CONTROL AND OPTIMIZATION OF VOLTAGE PROFILES AND SAG MITIGATION IN LOW-VOLTAGE POWER NETWORKS

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Voltage sags, swells, and fluctuations in low-voltage networks can disrupt sensitive equipment, reduce industrial productivity, and accelerate component aging. This paper reviews common assessment practices, including ITIC/CBEMA curves and waveform analysis, and proposes an enhanced method that also considers pre- and post-event intervals to better quantify disturbance severity and recovery behavior. A disturbance direction detection procedure is presented to support source localization and targeted mitigation. As an alternative to conventional UPS-based solutions, active voltage conditioners (AVC)/dynamic voltage restorers (DVR) are discussed for fast compensation without energy storage and with high tolerance to voltage variations, while not covering complete interruptions. The main contribution is a combined DVR/AVC and active filtering solution that improves voltage stability, power factor, and harmonic content, enabling a cleaner, more reliable supply.

1. INTRODUCTION

A voltage sag (also called a voltage dip/drop in IEC terminology) is a short-duration reduction in RMS voltage in an electrical power system. According to IEEE Std 1159 [1] and IEC61000-4-30 standard [2], it occurs when the voltage drops between 10% and 90% of the nominal voltage, and the duration is greater than 0.5 cycles and less than or equal to 1 minute (typically 0.5 cycles to a few seconds). Sags are among the most frequent power quality issues [3]. Common causes include faults on transmission or distribution networks or external factors (*e.g.*, lightning strikes, falling trees over the active conductors, severe weather, or accidents on power lines).

Among the consequences of the voltage sags, we can list disruption of sensitive equipment such as continuous production lines, lighting and safety systems, and computer equipment. Increased current draw in electronic devices during sags can lead to overheating and long-term degradation. Even a sag lasting a few hundred milliseconds can cause unscheduled downtime for hours.

A voltage swell is a short duration increase in RMS voltage above the nominal level in an electrical power system. According to IEEE Std 1159 [1] and IEC 61000-4-30 [2] it occurs when the voltage rises to between 110% and 180% of nominal voltage. The duration is greater than 0.5 cycles and less than or equal to 1 min (typically milliseconds to a few seconds). Among the cases we enumerate are sudden reduction of large loads, single-phase faults in ungrounded systems, capacitor bank switching, transformer tap changes, or fault-clearing operations in the network.

Power outages generated by side effects of the voltage sags or swells have a significant economic impact, with the industrial sector recording an average of 56 such events annually in certain geographical regions [4–6]. According to EPRI (Electric Power Research Institute) estimates, the total annual cost of power quality-related events for U.S. companies can reach around $230 billion [4]. The identification and analysis of voltage variations, like voltage sags or swells, is very important for the evaluation of energy quality and the implementation of customized solutions for each case. Given the negative effects on most types of equipment, it is essential that voltage drops are identified, quantified, characterized, and analyzed quickly and accurately. Current methods often use graphical representations in the form of scatter plots on tolerance curves defined by the Information Technology Industry Council (ITIC) [6], SEMI F-47 [7]. While these curves are useful for summary reports, they only provide general recommendations for specific applications at certain voltage levels. The responsibility lies with end users to assess whether discrete voltage drops affected the system or load, what the effects were, their duration, and ways to reduce the future impact.

The paper highlights an alternative solution to the classical solution used with UPSs for voltage fluctuations and sags, with advantages (no energy storage and high tolerances for voltage fluctuations) and disadvantages (not addressing voltage interruptions). The originality is the mixed solution between dynamic voltage restorers and active filters working together for a more reliable and cleaner electrical network by providing a more stable network with an excellent power factor and less harmonic content.

2. CURRENT METHODOLOGIES FOR ASSESSING THE IMPACT OF VOLTAGE SAGS AND SWELLS

The methods currently used for the analysis and understanding of the rapid voltage variations generally focus on the characteristics of the event in the interval in which it occurs, more specifically, on the parameters during the period when the voltage deviates from the accepted normal range. The characterization and assessment of the magnitude variation, duration, phase(s) affected, phase shift, and other relevant characteristics provide essential information, as exposure to any of these elements can negatively influence the operation of industrial equipment and processes.

The ITIC curve [6] provides an AC voltage boundary that most information technology equipment can tolerate or ride through without experiencing unexpected shutdowns or malfunctions. Information technology equipment could include single-phase computers, printers, scanners, etc. [8-10]. Figure 1 depicts the characterization of the ITIC curve. The horizontal axis represents time (in electrical cycles), and the vertical axis represents the Voltage magnitude in percentage from the nominal voltage. If a disturbance defined by voltage magnitude and duration is plotted inside the curve, then the disturbance may not affect electronic devices, while the disturbances plotted outside the curve may have consequences on the electronic devices.

