VOL. 09 NO. 5,
AUGUST, 2025
E-ISSN 3027-1339
P-ISSN 3026-8257

*African Scholar Publications & Research International*
www.africanscholarpub.com

*Journal of Systematic, Evaluation and Diversity Engr. (JSEDE)*

# Evaluation of DVR and SSFCL in Mitigating Voltage Sags and Interruptions in Power Distribution Network

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**DOI:** https://doi.org/10.70382/ajsede.v9i5.012

## *Abstract*

This study investigates the performance of Dynamic Voltage Restorers (DVRs) and Solid-State Fault Current Limiters (SSFCLs) through simulations, addressing the problem of voltage sags and interruptions in power systems that can disrupt power quality and cause significant operational issues, particularly in environments with sensitive equipment. The research aims to develop simulation models for voltage disturbances and assess the impact of advanced mitigation techniques on power quality and distribution network reliability. Using MATLAB/Simulink, key parameters such as line voltage, current, and load voltage were simulated under conditions including a 115V voltage sag (0.02 to 0.04 seconds) and a 0V interruption (0.06 to 0.08 seconds). The findings indicate that the DVR effectively compensates for voltage sags and interruptions, maintaining a stable load voltage of 230V throughout disturbances. The DVR's ability to inject compensating voltage makes it ideal for sensitive applications, such as data centers and hospitals, where consistent voltage is critical. In contrast, the SSFCL allows load voltage to follow line voltage disturbances but limits line current during faults, protecting network components from overcurrent. The SSFCL's current-limiting feature effectively prevents damage to infrastructure but does not address voltage instability, making it more suited for industrial settings where fault protection is a priority. Both devices improve system stability and power quality, but cater to different operational needs. The DVR is recommended for environments requiring voltage stability, while the SSFCL is best suited for power distribution networks focused on current protection. Further research into hybrid systems integrating both devices could

offer enhanced protection and power quality management for modern distribution networks.

**Keywords:** Dynamic Voltage Restorers (DVRs), Solid-State Fault Current Limiters (SSFCLs), Voltage Sags, Voltage Disturbances, Overcurrent, Power Systems Stability.

# *Introduction*

Electric distribution networks form the backbone of modern electrical power systems, delivering electricity from generation sources to end-users across residential, commercial, and industrial sectors (Fred et al., 2015; Mohd Azmi et al., 2022; Onyegbadue et al., 2022). The primary objective of these networks is to ensure a stable, uninterrupted supply of electricity, facilitating the efficient operation of electrical devices and supporting various industries (Gallegos et al., 2024). However, a significant challenge faced by these distribution networks is maintaining voltage stability, which directly influences the performance, reliability, and lifespan of electrical equipment (Bandara et al., 2024; Nyiekaa & Onyegbadue, 2021). Voltage stability is crucial in ensuring that power systems remain operational and that sensitive equipment continues to function efficiently without interruption (Afzal et al., 2020).

Voltage disturbances, such as voltage sags and interruptions, are common occurrences in power distribution networks, posing substantial threats to the continuity of electrical service (Makinde et al., 2021; Omorodion et al., 2025). Voltage sags are temporary reductions in the root mean square (RMS) voltage, often lasting for short durations ranging from a few milliseconds to several seconds, with the magnitude typically between 10% and 90% of the nominal voltage (Cebrian et al., 2023). Voltage interruptions, on the other hand, involve a complete loss of voltage supply for a specific period, resulting in more significant and extended disruptions in service (Visakh & Selvan, 2023). These disturbances are primarily caused by faults within the distribution system, switching operations, lightning strikes, and equipment failures (Bandara et al., 2023).

