# MODERN METHODS FOR RAPID CORRECTION OF VOLTAGE ANOMALIES IN SENSITIVE LOADS USING DVR (DYNAMIC VOLTAGE RESTORER) SYSTEMS

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**Abstract:** *This paper analyzes the impact of voltage anomalies, particularly voltage sags and short-duration swells, on sensitive electrical and electronic equipment. The causes of these network disturbances and their rapid detection methods are presented. The main focus of the work is the evaluation of active compensation technologies, with an emphasis on the Dynamic Voltage Restorer (DVR). The paper outlines the control architecture, inverter topology, and voltage injection strategies required to ensure an uninterrupted power supply to critical loads.*

*The control architecture utilizes the Park Transform (d-q-0) and a Phase-Locked Loop (PLL) for quasi-instantaneous detection, enabling disturbance compensation with a response time of less than half a cycle of the fundamental wave (<10 ms). The system's performance is validated through MATLAB/Simulink simulations under severe voltage variation scenarios (30% voltage drops and rises). The results confirm that the DVR system is the most technically and economically efficient method for protecting critical loads, preventing the accidental shutdown of production lines, and eliminating major financial losses.*

**Keywords:** Power Quality; Voltage Sag; Voltage Swell; Dynamic Voltage Restorer (DVR); Park Transform; Active Compensation

## 1. INTRODUCTION

In the current context of industrial development and the accelerated transition toward concepts specific to Industry 4.0, power quality (PQ) has become a critical factor in ensuring the continuity, safety, and efficiency of production processes. Although power distribution networks are designed to supply energy at constant nominal parameters, the increasing complexity of power systems and the interconnection of a vast number of non-linear loads make ideal power supply, in practice, impossible to maintain permanently[1].

### 1.1. Power Quality and the Sensitivity of Modern Equipment

The regulatory framework regarding the characteristics of the voltage supplied in public distribution networks is regulated at the European level by the EN 50160 standard. This defines the acceptable limits for voltage variations, frequency, asymmetries, and harmonic content. However, even when the parameters fall within the statistical limits imposed by the standard, short-term disturbances can have devastating effects on consumers. Modern equipment is based on semiconductor and microprocessor technologies, which operate at low voltages and high frequencies [2]. Among the most vulnerable equipment are:

- **Programmable Logic Controllers (PLCs):** Sensitive to micro-interruptions and voltage variations, which can cause a reset of the control logic and the shutdown of the entire production line.
- **Industrial Robots and Adjustable Speed Drives (VFD / ASD):** Power supply voltage variations directly affect the direct current intermediate circuit (DC link), triggering the inverters' undervoltage or overvoltage protection systems.
- **Servers and Data Centers:** Require perfectly continuous power supply to prevent corruption or irretrievable loss of data.
- **Precision Medical Equipment:** Imaging systems (MRI, CT) require absolute voltage stability to guarantee diagnostic accuracy and patient safety [3].

### 1.2. Definition of Transient Voltage Disturbances

Among all the anomalies affecting power quality, short-duration variations in the fundamental voltage amplitude are considered the most frequent and have the greatest economic impact. In the specialized literature and international standards (such as IEEE 1159), these are primarily classified into two major categories:

- Voltage Sag (Dip): Defined as a sudden decrease in the root mean square (RMS) voltage to a value between 10% and 90% of the nominal voltage. This disturbance lasts for a very short duration, ranging from half a cycle of the fundamental wave (10 ms for 50 Hz networks) to 1 minute. Although they are short-duration events, voltage sags account for over 80% of all power quality problems reported in the industrial environment.
- Voltage Swell: Represents the opposite phenomenon of a voltage sag and consists of an increase in the RMS voltage to a value between 110% and 180% of the nominal voltage. Its duration is identical to that of voltage sags, varying from 10 ms to 1 minute. Although they occur less frequently than voltage sags, transient overvoltages can cause immediate physical damage by breaking down insulation and burning out sensitive electronic components.

An exact understanding of these parameters is essential for the proper sizing of active compensation equipment. To ensure the immunity of critical loads against these events, a transition from classical protection methods to ultra-fast dynamic response systems, capable of intervening within the first milliseconds of a fault's occurrence, is imperative [4], [5].

## 2. CAUSES AND EFFECTS OF VOLTAGE ANOMALIES

In order to design and implement efficient DVR compensation systems, it is imperative to understand the physical mechanisms underlying network disturbances, as well as their impact on equipment.

### 2.1. Causes of Voltage Sags

Voltage sags are generated, in the overwhelming majority of cases, by a sudden increase in network currents, which causes an additional voltage drop across the impedances of system elements (transformers, power lines) [6].

The main cause of voltage sags is represented by faults (short circuits) in the transmission and distribution network. From an analytical point of view, the phenomenon can be explained in a simplified manner using the voltage divider model.