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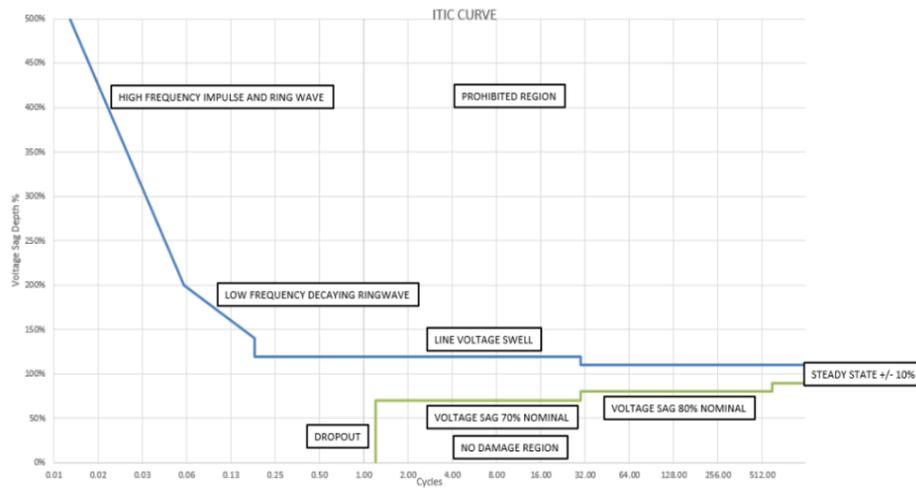
Fig. 1 – Characterization of the ITIC curve [10].

The literature provides examples of the characterization of voltage sags and methodologies for testing immunity to these phenomena [10–15]. As an example, in Fig. 2, a waveform capture for voltages (upper waveform) and currents (bottom waveform) from a power quality meter is presented when a voltage disturbance was detected in the electrical network.

The approach based on the characterization and evaluation of parameters within the sag event is direct and useful for comparing, analyzing, and quantifying the exposure to voltage sags at discrete points of the electrical system. Moreover, advanced measuring devices such as power quality meters with advanced-analysis software tools have been designed to characterize such events. This methodology is now considered standard and expected by users purchasing monitoring equipment and solutions [16–19].
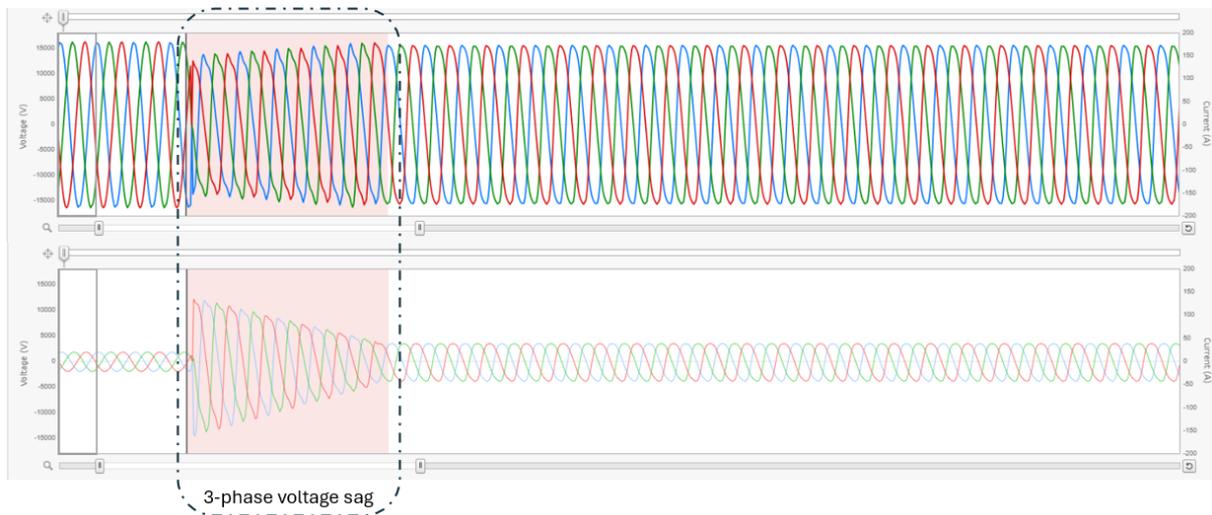

Fig. 2 – Waveform capture for a three-phase fault with the indication of the analysis area.

An established and widely used approach to the analysis of voltage sags and swells is the use of tolerance curves, which represent, in the form of a scatterplot, multiple events of voltage sag or swell on a single diagram. These graphs allow users to quickly assess key parameters associated with voltage sag/swell, such as the amplitude and duration of the event, to determine characteristic trends or the frequency of occurrences. At the same time, they can be useful for estimating the efficiency of equipment dedicated to maintaining operation in such conditions [20,21].