The effects of voltage disturbances are far-reaching. In commercial and industrial settings, voltage sags can lead to equipment malfunctions, data loss, and production downtime, resulting in significant economic losses (Malik et al., 2024; Ukagu et al., 2025). In manufacturing plants, even brief voltage sags can cause machinery to malfunction or halt operations, leading to costly repairs and production delays (Motoki et al., 2021). In healthcare facilities, voltage fluctuations can disrupt the operation of critical medical equipment, endangering patient health and safety (Chobanov, 2021). Similarly, in data centers, where the continuous operation of servers and other electronic systems is essential, voltage disturbances can result in data corruption, system crashes, and prolonged downtime (Ahmed et al., 2021).

As the integration of sensitive electronic

devices and industrial machinery increases, the susceptibility of distribution networks to voltage disturbances becomes more pronounced (Yang & Teh, 2023). Modern electronic equipment, including computers, medical devices, automated manufacturing systems, and communication technologies, requires a stable voltage to function properly. A brief voltage sag can lead to serious operational disruptions, including data corruption, equipment malfunction, and production shutdowns (Tang et al., 2022). In extreme cases, these disruptions can result in considerable financial losses, reputational damage, and even safety hazards.

Traditional solutions for mitigating voltage sags and interruptions, such as voltage regulators, circuit breakers, and uninterruptible power supplies (UPS), have been commonly used in power systems (Rozhkov et al., 2023). However, these methods often fall short in addressing the dynamic nature of modern voltage disturbances. Voltage regulators are designed to maintain a constant output voltage by adjusting the input voltage, making them effective for steady-state voltage variations (Sikander & Thakur, 2020). However, they typically cannot respond quickly enough to transient events like voltage sags or interruptions. Circuit breakers, while effective in protecting against severe faults, do not mitigate short-duration disturbances such as voltage sags or interruptions (Smeets & Belda, 2021). UPS systems, on the other hand, provide temporary backup power during outages, ensuring the continuity of service for critical applications (Borujeni et al., 2022). However, UPS systems are limited by their battery capacity and typically do not address the root causes of voltage disturbances, nor do they provide long-term solutions for power quality management.

These limitations of traditional mitigation techniques have led to the exploration of more advanced solutions, specifically custom power devices like Dynamic Voltage Restorers (DVRs) and Solid-State Fault Current Limiters (SSFCLs). These devices offer dynamic, real-time solutions for mitigating voltage sags and interruptions and are better suited to the demands of modern power systems, where rapid and precise responses are necessary to maintain stability and protect sensitive loads(Mbuli, 2023).

The DVR is an advanced power electronic device designed to restore the nominal voltage during voltage sags, thereby ensuring that sensitive loads continue to receive stable voltage despite disturbances in the power supply (Moghassemi & Padmanaban, 2020). The DVR operates by injecting compensating voltage into the distribution system, typically using energy storage components such as capacitors or batteries. This compensating voltage is carefully controlled in terms of magnitude and phase angle to counteract the sag, restoring the load voltage to its nominal value in a fraction of a second. The DVR is particularly effective for short-duration disturbances, such as voltage sags, which may last from a few milliseconds to several seconds, and is widely used in critical applications, such as data centers, hospitals, and manufacturing plants, where a stable power supply is vital for maintaining operational continuity (Osaloni & Saha, 2020).

One of the primary advantages of DVRs is their rapid response time, which enables them to restore voltage within milliseconds of detecting a disturbance (H. Zhang et al., 2022). This makes DVRs highly effective for applications that demand high power quality and continuity,

such as telecommunications, healthcare, and sensitive industrial processes (Mahmoud et al., 2022). In addition to voltage restoration, DVRs can also provide fault isolation, preventing damage to sensitive equipment and ensuring that disturbances do not propagate throughout the network (Farhadi-Kangarlu et al., 2017).