The voltage at the point of common coupling (PCC) during a fault, $V_{sag}$, can be calculated as follows:

$$V_{sag} = V_s \cdot \frac{Z_f}{Z_s + Z_f} \tag{1}$$

where:

- $V_s$ is the equivalent source voltage;
- $Z_s$ is the source impedance (including the upstream network);
- $Z_f$ is the fault impedance (the distance from the measurement point to the fault location).

Another frequent cause in the industrial environment is the starting of high-power asynchronous motors. During the starting transient, the absorbed current can be 5 to 7 times higher than the nominal current ($I_{start} \approx 6 \cdot I_{nom}$), behaving similarly to an attenuated short circuit and causing voltage sags with durations on the order of seconds [7].

To visually illustrate the dynamics of this transient phenomenon, Figure 1 presents the simulation of a typical voltage sag. As can be observed on the graph, the nominal condition is disturbed at the time $t = 0.04$ s, when the wave amplitude drops suddenly to 0.5 p.u. (50% of the nominal value) . This anomaly persists for an exact duration of 5 cycles (100 ms), until the time $t = 0.14$ s, when the network fault is considered isolated, and the voltage returns to its initial parameters. Although the occurrence interval is extremely short, the insufficient energy transferred to the load within this time window is often the main cause for the tripping of undervoltage protections in sensitive industrial equipment, resulting in the unplanned shutdown of technological processes [8].

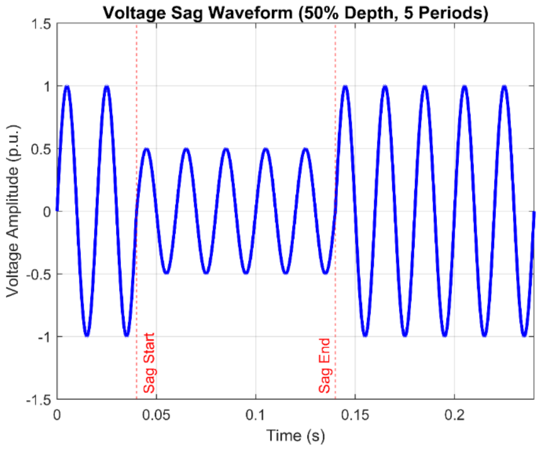

Figure 1. Waveform of a voltage sag with a depth of 50% and a duration of 5 cycles in a 50 Hz network

### 2.2. Causes of Short-Duration Voltage Increases (Voltage Swells)

Although statistically less frequent compared to voltage sags, transient overvoltages (swells) present a high degree of danger because they can cause the instantaneous destruction of equipment through dielectric breakdown. From a physical point of view, these phenomena are generated by a sudden change in network parameters or a redistribution of reactive power. The main causes are:

- **Asymmetrical faults (Single-line-to-ground fault):** This is the most common scenario that generates temporary overvoltages. In a three-phase network with an isolated neutral or one grounded through a compensation coil (Petersen coil), the occurrence of a solid fault on one of the phases (for example, phase A, where the potential becomes zero) causes a displacement of the neutral point potential. Consequently, the voltages of the "healthy" phases (B and C) to ground will no longer be phase voltages, but will increase to the value of the line-to-line voltages. Thus, the RMS voltage on the unaffected phases theoretically increases by a factor of $\sqrt{3}$ , reaching approximately 173% (1.73 p.u.) of the nominal value. This swell condition is maintained until the fault is isolated by specific protections [9].
- **Sudden disconnection of major loads (Load Rejection):** In normal operation, the current absorbed by a massive load causes a voltage drop across the equivalent upstream network impedance. When such a load is suddenly disconnected (for example, due to the accidental tripping of a circuit breaker), this voltage drop disappears instantaneously, resulting in an abrupt voltage increase at the point of common coupling (PCC). Additionally, in the case of disconnecting highly inductive loads (large motors, transformers), the rapid variation of current with respect to time generates an auto-induced switching overvoltage, according to the law of electromagnetic induction:

$$v_L = L \cdot \frac{di}{dt} \tag{2}$$

where:

- $v_L$ is the self-induced switching overvoltage;
- $L$ is the equivalent inductance of the disconnected load (or system);
- $\frac{di}{dt}$ is the rate of change of current with respect to time.

The magnetic energy stored in the system's inductances seeks a discharge path, forcing the occurrence of an oscillating swell at the terminals of the remaining connected equipment [10].

- **Switching of capacitor banks:** To correct the power factor and support the voltage level on the busbars, capacitor banks (or steps) are utilized in substations. At the moment of energizing a discharged capacitor bank, it initially behaves as a short circuit, because the voltage across a capacitor cannot change instantaneously. This inrush current is immediately followed by an oscillatory transient regime between the newly connected capacitance and the inductance of the supply network. The resonance frequency of this oscillating circuit ($f_r$) can be approximated by the following equation:

$$f_r = f_s \cdot \sqrt{\frac{S_{SC}}{Q_C}} \tag{3}$$

where $f_s$ is the system frequency (50 Hz), $S_{SC}$ is the short-circuit power of the network, and $Q_C$ represents the reactive power of the capacitor bank. During this high-frequency oscillation, the voltage can reach transient peaks of up to 200% (2.0 p.u.), which gradually dampen, transforming into a temporary increase in the RMS value [11].