Figure 3 describes multiple incidents (disturbances) captured by a power quality meter within a specific period in an ITIC curve representation. Each point in the graph represents a disturbance characterized by magnitude (%) from the nominal voltage and duration.
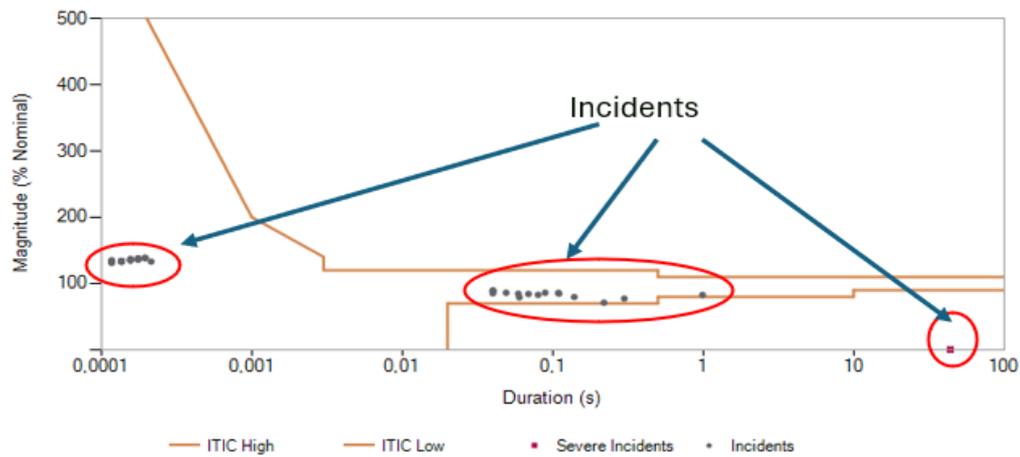
Worst Disturbance per Incident						
ID	Incident Time	Meter	Type	Phase	Duration (s)	Magnitude (%)
1	02.09.2025 05:23:18	Main PQ Meter	Sag	V3	0.059	84.51
2	03.09.2025 12:31:12	Main PQ Meter	Sag	V2	0.109	85.72
3	03.09.2025 13:54:42	Main PQ Meter	Sag	V2	0.110	84.61
4	03.09.2025 13:56:44	Main PQ Meter	Interruption *	V1	972.000	0.00
5	03.09.2025 14:30:45	Main PQ Meter	Interruption *	V1	137.000	0.00
6	05.09.2025 06:21:43	Main PQ Meter	Interruption *	V1	413.000	0.00
7	05.09.2025 06:48:15	Main PQ Meter	Interruption *	V1	282.000	0.00
8	05.09.2025 09:36:04	Main PQ Meter	Interruption *	V1	44.000	0.00
9	08.09.2025 05:14:47	Main PQ Meter	Sag	V2	0.040	89.05
10	18.09.2025 23:17:07	Main PQ Meter	Sag	V3	0.139	79.61
11	28.09.2025 01:41:07	Main PQ Meter	Sag	V3	0.219	70.95
12	29.09.2025 06:05:51	Main PQ Meter	Interruption *	V1	6,165.000	0.00

Fig. 3 – Multiple power quality incidents visualization using tolerance curves [11].

Other methods may involve analyzing the waveform characteristics of the voltage variation to identify the cause and/or location of the event. Determining the cause and location of voltage drops is a critical element for diagnosing and mitigating these phenomena. In this context, it is necessary to simultaneously evaluate the voltage and current waveforms associated with the voltage drop event.

3. NEW APPROACH TO ASSESSING THE IMPACT OF SAGSVOLTAGE SAGS AND SWELLS

Understanding an event's impact on network operation requires attention not only to the characteristics of voltage variations, but also to the wider system-level context. When a voltage variation occurs, we need to evaluate the impact of the disturbance on the customer network based on a summary or complex power quality audit. The evaluation depends on several factors, but mainly on whether the client's activity has been affected or not (power supply continuity, damage to the equipment, *etc.*). No customer wants to be exposed to voltage disturbances, and not all voltage variations have the same impact on the customer's network.

Questions that can be asked by clients to better understand the context may include [4]:
- Where did the voltage variation occur?
- What caused the voltage variation?
- How long did it take to restore the system?
- What happened after the waveform capture ended?
- Did the biggest/worst impact on the total load occur during waveform capture or after?
- How long did it take to fully restore the electrical system?
- How much energy was expended during recovery?
- How does restoration after voltage drops affect the system's ability to produce a product?
- What is the optimal approach (cost vs. benefits) for mitigating voltage drops in the system?