While DVRs are highly effective in voltage regulation, their function is limited to mitigating voltage disturbances, and they do not directly address fault currents or the potential overcurrent situations that may arise during system faults (Abas et al., 2020). This is where Solid-State Fault Current Limiters (SSFCLs) come into play. Unlike traditional mechanical fault current limiters, which rely on mechanical switches to interrupt the current flow during faults, SSFCLs use power electronic devices and advanced semiconductor technology to limit fault currents (Saeed Majeed et al., 2023). The SSFCL works by rapidly inserting impedance into the faulted circuit, which restricts the flow of fault current and prevents it from exceeding a predetermined limit. By controlling fault currents, SSFCLs help protect critical network components, such as transformers and circuit breakers, from damage due to excessive currents. SSFCLs are particularly valuable in power distribution networks where fault currents can cause severe damage to electrical components and lead to system instability (El-Ela et al., 2022). The SSFCL's ability to respond within microseconds allows it to limit fault currents before they can cause significant harm to the system. In addition, SSFCLs help maintain network stability during fault conditions by minimizing the stress placed on other protective devices, such as circuit breakers, and improving the overall reliability of the power system (Khalil et al., 2024).

The aim of this research is to evaluate the effectiveness of DVRs and SSFCLs in mitigating voltage sags and interruptions and enhancing power system reliability. The objectives of the study are to: i. develop a simulation model that represents typical voltage sag and interruption events in a 415V distribution network, ii. evaluate the ability of DVRs to compensate for voltage sags and interruptions, ensuring that sensitive loads receive stable voltage during disturbances, ii. assess the effectiveness of SSFCLs in limiting fault currents during disturbances, protecting network components from overcurrent damage, iii. compare the performance of DVRs and SSFCLs in mitigating voltage disturbances, focusing on their respective strengths and limitations, iv. provide recommendations for integrating DVRs and SSFCLs in modern power systems to enhance reliability and power quality.

## LITERATURE REVIEW/THEORETICAL UNDERPINNING

Voltage sags and interruptions in electrical distribution systems are significant disturbances that can have detrimental effects on both the operation and safety of electrical devices and industrial equipment (Almeida & Cebrian, 2021; TC Madueme & IA Onyegbadue, 2018). These disturbances, while often brief, can cause considerable disruptions across multiple sectors, including industrial operations, healthcare, and commercial enterprises. Voltage sags, often referred to as voltage dips or short-duration voltage variations, occur when the voltage in an electrical network drop below the normal operating level, usually for a brief period.

These disturbances can last anywhere from a few milliseconds to several seconds, and typically, the voltage magnitude falls between 10% and 90% of the nominal voltage (Alshareef, 2023). Interruptions, on the other hand, involve the complete loss of voltage for a short duration, often less than a few seconds. These events are critical as they disrupt the normal functioning of electrical equipment and can lead to malfunctions, data loss, or even physical damage to devices, particularly in sensitive systems such as medical equipment, computers, and automated industrial processes (Balducci et al., 2021).

The causes of voltage sags and interruptions are varied and include both natural and man-made factors. Lightning strikes can cause transient faults on power lines, leading to sudden voltage drops. Equipment failures, such as malfunctions in transformers or circuit breakers, are also common causes (Zalhaf et al., 2022). Switching operations in the grid, intended to isolate faults or conduct maintenance, can similarly introduce temporary voltage sags or interruptions (Liubčuk et al., 2023). In modern electrical grids, these disturbances are more prevalent due to the increasing complexity of distribution systems and the integration of sensitive electronic loads that demand high-quality power.

The impacts of voltage sags and interruptions are widespread, affecting both end-users and utility providers. For end-users, even momentary voltage sags can disrupt the operation of sensitive equipment, leading to downtime, product quality issues, or even equipment damage (Liubčuk et al., 2023). For instance, in industrial settings, voltage sags can halt production processes, leading to significant financial losses. In healthcare, interruptions can disrupt critical medical devices, compromising patient safety (P. Zhang et al., 2019). The economic and operational consequences of these disturbances are therefore a major concern, particularly for sectors reliant on continuous and stable power, such as data centers, medical facilities, and automated manufacturing plants.