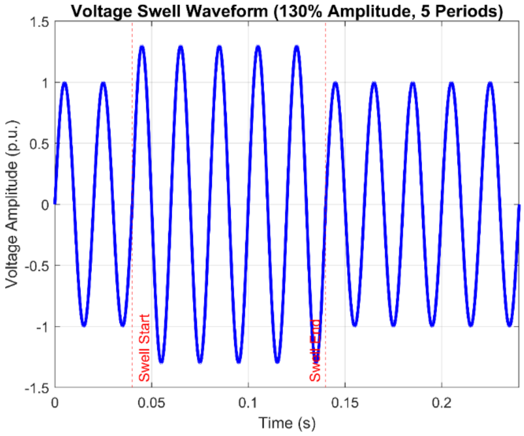

**Figure 2.** Waveform of a voltage swell with an amplitude of 130% (1.3 p.u.) and a duration of 5 cycles in a 50 Hz network.

Complementary to the voltage sag analysis, Figure 2 illustrates the dynamics of a transient overvoltage (swell). In this simulated scenario, it can be observed how the amplitude of the voltage wave abruptly increases to 1.3 p.u. (130% of the nominal value) starting at time $t = 0.04$ s. The disturbance is maintained for a duration of exactly 5 cycles of the fundamental wave (until time $t = 0.14$ s), after which the system returns to normal operation. Although the event is of short duration (100 ms), such an increase in the voltage level is particularly dangerous for sensitive loads. The excess energy transferred during this interval severely stresses the capacitor dielectrics and the semiconductor components in power supplies, potentially causing irreversible destruction through thermal breakdown of the insulation before conventional protections have the necessary physical time to act [12].

### 2.3. Effects of Anomalies on Sensitive Loads

The analysis of the impact of voltage anomalies must extend beyond the technical sphere, also addressing the economic and long-term reliability dimensions. The sensitivity of the equipment is not uniform, as it depends on the internal architecture of the power supplies and the configured protection thresholds.

### 2.3.1. Vulnerability of Automation and Drive Systems

In the industrial environment, the most sensitive elements are electromagnetic contactors and variable frequency drives (VFDs).

- Contactors: These operate on the principle of equilibrium between the coil's electromagnetic force and the restoring spring force. A voltage sag that drops below 60-70% of the nominal value reduces the holding force below the critical threshold, causing the contacts to open in less than one cycle (20 ms). This leads to the instantaneous shutdown of motors and, consequently, of the technological workflow.
- Variable Frequency Drives (VFDs): Most industrial inverters monitor the voltage on the direct current intermediate circuit (DC bus). A voltage sag leads to the rapid discharge of the filter capacitors below the "undervoltage" threshold, triggering the blocking of the IGBT transistors to protect the motor, resulting in process interruption.

### **2.3.2.** Dielectric Stress and Degradation of Electronic Components

Short-duration voltage increases (swells) are the main enemy of power electronic systems.

- Capacitor stress: Switched-mode power supplies (SMPS) utilize electrolytic capacitors sized for a maximum operating voltage. Exceeding this value, even for a few tens of milliseconds, accelerates the electrolyte evaporation process or can lead to the breakdown of the oxide film.
- Insulation aging: According to Arrhenius' law, the insulation degradation rate increases exponentially with temperature and electrical stress. Repeated overvoltages, although not causing immediate failure, drastically reduce the lifespan of motor and transformer windings through micro-breakdowns of the insulating varnish [13].

### **2.3.3.** The Reference Framework: ITIC (CBEMA)

Tolerance Curves To quantify whether an equipment will survive an anomaly, the industry utilizes the ITIC (formerly CBEMA) Curve. This defines a "safe zone" on a graph correlating voltage magnitude (in percentages) with the event duration (in seconds).

- Normal operating zone: Comprises variations of ±10% for an indefinite duration.
- "Ride-Through" zone: Allows severe voltage sags (down to 0%) but for extremely short durations (under 20 ms).
- Prohibited Region: Any event exceeding these limits (e.g., a 140% swell longer than 100 ms) will most likely lead to hardware failure of the equipment.

The dynamics of these sensitivity thresholds are illustrated in detail in Figure 3. Analyzing the graph highlights a critical aspect: although the equipment can withstand severe voltage deviations (including a drop to 0 p.u.), this immunity is strictly limited to durations on the order of milliseconds (typically, under 20 ms). As the duration of the disturbance increases, the tolerance window narrows asymptotically toward the ±10% band corresponding to steady-state operation. This representation fundamentally demonstrates the limitations of classical protection systems (such as voltage relays or thermal releases), whose inert response times allow the operating point to deviate into the Prohibited Region or the No Damage Region. Therefore, the ITIC curve technically justifies the necessity of implementing ultra-fast dynamic response compensation systems, capable of correcting the anomaly and maintaining the voltage profile exclusively within the Safe Operating Zone [14].