Figure 4 highlights additional useful information about the waveform capture event compared to Fig. 2 by adding two analysis areas: pre-event and post-event. These additional areas are useful for a deeper understanding of the entire event. The pre-event data provides a "benchmark" of the nominal characteristics of the system before the occurrence of disturbance, and the post-event data are essential for describing the changes that occurred in the system caused by the event and what impacts they generate. The goal of pre-event and post-event analysis is to generate new and useful event information from the initial impact of the disturbance to full system restoration. This information is useful to know what voltage variations mitigation solutions are suitable for implementation.
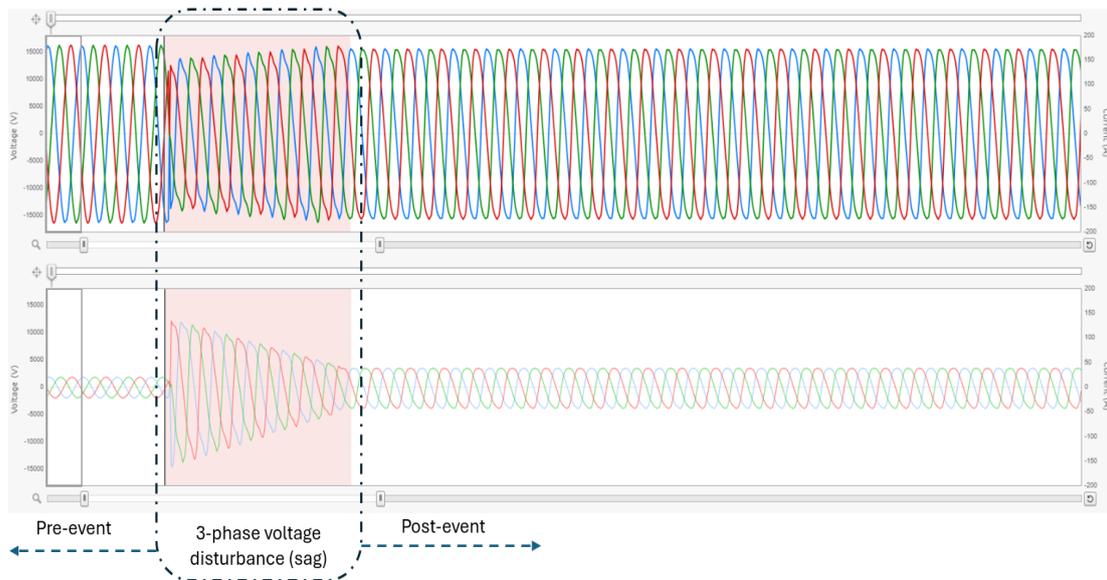
Fig. 4 – Waveform capture for a three-phase fault with the indication of the analysis area and pre & post event analysis area.

3.1 DISTURBANCE DIRECTION DETECTION

By analyzing the voltage, current, and power evolution during a disturbance event, we can determine if the event occurs upstream or downstream of the measurement point, which can give us an indication of the direction of occurrence of the disturbance. In power quality (PQ) metering, the terms upstream and downstream are relative, directional concepts. They describe where a disturbance comes from and how it propagates through the electrical system, always referring to the location of the meter.

For example, if a load is connected downstream of the measurement point, the meter can record the corresponding increase in current and decrease in voltage and determine that the event occurred downstream. Under ideal conditions with stable waveforms prior to the event, this determination can be made easily and reliably by simply identifying the point in the waveform that differs from previous waveforms. However, when waveforms vary and are "noisy", the sample of previous waveforms is small, and the amplitude of the event is reduced, it becomes much more difficult to locate the event in the waveform data and correctly determine its direction [10,19–22]. This analysis can be done by power quality experts' teams by analyzing the recorded data by the power quality meters, or can be done automatically by advanced power quality meters with disturbance direction detection capabilities and analysis software tools. Disturbance direction detection capabilities help determine the location of a power system disturbance.

When a disturbance occurs, the meter analyzes the disturbance information to determine the direction of the disturbance relative to the meter. This analysis includes a confidence level indicating the level of certainty (indeterminate, low, medium, high) that the disturbance is in the determined direction and is stored in your meter's event log [19–22]. If we have multiple meters in the same network with this functionality, we can detect the location of the disturbance more accurately. Figure 5 illustrates the disturbance direction detection principle. If additional dedicated software tools are used together with the meters, the information is displayed in a user-friendly manner.

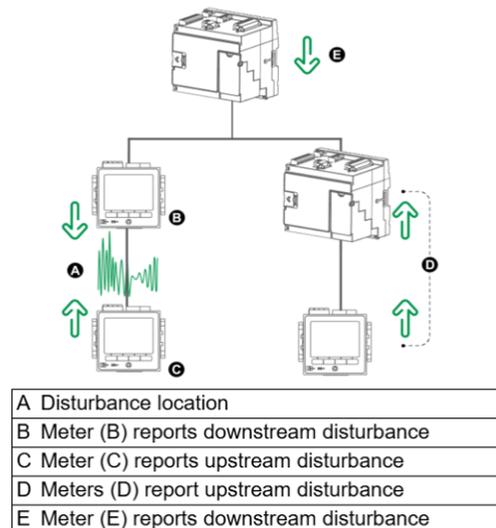| A | Disturbance location |
B	Meter (B) reports downstream disturbance
C	Meter (C) reports upstream disturbance
D	Meters (D) report upstream disturbance
E	Meter (E) reports downstream disturbance

Fig. 5 – Disturbance direction detection principle implemented in some advanced power quality meters [15].