From a utility perspective, voltage disturbances also pose challenges in maintaining grid stability and reliability. As the grid becomes more interconnected and complex, with renewable energy sources and sensitive loads integrated into the system, ensuring voltage stability becomes increasingly difficult. Voltage sags and interruptions can trigger cascading failures, affecting large portions of the grid and potentially leading to wide-scale blackouts if not properly managed (Zhu et al., 2023). This necessitates the development of effective solutions to both mitigate the occurrence of these disturbances and limit their impact on the grid and its users.

Traditionally, voltage sags and interruptions have been mitigated using devices such as voltage regulators, uninterruptible power supplies (UPS), and circuit breakers. Voltage regulators are designed to stabilize the output voltage despite variations in the input, ensuring that sensitive loads receive a constant supply. However, these devices are often slow to respond to transient disturbances and may not be effective in addressing short-duration voltage sags (Al-Gahtani et al., 2022). Circuit breakers, while effective in protecting the grid from severe faults, do not address issues like voltage sags or momentary interruptions (Sanstad et al., 2020).

Uninterruptible power supplies (UPS) offer temporary backup power during outages, ensuring continuity of service for critical applications. However, UPS systems are limited by their battery life and capacity, and they do not address the root causes of voltage disturbances. Moreover, they tend to be costly and require regular maintenance, which makes them less suitable for long-term power quality management (Lopes et al., 2020).

While these traditional devices provide some degree of protection, they are often insufficient in addressing the dynamic nature of voltage disturbances in modern electrical systems. This has led to a growing interest in advanced mitigation techniques that use custom power devices, which offer more adaptive and responsive solutions.

DVRs are designed to mitigate voltage sags by injecting compensating voltage to restore the nominal voltage level at the load. These devices are typically installed in series with the distribution line and use energy storage components such as capacitors or batteries to provide the necessary compensating voltage during voltage sags (Tang et al., 2022). The DVR responds rapidly to voltage disturbances, compensating for voltage drops and maintaining a stable supply to sensitive loads.

DVRs are particularly useful in applications requiring continuous voltage supply, such as hospitals, data centers, and industrial processes. Their ability to react quickly to voltage sags and interruptions makes them highly effective in these settings, where even short-term disruptions can lead to significant losses. Advances in control strategies, such as proportional-integral (PI) controllers and fuzzy logic controllers, have enhanced the performance of DVRs, allowing them to operate efficiently under dynamic conditions (Deshpande et al., 2023).

SSFCLs are designed to limit fault currents during voltage disturbances, thereby protecting the electrical network from potential damage. These devices operate by inserting a high-impedance element into the circuit when a fault is detected, limiting the fault current to a predetermined value (Hojatpanah et al., 2023). Unlike traditional mechanical circuit breakers, which are relatively slow to respond, SSFCLs can react within microseconds, providing a more effective solution for fault protection in modern grids.

While SSFCLs do not compensate for voltage sags, they play a crucial role in protecting the system from overcurrent conditions during faults. This makes them an ideal solution for power distribution networks and industrial settings, where overcurrent protection is a priority. However, because they do not regulate voltage, they are less suited for applications where voltage stability is essential, such as in hospitals or data centers.

Simulation-based studies have been crucial in evaluating the effectiveness of DVRs and SSFCLs in mitigating voltage sags and interruptions. Recent studies have modelled the performance of these devices under various fault conditions and voltage disturbances to assess their response and effectiveness in real-world applications (Li et al., 2023).

Simulations of DVRs have shown that these devices can maintain a stable load voltage even during significant voltage sags, ensuring continuity of power supply. The DVR's ability to inject compensating voltage allows it to restore the load voltage to its nominal value, even

when the line voltage drops significantly (Mohammed et al., 2019). These simulations have confirmed the DVR's suitability for critical applications where power quality is paramount.
In contrast, simulations of SSFCLs have demonstrated their ability to limit fault currents effectively during disturbances. The SSFCL caps the fault current at a predetermined level, preventing system damage and improving the overall reliability of the power network (Gholizadeh et al., 2024).