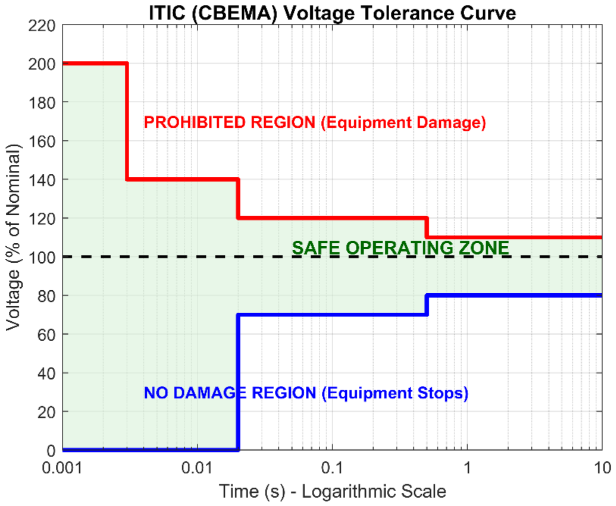

**Figure 3.** Representation of the ITIC (CBEMA) disturbance tolerance curve, highlighting the safe operating limits for IT and sensitive electronic equipment based on the amplitude and duration of the voltage variation.

## 3. TECHNOLOGIES FOR VOLTAGE ANOMALY CORRECTION

To mitigate the technical and economic effects of transient voltage disturbances on sensitive loads, the industry has developed various protection and compensation technologies. Choosing the optimal solution is not solely based on technical correction capability but requires a detailed analysis of response time, overall energy efficiency, and capital (CAPEX) and operational (OPEX) costs. A comparative evaluation of the main available solutions is presented below.

### 3.1. Uninterruptible Power Supplies (UPS)

Classic UPS systems, particularly those with a double-conversion topology (Online UPS), provide comprehensive protection against all network anomalies, ensuring power supply even during long-duration outages (blackouts). In this operating mode, the energy drawn from the grid is rectified into direct current, temporarily stored in a battery bank, and then inverted back into alternating current to supply the load.

However, although they provide ideal isolation of the load from the network, utilizing high-power UPS systems in an industrial environment presents major technical and economic limitations. Their implementation involves extremely high initial costs and a massive footprint required for battery room installations, compounded by a rigorous and expensive maintenance regime. Another critical disadvantage stems from their operating topology: because the entire amount of energy absorbed by the load continuously passes through the double-conversion process (AC-DC-AC), the overall system efficiency drops considerably. This continuous conversion introduces permanent thermal losses into the system, often necessitating supplementary cooling installations and thus generating operational costs (OPEX) that are unjustified for mere protection against short-duration transient variations [15].

### 3.2. On-Load Tap Changers (OLTC) Transformers

Transformers equipped with OLTC systems are widely used in power distribution substations to maintain the voltage profile on the busbars within predefined limits. This regulation is achieved by altering the transformation ratio, an action executed through the mechanical switching of taps on the primary or secondary winding, with the major advantage of not interrupting the power supply to the load during the process.

However, the main impediment of OLTC technology in the context of power quality is the mechanical and control inertia of the switching system. Because the times required to change a tap are on the order of seconds or even minutes, these devices are effective exclusively for slow voltage regulation, compensating for long-term variations caused by load curve fluctuations. Due to this extremely slow dynamic response, OLTC transformers are completely ineffective against transient voltage anomalies (short-duration sags or swells), whose duration is only a few tens of milliseconds, thus leaving sensitive loads entirely unprotected during the fault [16].

### 3.3. Shunt-Connected Devices (Synchronous Condensers and STATCOM)

Shunt-connected compensation systems, such as synchronous condensers or Static Synchronous Compensators (STATCOM), are designed to regulate the voltage level at the point of common coupling (PCC) through the controlled injection or absorption of reactive power. Although these devices are essential for maintaining the overall stability of the power system at a macroscopic level, their ability to correct a deep voltage sag at the local consumer level is strongly limited by the value of the upstream network impedance. To restore the nominal voltage level on a bus affected by a fault, a shunt-type device must inject massive reactive currents into the network, with a large portion of this energy dissipating toward the faulted branch of the system, rather than to the protected load. Consequently, the exclusive use of these topologies for the local protection of sensitive industrial equipment is technically inefficient and heavily oversized from an implementation cost perspective [17].

### 3.4. Dynamic Voltage Restorer (DVR)

Unlike the previously analyzed solutions, the Dynamic Voltage Restorer (DVR) represents a state-of-the-art active compensation technology, connected exclusively in series between the power supply network and the critical load. This topology offers a decisive functional advantage: the system continuously monitors the grid voltage wave, and upon detecting an amplitude deviation (voltage sag or swell), the integrated inverter instantaneously synthesizes the required compensation voltage, injecting it into the circuit perfectly in phase with the fundamental wave.