4. WAVEFORM ANALYSIS AND LOAD IMPACT ASSESSMENT

The first essential parameter to be calculated is the impact of the voltage drop on the load. In Fig. 6 we have the waveform capture at disturbances that have the probable cause of an upstream voltage drop with the voltage dropping to 84.5% of the nominal voltage, the total duration of 79.2 ms (the representative event having a duration of 58.3 ms) and the power loss at the load level of -69.02 kW (the active power at the beginning of the event was 124.22 kW, and the active power at the end of the event was 55.21 kW). The maximum current was 232 A, and the minimum current reached 79.97 A.
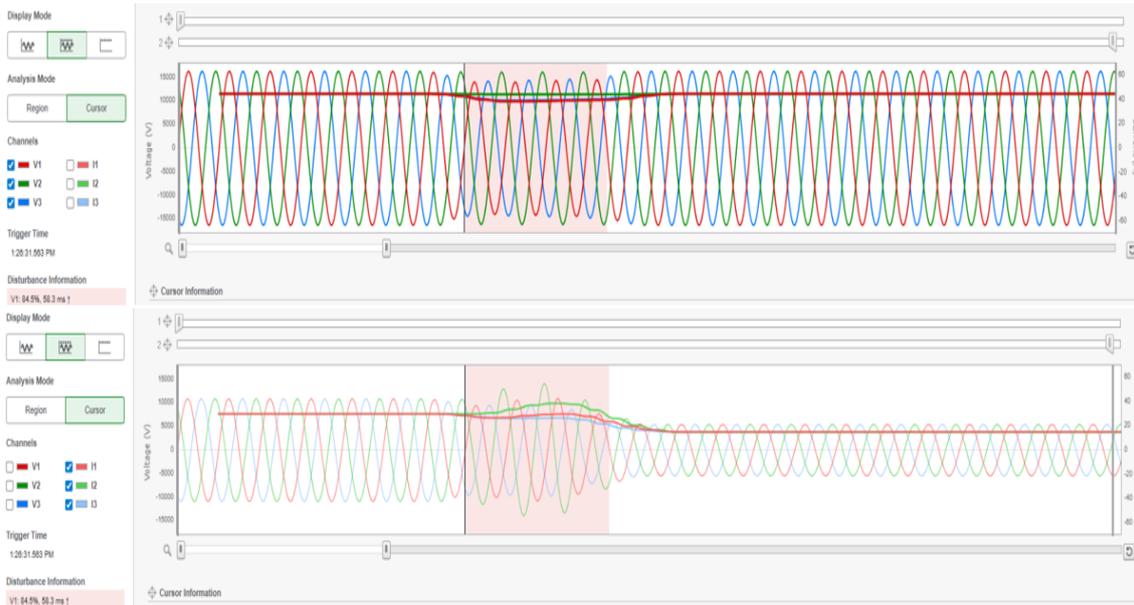
Fig. 6 – Waveform capture and details of an upstream voltage sag

In Fig. 7, we represent the same disturbance as in Fig. 6 using the ITIC/CBEMA tolerance curve. In this case, we have only one incident, and the power quality monitoring software provides additional information about the event (start and end time, time duration, magnitude, direction of the propagation of the disturbance: upstream or downstream from the location of the meter).
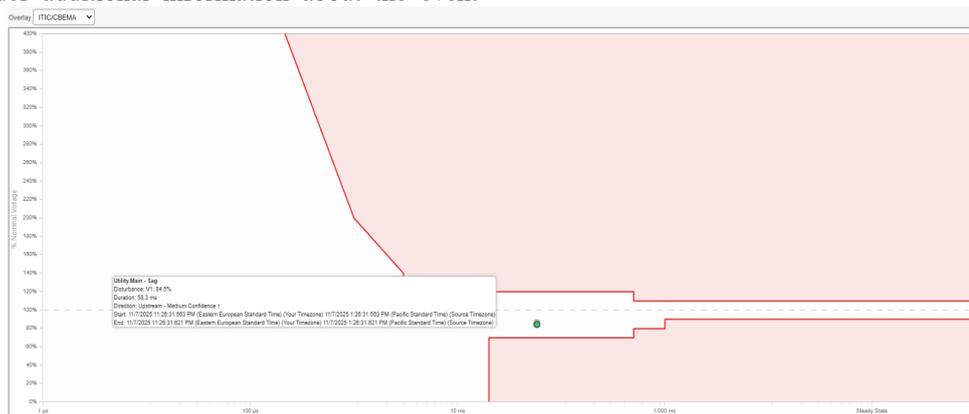

Fig. 7 – Waveform capture and details of an upstream voltage sag.