## METHODOLOGY

The simulation models for voltage sag and interruption events in a 415V distribution network were designed to evaluate advanced mitigation techniques, using Dynamic Voltage Restorers (DVRs) and Solid-State Fault Current Limiters (SSFCLs). A detailed simulation model of a typical 415V distribution network was created using MATLAB/Simulink. This model included network components such as transmission lines, transformers, loads, and protective devices. Simulations were carried out in the time domain to capture how the system responded to disturbances like voltage sags and interruptions. These events were introduced either by altering the source voltage or by simulating fault conditions, such as short circuits or load fluctuations, at specified times. This approach allowed for the assessment of the system's dynamic behaviour during these disturbances.
To address voltage sags and interruptions, the simulation was extended to include DVRs. The DVR was designed to detect voltage deviations from the nominal value and inject compensating voltage to restore the system's voltage to its required level. The DVR's control algorithms were incorporated into the model, ensuring that it injected the correct voltage waveform to stabilise the voltage at sensitive loads. The DVR's performance was evaluated by simulating various voltage sag scenarios, examining how quickly and effectively it compensated for voltage dips. Key performance indicators, such as the time taken for voltage restoration, compensation accuracy, and the stability of the load voltage during disturbances, were measured and analysed to assess the DVR's effectiveness.
Alongside the evaluation of the DVR, the methodology also included the assessment of SSFCLs, which are designed to limit fault currents during disturbances. Fault conditions were simulated by introducing short circuits or other fault events into the distribution network, with the SSFCL integrated to limit fault currents. The SSFCL's control algorithm adjusted the device's impedance to limit fault currents to a predetermined safe level, thus preventing damage to network components. The SSFCL's performance was evaluated by monitoring its fault current limiting capabilities, response time, and the protection it provided to key network components such as transformers and generators. The performance was assessed based on the SSFCL's ability to limit fault currents, maintain system stability, and protect sensitive equipment from overcurrent damage.
The performance of both the DVR and SSFCL was compared and tested under similar fault and voltage disturbance scenarios. Key performance indicators, such as the time taken for voltage restoration by the DVR, the effectiveness of the SSFCL in limiting fault currents, and

the overall system stability during disturbances, were compared. This comparison provided valuable insights into the strengths and limitations of each device, highlighting areas where each device excelled and where improvements could be made.

The simulation environment was configured with critical system parameters, including line properties such as resistance $R_{line}$=0.1 Ω, $R_{line}$=0.1Ω and inductance $L_{line}$=0.5 H, $L_{line}$=0.5H, load characteristics defined by capacitance $C_{load}$=0.2 F, $C_{load}$=0.2F, with active power consumption $P_{load}$=100 W, $P_{load}$=100W and reactive power demand $Q_{load}$=50 VAR, $Q_{load}$ =50VAR, and source specifications operating at 230V, 50Hz standard grid conditions. These parameters were crucial for configuring the simulation environment and enabled a thorough analysis of the performance, stability, and response characteristics of the DVR and SSFCL under various operational and fault conditions. The parametric framework defined the electrical characteristics of the system, established the timing of critical events, and characterised system behaviour during power quality disturbances such as voltage sags and interruptions. Voltage disturbances, such as sag events reducing supply voltage to 50% of the nominal value and complete voltage interruptions, were introduced into the simulation to assess the system's performance under adverse conditions. The flow chart is seen in Figure 1.