Detection and effective compensation are achieved in an extremely short time interval, typically under half a cycle of the fundamental wave (less than 10 milliseconds), thus protecting the technological process before the undervoltage or overvoltage protections of sensitive equipment can trip. From an energy and economic efficiency standpoint, the DVR system is significantly superior to a classic UPS because the inverter and the energy storage unit do not need to be sized to supply the entire load power, but only the voltage fraction required to cover the difference to the nominal value (generally, a maximum of 40-50% of the nominal voltage). Moreover, during normal operation, without network disturbances, the DVR operates in a standby state (active stand-by), ensuring an overall line efficiency approaching 99%, with negligible thermal losses and exceptional reliability.

## 4. ARCHITECTURE AND CONTROL OF THE DVR (DYNAMIC VOLTAGE RESTORER)

System The efficiency of a DVR system in protecting sensitive loads derives from its ability to actively intervene in the power circuit within a time frame on the order of milliseconds. This dynamic performance is the result of a perfect synergy between an optimized power hardware architecture and an advanced mathematical control algorithm, capable of processing voltage signals in real time.

### 4.1. Basic Equipment Topology

From a constructive standpoint, the hardware architecture of a DVR system is designed to provide a rapid bidirectional interface between the disturbed power grid and the consumer. The system is connected in series on the power line, and its fundamental components work together to synthesize the missing wave. The central active element is the Voltage Source Inverter (VSI), typically a three-phase bridge equipped with Insulated-Gate Bipolar Transistors (IGBTs), capable of switching at high frequencies. This inverter is supplied by an energy storage system connected to the direct current intermediate circuit (DC link), which can consist of battery banks or supercapacitors, providing the active power necessary for compensation during deep voltage sags.

Because the voltage generated by the inverter through pulse-width modulation (PWM) contains a rich spectrum of switching harmonics, it is passed through an LC-type passive low-pass filter. The filter's role is to smooth the waveform, ensuring a purely sinusoidal voltage variation. Subsequently, this compensating voltage is introduced into the main circuit via an injection transformer connected in series with the load. The transformer fulfills a dual role: it adapts the inverter's voltage level to the line's requirements and provides the essential galvanic isolation between the power electronics side and the distribution network.

### 4.2. Mathematical Model and Fundamental Compensation Principle

The analysis of the DVR system's operation is based on the application of Kirchhoff's voltage law to the main circuit loop, utilizing the principle of phasor superposition. The ultimate objective of the system is to maintain the voltage at the load terminals ($V_{\mathrm{load}}$) at a constant value, regardless of source fluctuations. This equilibrium condition is described by the following fundamental operating equation:

$$V_{load} = V_{grid} + V_{DVR} \tag{4}$$

where:

- $V_{\mathrm{load}}$ is the phasor voltage at the load terminals (the desired reference value);
- $V_{\mathrm{grid}}$ is the voltage measured at the supply network level (affected by the disturbance);
- $V_{\mathrm{DVR}}$ s the compensation voltage, synthesized and injected in series by the inverter.

Under nominal operating conditions, when the grid voltage ($V_{\mathrm{grid}}$) is ideal, the inverter generates zero voltage or only a minimal value to compensate for the voltage drops across the injection transformer. However, upon the occurrence of a transient disturbance, the amplitude and/or phase of $V_{\mathrm{grid}}$ change abruptly. The DVR system instantaneously calculates and injects the differential voltage ($V_{\mathrm{DVR}}$) so that the vector sum of the disturbed grid voltage and the injected voltage results in a sinusoidal wave of nominal amplitude at the consumer's terminals.

### 4.3. Control Strategy and Rapid Detection Algorithm

The overall compensation performance is dictated exclusively by the speed at which the control system manages to identify the anomaly (sag or swell) and calculate the voltage reference for the inverter. Classical Root Mean Square (RMS) measurement methods require at least half a cycle (10 ms) to validate a fault, an unacceptably long time for protecting ultra-sensitive equipment. Therefore, detection must be performed quasi-instantaneously.

In modern industrial practice, the predominant and most efficient method utilizes the theory of symmetrical components through the application of the Park Transform ($d - q$ - $0$), executed in parallel with a Phase-Locked Loop (PLL). The PLL is responsible for the continuous and precise extraction of the grid phase angle ($\theta$), which is necessary for synchronizing the calculations [18].