By knowing the disturbance direction with reference to the point of common coupling, we can identify the best solutions for voltage sags.

If the voltage sags are generated downstream from the sensitive loads, then a possible solution for voltage sag mitigation is to use electronic voltage compensators with a very fast response time (up to 5 ms). If the voltage sags are generated upstream from the point of common coupling (PCC), in the electrical distribution or transmission network (short circuits, line-to-ground faults, or external factors like lightning strikes, falling trees, severe weather, or accidents on power lines), then mitigation sag solutions can include uninterruptible power supply (UPS) systems, dynamic voltage restorers (DVR) or active voltage conditioners (AVC) and voltage regulators. The next chapter details dynamic voltage restorers or active voltage conditioners.

5. VOLTAGE SAG MITIGATION WITH ACTIVE VOLTAGE CONDITIONERS (AVC)

Power grids consist of transmission and distribution networks, reflecting the long distances between generation sites and load centers. Grid robustness describes the ability to withstand sudden power changes; long transmission corridors to remote areas tend to weaken the system and degrade delivered power quality.

A key consequence of a weak grid is voltage instability. Limited capability to absorb rapid variations causes voltage fluctuations that disrupt industrial processes, reduce product and service quality, and accelerate equipment failure rates and shorten machine lifetime. The massive integration of renewables, such as photovoltaics and wind energy, amplifies grid instability, as their production is variable and difficult to control. Phenomena such as "brownouts" (a temporary sag in voltage in an electricity supply system, rather than a complete loss of energy), surges, and phase imbalances, characteristics of weak grids, generate inefficient use of resources and require the use of expensive backup power systems, such as diesel generators.

For compensating for voltage sag events, but also for overvoltages that are generated from the transmission and distribution network, an innovative solution is represented by AVC, also known as DVR or sag fighters [13–16].

As defined by IEEE 1409-2012 [8], a DVR is "a power electronics-based waveform synthesis device that is series connected directly into the primary distribution circuit by means of a set of series-connected single-phase injection transformers." A DVR can regulate voltage by boosting or bucking the instantaneous voltage during momentary changes to the primary feeder voltage.

Among the applications, one can list the protection of sensitive consumers in the industrial and commercial environment against voltage sags/swells and the flicker phenomenon, but also the continuous voltage regulation.

Active voltage conditioners help manage various electrical energy quality issues, including voltage sags and swells, continuous voltage regulation (stabilization), phase imbalance, phase-shifting correction, voltage fluctuations, and flicker.

5.1 WORKING PRINCIPLE

An active voltage compensator can regulate voltage by instantaneously increasing or decreasing voltage during momentary voltage variations on the main supply. In addition, this equipment may be able to inject non-fundamental voltage frequencies to control and mitigate harmonic voltage distortion into the circuit. DVRs are generally used in low and medium voltage applications and can provide continuity in the event of voltage drops of up to 40-60% and continuously adjust voltages up to approximately within ±10% from the nominal voltages and

some vendors can continuously adjust the voltages within ±20% from the nominal voltage.

The schematic electrical diagram of an active voltage compensator is detailed in Fig. 8 [15].
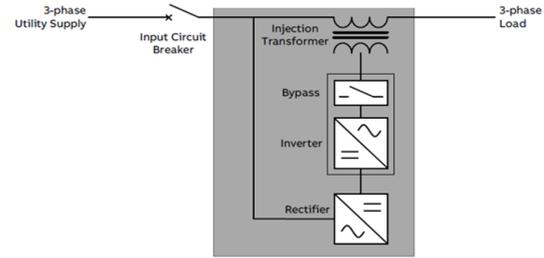
Fig. 8 – Schematic diagram of an active voltage compensator [15].

The AVC system uses a voltage source inverter and a series Injection Transformer between the supply and load, enabling fast correction of supply voltage disturbances. A bypass system activates during faults or inverter overloads, redirecting the load away from the inverter. When in bypass mode, the load receives standard utility voltage [13–16].