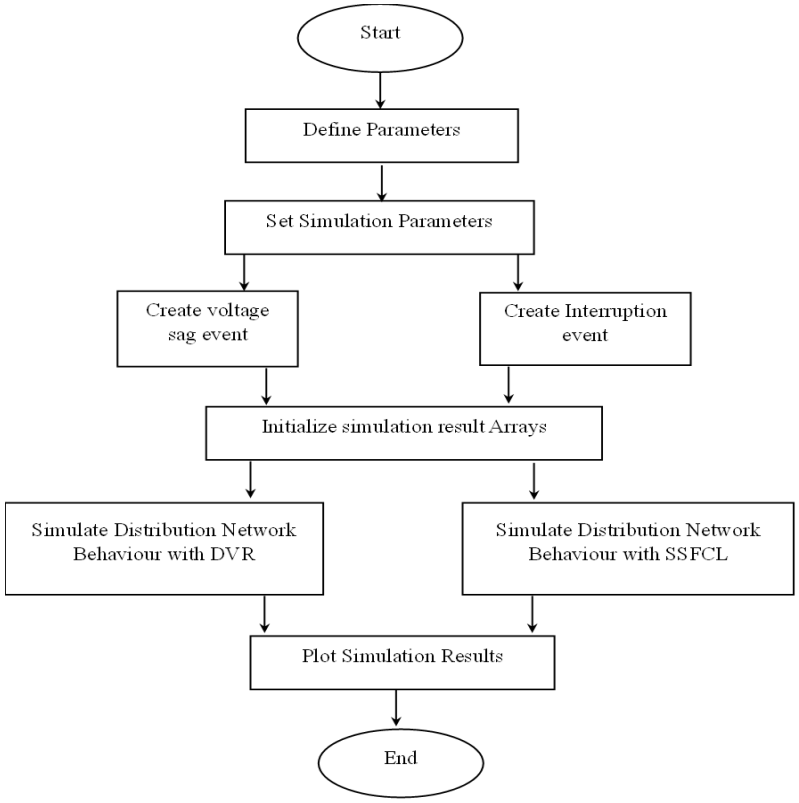



**Figure 1:** The Simulation flow chart

**Fundamental equations govern the simulation models**

Kirchhoff's Voltage Law states that the sum of voltage rises and drops around any closed loop in a circuit is zero. This can be expressed as:

$$\sum_{k=1}^{n} V_k = 0 \quad (1)$$

Where:

$V_k$ represents the voltage across each component in the loop.

Kirchhoff's Current Law states that the algebraic sum of currents entering and leaving a node in a circuit is zero. This can be expressed as:

$$\sum_{k=1}^{n} I_k = 0 \quad (2)$$

Where:

$I_k$ represents the current entering or leaving the node.

**1. Transient Stability Equations:**

Transient stability equations describe the dynamic response of synchronous machines to sudden changes in system conditions. One of the basic equations governing transient stability is the rotor angle equation, which can be expressed as:

$$\frac{d\theta_i}{dt} = \omega_i \quad (3)$$

Where:

$\theta_i$ is the rotor angle of machine i and

$\omega_i$ is the synchronous frequency.

**2. Fault Current Equations:**

The fault current equation determines the magnitude of fault current following a fault occurrence. It can be calculated using Ohm's Law:

$$I_f = \frac{V_{fault}}{Z_{fault}} \quad (4)$$

Where:

$I_f$ is the fault current,

$V_{fault}$ is the fault voltage, and

$Z_{fault}$ is the fault impedance.

**3. Voltage Sag Propagation Equations:**

Voltage sag propagation equations model the propagation of voltage sags through the power distribution network. One simple equation for this purpose is:

$$V_{end} = V_{end} - I_{total} \times Z_{total} \quad (5)$$

Where:

$V_{end}$ is the voltage at the end of a transmission line,
$V_{start}$ is the voltage at the beginning of the line,
$I_{total}$ is the total current flowing through the line, and
$Z_{total}$ is the total impedance of the line.

These equations, when utilized appropriately, enable an accurate representation of power system behavior during transient events such as voltage sags and interruptions.