The instantaneous three-phase voltages ($v_a$, $v_b$, $v_c$) from the stationary reference frame are projected onto the axes of the synchronously rotating reference frame ($d, q, 0$). Analytically, this mathematical transformation (known as the Park Transform) is decomposed into the following three individual linear equations:

Direct axis component (*d*):

$$v_d = \frac{2}{3}\left[v_a \cos(\theta) + v_b \cos\left(\theta - \frac{2\pi}{3}\right) + v_c \cos\left(\theta + \frac{2\pi}{3}\right)\right] \tag{5}$$

Quadrature axis component (*q*):

$$v_q = -\frac{2}{3}\left[v_a \sin(\theta) + v_b \sin\left(\theta - \frac{2\pi}{3}\right) + v_c \sin\left(\theta + \frac{2\pi}{3}\right)\right] \tag{6}$$

Zero-sequence component (0):

$$v_0 = \frac{1}{3}\left(v_a + v_b + v_c\right) \tag{7}$$

The major advantage of this algorithm lies in the transformation of alternating quantities into direct current (DC) quantities, which are much easier to process in control loops. In a balanced and fault-free network, the projection of the voltage vector on the direct axis ($v_d$) is a constant DC value (representing the wave amplitude), while the projection on the quadrature axis ($v_q$) is zero.

The system's dynamics change radically upon the occurrence of a voltage sag or swell. Any amplitude variation in the network translates immediately, without computational delay, into a decrease or increase of the DC component $v_d$. This variation provides a clear error reference ($E_d = V_{d\_ref} - v_d$ The error is immediately fed into a Proportional-Integral (PI) controller, whose role is to nullify the deviation and ensure system stability. The resulting control signal at the output of the PI controller then passes through an inverse Park transform, returning to the three-phase system ($a - b$ - $c$) in the form of reference signals. These are applied to the PWM modulator, which commands the precise opening and closing of the inverter's transistors, thus generating exactly the compensation voltage $V_{DVR}$ required for correction.

A schematic representation of this signal processing flow and the closed-loop control is illustrated in Figure 4. This topology clearly highlights the logical control path: from acquiring feedback from the disturbed network, passing through the synchronization and transformation algorithm, and comparing it with the ideal reference, to the active generation of the compensation wave by the inverter.

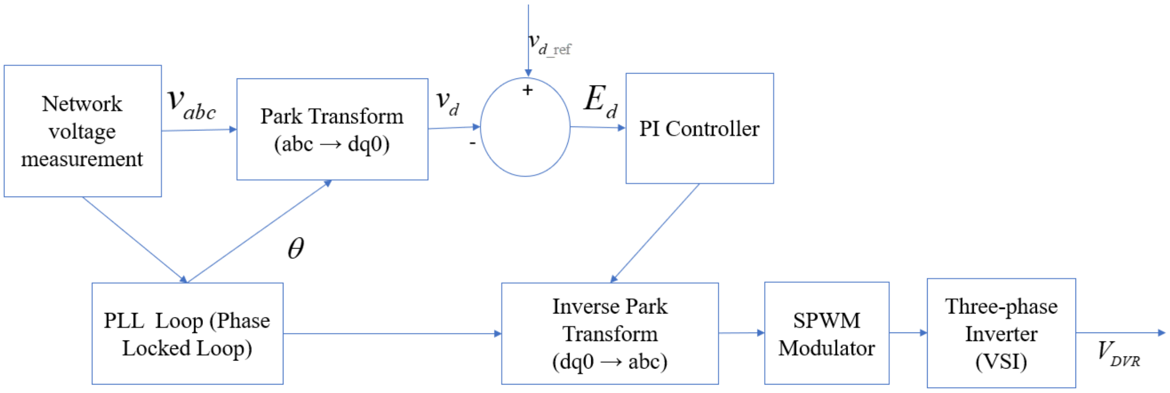

Figure 4. Block diagram of the DVR system's control architecture, based on the Park Transform ($d - q$ - $0$) and a Proportional-Integral (PI) controller.

## 5. SIMULATIONS AND PERFORMANCE VALIDATION IN THE MATLAB/SIMULINK ENVIRONMENT

To validate the efficiency of the hardware architecture and the control algorithm based on the Park Transform ($d - q$ - $0$), detailed in the previous section, a simulation model was developed in the MATLAB/Simulink environment. The main objective of this case study is to demonstrate the dynamic capability of the DVR system to maintain an ideal voltage profile at the terminals of a critical industrial load under the conditions of severe transient disturbances occurring on the supply line.

### 5.1. Simulated Model Parameters

To accurately reflect a real industrial scenario (such as powering an automated packaging line or a data center), the model was configured for a low-voltage distribution network. The nominal operating parameters were set to a line voltage of 400 V (phase voltage of 230 V) and a fundamental frequency of 50 Hz. The Voltage Source Inverter (VSI) within the DVR system operates at a switching frequency of 10 kHz, a value chosen to ensure an optimal compromise between response speed and switching losses. The DC link voltage is assumed to be constant and sufficient to sustain the power injection during the fault.