Figure 9 shows two scenarios: the voltage compensator addresses either a sag (left) or a swell (right). When utility voltage strays from the nominal value due to sags, surges, undervoltage, overvoltage, or imbalance, the inverter injects a correcting voltage through the Injection Transformer. The amount of correction depends on the disturbance level, with energy supplied by the utility via the rectifier [13–16].
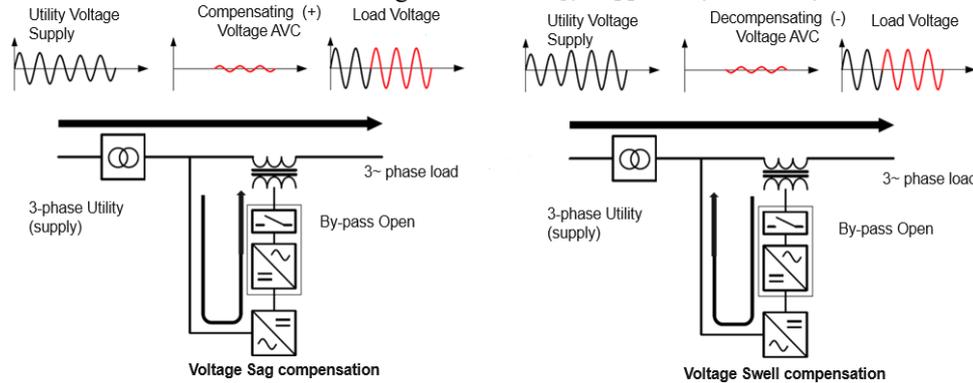

Fig. 9 – Voltage regulation principle at the output of the AVC [16].

Figure 10 presents the regulation characteristics of the active voltage compensators as input–output curves, relating the supply (network) input voltage to the compensated output voltage. The curves define the expected corrected output voltage as a function of the input voltage at the compensator terminals [13–16].
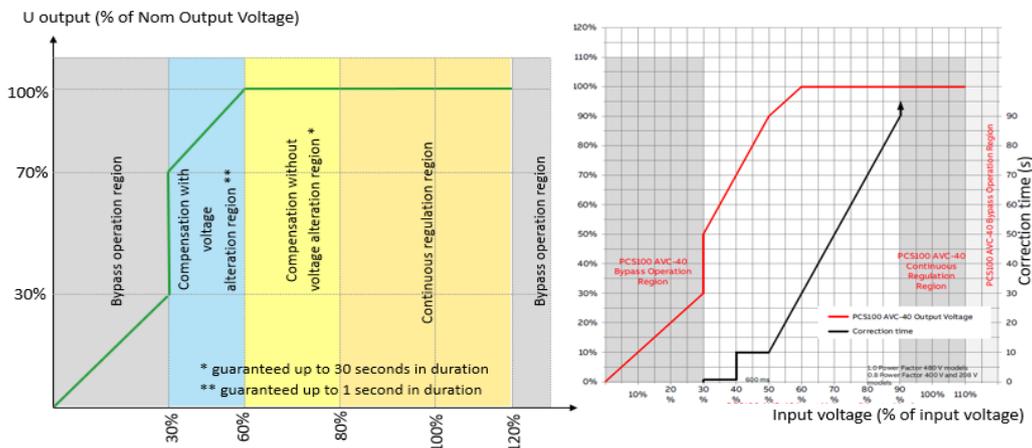

Fig. 10 – Voltage regulation principle at the output of the AVC from two different manufacturers: Schneider Electric (left) and ABB (right) [16, 17].

These devices can compensate for single-phase voltage sags as well, using a different performance curve. Rectifier modules convert three-phase AC into a regulated DC voltage. By integrating power electronics with sinusoidal filters in a single module using advanced IGBT technology, these rectifiers minimize harmonics and maintain power quality on the grid [13–16]. Inverter modules use IGBT technology to quickly respond to power disruptions, ensuring precise voltage compensation. With sinusoidal and integrated RFI filters, they minimize power quality impact under load. Each module includes a fail-safe bypass circuit, which disconnects the inverter during overload or manual bypass by shorting the serial transformer from the voltage compensator [13–16].

The Fail-Safe Bypass circuit is intended to disconnect the output inverter from the system during overloads or when operating in manual bypass mode. It does this by short-circuiting the inverter through an injection transformer. This setup uses both high-speed silicon controlled rectifier (SCR) electronic switches and mechanical contactors, offering two layers of redundancy. As a result, the inverter can be quickly and safely short-circuited without affecting the load [13–16]. An injection transformer (booster) adapts the mains input voltage to the compensator's regulated output for the load. It is a dry-type transformer [13–16].

5.2 CASE STUDY AND SOLUTION IMPLEMENTATION

Active voltage conditioners have similar working principles to UPS, with the difference that UPSs can handle voltage interruptions while AVCs can sustain only voltage sags. The main advantage of the AVC vs UPS is the compensation principle: AVC does not store the energy in batteries like UPS or capacitors. When the device is requested to compensate for a sag, it draws more current from the supply network. Being a battery-free storage device, the operating and maintenance costs are reduced compared to a UPS. The efficiency of an AVC is higher than 97-98%, similar to the UPS.

Unlike computer-grade devices or UPS systems, industrial-grade active voltage conditioners are built for production environments with frequent high inrush loads. Thanks to their durable design and advanced overload protection, oversizing is unnecessary. The connection of active voltage conditioners is in series with the protected load, like a UPS.

In terms of investment costs, AVC is more effective than a UPS over a 600 kVA apparent power range, due to the high costs of the batteries required by UPS solutions.