**DERIVATION OF EQUATIONS RELEVANT TO DVRS AND SSFCLs**

**1. DVR Principles of Operation:**

DVRs are dynamic voltage restorers used to mitigate voltage sags in power systems. They inject a compensating voltage to restore the voltage at the load to its nominal value. The compensating voltage injected by the DVR can be calculated using control algorithms based on the following principles:

$$V_{comp} = k \times (V_{nom} - V_{meas}) \quad (6)$$

Where:

$V_{comp}$ is the compensating voltage injected by the DVR,
k is the gain or scaling factor of the DVR control algorithm;
$V_{nom}$ is the nominal voltage level;
$V_{meas}$ is the measured voltage at the load.

**2. Simulation Setup for DVRs:**

The simulation setup for DVRs involves integrating the DVR control algorithm with the power system model. This typically includes:

a. Modeling the voltage sag event.
b. Implementing the DVR control algorithm.
c. Injecting the compensating voltage into the system.
d. Monitoring and analyzing the system response.

**3. SSFCL Principles of Operation:**

SSFCLs are Solid State Fault Current Limiters used to mitigate fault currents in power systems. They limit the fault current to a predetermined level by controlling the impedance of the system. The impedance of the SSFCL can be adjusted based on the fault current using the following principle:

$$Z_{SSFCL} = \frac{V_{fault}}{I_{fault}} \quad (7)$$

Where:

$Z_{SSFCL}$ is the impedance of the SSFCL.
$V_{fault}$ is the fault voltage.
$I_{fault}$ is the predetermined limit for the fault current.

**4. Simulation Setup for SSFCLs:**

The simulation setup for SSFCLs involves modeling the fault condition and integrating the SSFCL control algorithm with the power system model. This typically includes:

a. Modeling the fault condition, including fault location and fault impedance.
b. Implementing the SSFCL control algorithm to adjust its impedance.
c. Limiting the fault current to the predetermined level.
d. Analyzing the system response to the fault with the SSFCL in operation.

These equations and principles serve as the foundation for simulating the operation of DVRs and SSFCLs in power systems and provide insights into their effectiveness in mitigating voltage sags and fault currents, respectively.

**MODEL DEVELOPMENT CONSIDERATIONS**

There are the equations and principles relevant to the assessment of advanced mitigation techniques for voltage sag and interruption events integration into the distribution network:

**1. Integration of Custom Power Devices into the Distribution Network:**

Advanced mitigation techniques involve the integration of custom power devices such as DVRs and SSFCLs into the distribution network to enhance system reliability and mitigate voltage sag and interruption events. The integration process includes:

a. **Network Impedance Estimation:** Determine the impedance profile of the distribution network, including transmission lines, transformers, and distribution feeders. This information is crucial for designing the control algorithms of custom power devices.
b. **Placement Optimization:** Identify optimal locations for installing custom power devices based on network topology, load distribution, and criticality of the loads. Placement optimization aims to maximize the effectiveness of the devices in mitigating voltage sags and interruptions.
c. **Coordination Strategy:** Develop coordination strategies for the operation of custom power devices with existing protection and control systems in the distribution network. This ensures seamless integration and coordination of actions during transient events.

**2. Simulation Scenarios and Analysis Approach:**

The assessment of advanced mitigation techniques involves conducting simulations for various scenarios and analyzing the system response. Key aspects of simulation scenarios and analysis approach include:

a. **Voltage Sag Scenarios:** Simulate voltage sag events under different conditions, such as load fluctuations, network faults, and switching operations. Assess the effectiveness of custom power devices in mitigating voltage sags and restoring voltage quality at critical loads.

b. **Fault Current Scenarios:** Simulate fault conditions in the distribution network and evaluate the performance of SSFCLs in limiting fault currents to predetermined levels. Analyze the impact of SSFCLs on system stability and protection coordination.

These equations and principles provide a comprehensive framework for assessing advanced mitigation techniques for voltage sag and interruption events in distribution networks. By integrating custom power devices and conducting thorough simulations and analyses, it is possible to enhance system reliability and mitigate the impact of transient events on power quality.