### 5.2. System Response to a Voltage Sag

The first test scenario simulates the most frequent power quality anomaly: the transient voltage sag. To evaluate the robustness of the control algorithm, a sudden drop in the grid voltage ($V_{\text{grid}}$) with a depth of 30% compared to the nominal value (the remaining voltage being 70% or 0.7 p.u.) was programmed. The fault is initiated at time $t = 0.1$ seconds and is cleared at $t = 0.2$ seconds, simulating a temporary short circuit on an adjacent branch of the network.

The dynamics of the compensation process are illustrated in detail in Figure 5.

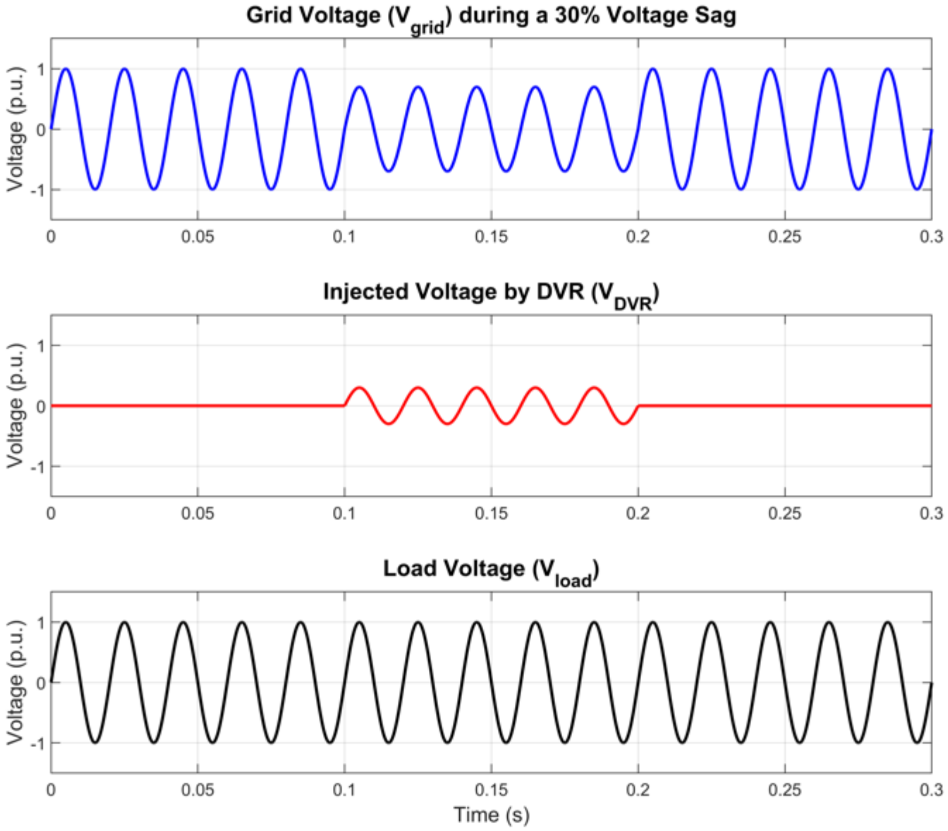

**Figure 5.** Performance of the DVR system during a 30% voltage sag. (Top) Disturbed grid voltage; (Middle) Compensation voltage injected by the inverter; (Bottom) Stabilized voltage at the load terminals

Analyzing the obtained waveforms, it can be observed that at time $t = 0.1$ s, concurrent with the amplitude decrease in the network, the $d$ - $q$ - $0$ algorithm immediately detects the error in the $v_d$ component. Without any noticeable delay, the PI controller commands the inverter to generate the compensation wave (Middle graph). The DVR system injects exactly the missing 30%, in phase with the grid voltage. The result of this vectorial addition is visible in the lower graph: the voltage at the load level ($V_{load}$) remains perfectly sinusoidal and at nominal amplitude (1.0 p.u.) throughout the entire duration of the disturbance. The consumer does not perceive any discontinuity in the power supply [19].

### 5.3. System Response to a Voltage Swell

Although less frequently encountered in practice than voltage sags, transient overvoltages can cause immediate destruction of insulation and semiconductor components. The second scenario evaluates the DVR's capability to operate in "buck" mode (voltage step-down) [20]. A sudden voltage increase of 30% above the nominal value (reaching 1.3 p.u.) is induced in the network [21], [22]. The dynamics of the attenuation process for this overvoltage and the inverter's behavior in absorption mode are illustrated in detail in Figure 6.