Because the injection transformer behaves as a series impedance with the relative impedance of about 2% in the primary winding, it has the following consequences for nonlinear loads:

- The compensator slightly reduces the current total harmonic distortion (THDi) at the output of the AVC on the electrical load side. For instance, if the load exhibits a THDi of 20% without an AVC, connecting the compensator typically lowers the value to approximately 17–18%.
- The voltage total harmonic distortion (THDu) increases at the AVC output. For example, with an input THDu of 6%, the output may rise to 8–9%. This parameter requires careful consideration. It is recommended that such solutions be implemented only where the installation's THDu does not exceed 5% to remain compliant with standard limits. Alternatively, additional measures such as installing active filters may be necessary to mitigate elevated THDu levels.

The solution is exemplified in Fig. 11, after a comprehensive network study to define the magnitude, duration, and direction of the voltage sags.
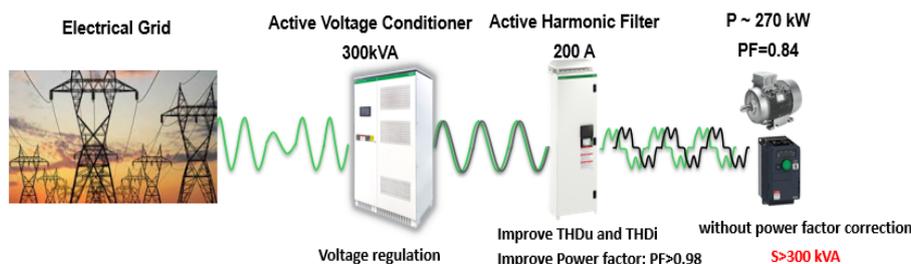

Fig. 11 – Combined solution active voltage conditioner and active filters [16].

Figure 11 is a combined solution to clean the network, decrease the current and voltage harmonics, and improve power factor correction generated by motors and variable speed drives (non-linear loads) using active harmonic filters on one side, and on the other side, a solution to mitigate voltage sags came from the utility network using active voltage conditioners to protect the sensitive loads.

An active harmonic filter is used to improve the fast and dynamic power factor by injecting the reactive energy required by the loads. In this way, we decrease the apparent power drawn from the network to be below the maximum apparent power supported by the active voltage conditioner (300 kVA). The active filter is connected in parallel with the loads. The second purpose of the active filter is to decrease the current and voltage harmonic content generated by non-linear loads, like variable speed drives (THDi generators), and the effect of increasing the THDu by installing the AVC in the network, as we explained above. An active voltage conditioner is installed in series between the network and the loads and the active filter.

6. CONCLUSIONS

Industrial active voltage conditioners are designed to ensure that equipment is consistently prepared for compensation, eliminating the need for resetting or recharging. This readiness contributes to operational reliability and minimizes downtime.

The systems offer low capital expenditure (Capex) and exceptionally low operational expenditure (Opex), with high efficiency rates exceeding 98%. This efficiency results in significant cost savings over the product's lifespan.

Utilizing IGBT-based technology, the active voltage conditioner addresses voltage sag and swell events. During a voltage sag, the device maintains the apparent power (kVA) by drawing increased current from the grid, protecting sensitive equipment and processes.

Compensation solutions are available across a wide power range, typically from 50 kVA up to 3600 kVA, making them suitable for various industrial applications. Maintenance requirements are minimal, as these devices do not rely on batteries for energy storage, unlike traditional UPS systems. The absence of batteries reduces both the complexity and the ongoing costs associated with maintenance. It should be noted that an active voltage conditioner does not ensure continuity in case of voltage interruptions. In some configurations, an AVC system can be combined with a UPS system to provide protection for voltage sags and outages.

Expanding the analysis of voltage drops beyond their simple occurrence to include the evaluation of their effects introduces a consequences-oriented perspective within consumer installations. The innovative parameters identified in this study serve as practical and appealing tools for examining the impacts of voltage drops. While the list of parameters provided is not exhaustive, it demonstrates the potential for introducing new dimensions into the assessment of these phenomena. It is important to recognize that consumer market segments are diverse and do not share the same operational concerns. Despite this diversity, many consumers rely on similar types of tasks and technologies. Consequently, voltage drops can influence each consumer's operations in distinct ways, even within the same market segment, although the equipment used may exhibit similar susceptibility to such events. Effectively applying this information requires a suitable level of technical expertise.

The approach proposed in this article makes the consequences of voltage sags more accessible to end-users. It facilitates the adoption of mitigation technologies, such as the Active Voltage Compensator (AVC/DVR), which, when combined with an Energy Monitoring System (EPMS), allows for effective performance demonstration and validation.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Gabriel Ioana: chapters 1, 5, and 6 (partial)

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Marilena Stănculescu: chapter 2, 3 (partial), 6 (partial)

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