red	red	green	green	green
30°-150°	yellow	yellow	orange	orange	yellow	green	green	orange	green	green	green	red	red	green	green
30°-180°	yellow	yellow	orange	orange	yellow	green	green	orange	yellow	green	green	red	red	green	green
30°-210°	yellow	yellow	orange	orange	green	green	green	orange	yellow	green	green	red	red	green	green
30°-240°	yellow	yellow	orange	orange	green	green	green	orange	yellow	green	green	red	red	green	green
30°-270°	yellow	yellow	red	orange	green	green	green	red	yellow	green	green	red	red	green	green
30°-300°	green	green	red	orange	green	green	green	red	green	green	green	red	red	green	green
30°-330°	green	green	red	orange	green	green	green	red	yellow	green	green	red	red	green	green
30°-360°	green	green	red	orange	green	green	green	red	orange	green	red	red	red	green	green
60°-90°	green	green	green	green	green	green	green	green	green	green	green	green	green	green	green
60°-120°	orange	orange	yellow	green	green	orange	orange	green	green	green	red	red	green	green	green
60°-150°	yellow	orange	orange	green	green	green	orange	orange	green	green	red	red	green	green	green
60°-180°	yellow	orange	orange	yellow	green	green	orange	yellow	green	green	red	red	red	green	green
60°-210°	yellow	orange	orange	yellow	green	green	orange	yellow	green	green	red	red	red	green	green
60°-240°	yellow	red	orange	yellow	green	green	red	orange	green	green	red	red	red	green	green
60°-270°	green	red	red	yellow	green	green	red	orange	green	green	red	red	red	green	green
60°-300°	green	red	red	yellow	green	green	red	red	green	green	red	red	red	green	green
60°-330°	yellow	red	red	yellow	green	yellow	red	red	green	green	red	red	red	green	green
60°-360°	orange	red	red	orange	green	yellow	red	red	yellow	green	red	red	red	green	green

In the depicted figure, it is possible to observe a slight deviation in the voltage waveform on the contact (red line) in the instant of the disturbance happening, as highlighted by the red circle. Meanwhile, the waveform of the input to the coil is depicted in yellow. It is worth noting that the disturbance does not occur immediately at the voltage sag trigger but typically manifests with a 90° delay.
As shown in the graph in Fig. 8, for C2 and C3, the tests where more openings occur, are those with a residual voltage of 20%, with 9 and 46 openings respectively out of 79 cases.

Table III: Test with DIP begin: 90°, 120°, 150°, 180°

Duration	Voltage residual [% Vn]														
	C1					C2					C3				
	0%	20%	40%	60%	80%	0%	20%	40%	60%	80%	0%	20%	40%	60%	80%
90°-120°															
90°-150°															
90°-180°															
90°-210°															
90°-240°															
90°-270°															
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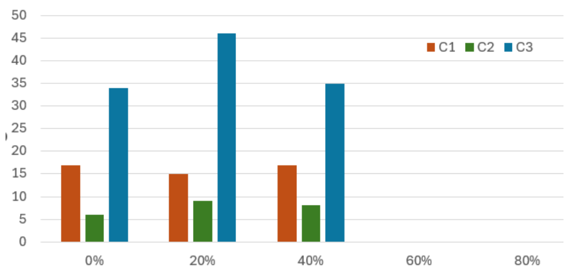

Fig. 8. Number of tests with contact openings

For C1, the worst cases are with a residual voltage of 0% and 40% equally with 17 cases out of 78 (22%). No openings occur with voltage dips of 60% and 80%, which complies with the regulatory standard. In other words, a voltage sag with residual voltage is more dangerous than one with zero voltage.

Table IV: Test with DIP begin: 210°, 240°, 270°, 300°, 330°

Duration	Voltage residual [% Vn]														
	C1					C2					C3				
	0%	20%	40%	60%	80%	0%	20%	40%	60%	80%	0%	20%	40%	60%	80%
210°-240°															
210°-270°															
210°-300°															
210°-330°															
210°-360°															
240°-270°															
240°-300°															
240°-330°															
240°-360°															
270°-300°															
270°-330°															
270°-360°															
300°-330°															
300°-360°															
330°-360°															

Reorganizing the tables into a graph for the case of Vr=40%, as shown in Fig. 9, it is evident that in all three contactors, the contact opening occurs if the voltage sag lasts at least 90°, and the likelihood of contact opening is higher if the sag not only lasts longer but also distorts the voltage waveform between 300° and 360°.

4. Conclusion

The conclusions of the experimental study on AC contactors clearly highlight the importance of voltage sag magnitude, duration, and onset point in influencing the sensitivity of such devices. It was found that differences in manufacturing and size of the contactors result in significant variations in their susceptibility. However, the overall evaluation of contactors' susceptibility to voltage sags revealed that many equipment do not fall within acceptable tolerance limits.

Voltage sags on contactors can lead to various issues [15], including interruption of ongoing operations or uncontrolled motor restarts, with undesirable consequences. Therefore, careful consideration of operational limit characteristics during such events is crucial to ensure industrial operations continuity.

Additionally, it was emphasized that the onset point of voltage sag significantly impacts the overall performance of the contactor.

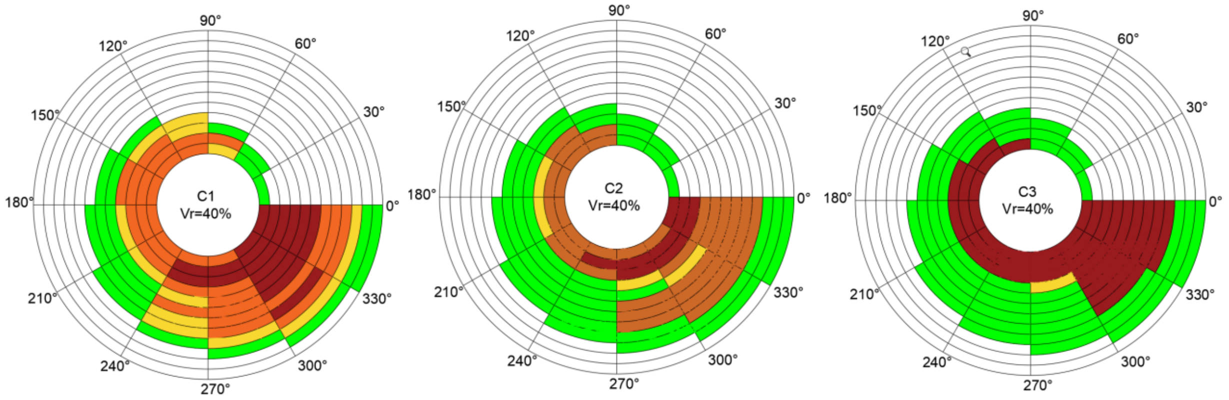

Fig. 9. Tests with Vr=40%

Furthermore, the sensitivity of contactors to voltage sags was evaluated through laboratory tests, confirming the importance of a detailed assessment of their performance under real conditions.

Regarding future developments [14], there is a clear need for further research aimed at improving the ride-through capability of AC coil contactors, an area that has received limited attention thus far. Furthermore, to ensure more comprehensive standards, it would be desirable to include additional variables such as phase angle jump, waveform distortion, and voltage change rate in the definition of future standards [16]. For a more in-depth study, it should also be considered to test contactors under voltage sags throughout their life-cycle, as contact performance can depend on factors such as temperature and repeated stress on the spring and contacts. Given that contactors are sensitive to voltage sags, it would be beneficial to power the contactor circuit not only with transformers or power supplies, but also with small online UPSs.

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