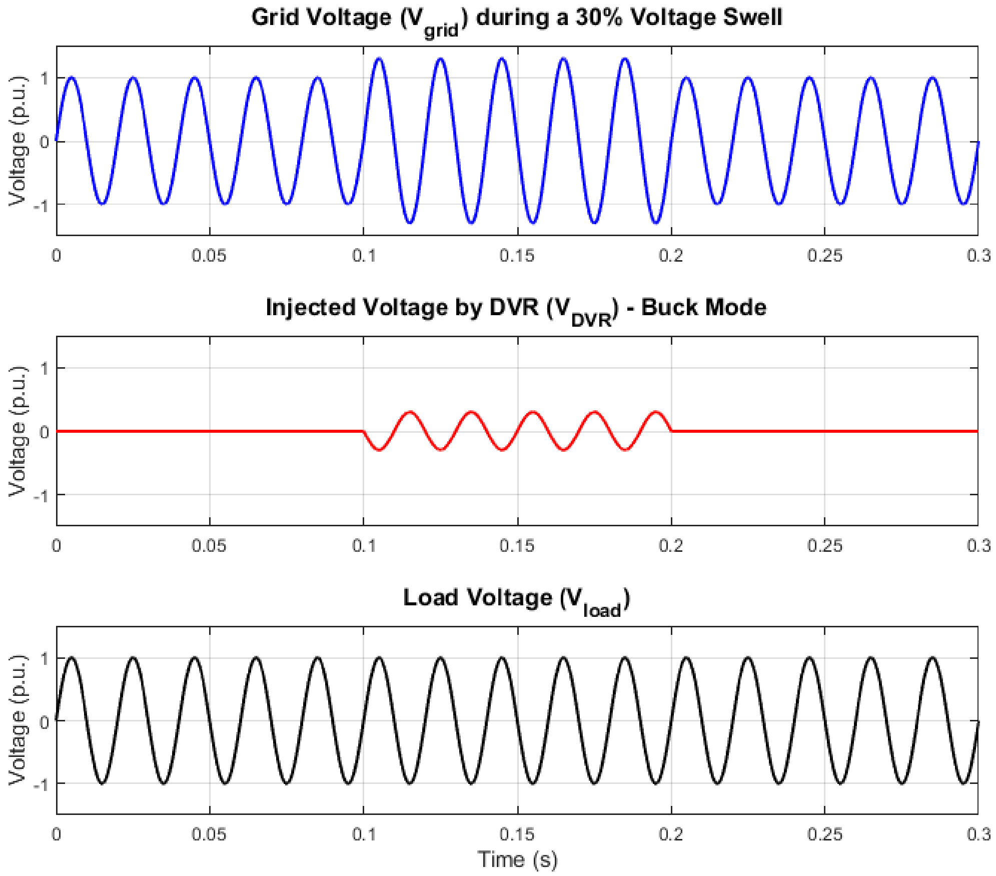

**Figure 6.** Performance of the DVR system during a 30% transient overvoltage. The system absorbs the excess energy, protecting the connected equipment

In this operating mode, the system's action is different, but equally rapid. Upon detecting the increase in the RMS value, the algorithm commands the inverter to synthesize a correction voltage in phase opposition (180 degrees out of phase) with respect to the fundamental voltage. The injected voltage $V_{\mathrm{DVR}}$ is practically subtracted from the grid voltage $V_{\mathrm{grid}}$ (represented by the high-amplitude wave in the first graph). As in the previous scenario, the compensation is precise; the waveform at the consumer's terminals ($V_{\mathrm{load}}$) is limited and strictly maintained at the 100% threshold, guaranteeing the integrity of the equipment.

## 6. CONCLUSIONS

Today, electrical power quality represents a critical factor for the stability of modern industrial processes. As demonstrated through the analysis of the ITIC (CBEMA) tolerance curves, automated systems and sensitive electronic equipment require an extremely strict power supply regime, being vulnerable to voltage fluctuations whose duration is measured in milliseconds. Traditional regulation and protection methods often prove inefficient in the face of these transient anomalies, fully justifying the necessity of implementing advanced active compensation technologies.

Following the analysis of the hardware architecture, the mathematical algorithm, and the performance validation through simulation in the MATLAB/Simulink environment, the present paper highlights the following fundamental conclusions:

- Superior technical and economic efficiency: The Dynamic Voltage Restorer (DVR) emerges as the most efficient method available on the market for protecting critical loads against voltage sags and swells. Unlike classic UPS systems, which continuously process the entire load power through double conversion and require massive battery banks, the DVR system is connected in series and strictly injects the energy fraction necessary to compensate for the fault. This intelligent topology significantly reduces the equipment's footprint, thermal losses, and, implicitly, the total implementation (CAPEX) and maintenance (OPEX) costs.
- Dynamic performance and prevention of financial losses: Validation through simulation demonstrated that the control algorithm based on the Park Transform ($d - q$ - $0$) ensures an exceptional reaction speed. The system's response time is under half a cycle of the fundamental wave (< 10 ms). This quasi-instantaneous correction guarantees that the voltage profile at the consumer's terminals remains at the nominal amplitude, regardless of the severity of the network disturbance. Consequently, the DVR equipment prevents the accidental shutdown of production lines (trip-outs) and the destruction of materials being processed, thereby eliminating major financial losses in the industrial sector.

In conclusion, the integration of DVR systems into the sensitive nodes of distribution networks goes beyond being a simple technical solution, representing an indispensable strategic economic investment for the modernization and security of current industrial infrastructures.

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