## INVESTIGATION OF CUSTOM POWER DEVICES (DVRs AND SSFCLs)

Custom power devices, such as Dynamic Voltage Restorers (DVRs) and Solid-State Fault Current Limiters (SSFCLs), offer innovative solutions for mitigating voltage sags, interruptions, and fault conditions in distribution networks. The investigation of these devices involves understanding their principles of operation and developing simulation setups to assess their performance and effectiveness.

### 1. Principles of Operation:

**a. Dynamic Voltage Restorers (DVRs):**

DVRs operate by injecting compensating voltage into the distribution network during voltage sag events to restore voltage levels to their nominal values. The operation of DVRs is based on real-time voltage sensing and control algorithms, which detect deviations from the desired voltage magnitude and phase and generate compensating signals to mitigate the sag. By dynamically adjusting the injected voltage waveform, DVRs provide uninterrupted and high-quality power supply to sensitive loads, ensuring system reliability and performance.

**b. Solid-State Fault Current Limiters (SSFCLs):**

SSFCLs are designed to limit fault currents in distribution networks by rapidly intervening during fault events and restricting the flow of excessive current. SSFCLs employ advanced power electronics and semiconductor devices to control the impedance of the network and limit fault current levels. By mitigating fault currents, SSFCLs prevent equipment damage, minimize disruption to power supply, and enhance the stability of distribution systems.

### 2. Simulation Setup for DVRs and SSFCLs:

The investigation of DVRs and SSFCLs will involve developing simulation setups to model their behavior and assess their performance under various operating conditions. The simulation setup typically includes:

a. **Component Modeling:** Define mathematical models for DVRs and SSFCLs based on their operational characteristics and control algorithms. This involves specifying parameters such as voltage injection capabilities, control bandwidth, and response times.

b. **Network Representation:** Create a representation of the distribution network in MATLAB. Define the network topology, component configurations, and load profiles to simulate realistic operating conditions.
c. **Event Simulation:** Generate voltage sag, interruption, and fault events within the distribution network to evaluate the response of DVRs and SSFCLs. Implement event triggers and control logic to activate the devices in response to simulated disturbances.
d. **Performance Analysis:** Analyze simulation results to assess the effectiveness of DVRs and SSFCLs in mitigating voltage sags, interruptions, and fault conditions. Evaluate performance metrics such as voltage restoration time, fault current limiting capability, and system stability improvement.

**ASSESSMENT OF ADVANCED MITIGATION TECHNIQUES**

Advanced mitigation techniques, such as the integration of custom power devices like DVRs and SSFCLs into distribution networks, offer promising solutions for enhancing system reliability, stability, and power quality. The assessment of these techniques involves integrating custom power devices into the distribution network and defining simulation scenarios and analysis approaches to evaluate their effectiveness in mitigating voltage sags, interruptions, and fault conditions.

**1. Integration of Custom Power Devices into the Distribution Network:**

Integrating custom power devices, such as DVRs and SSFCLs, into the distribution network requires careful planning and consideration of system configuration, device placement, and control strategies. The integration process involves:

a. **Device Placement:** Identify optimal locations for deploying DVRs and SSFCLs within the distribution network based on factors such as load concentration, critical infrastructure, and voltage profile requirements. Placement decisions aim to maximize the coverage and effectiveness of the devices in mitigating voltage disturbances and fault conditions.
b. **Control Strategy:** Develop control algorithms and coordination schemes to govern the operation of custom power devices in response to voltage disturbances and fault events. Control strategies aim to optimize device performance, minimize system disruptions, and ensure seamless integration into existing distribution network operations.

**2. Simulation Scenarios and Analysis Approach:**

Defining simulation scenarios and analysis approaches is essential for evaluating the effectiveness of advanced mitigation techniques in distribution networks. The simulation setup typically includes:

a. **Scenario Definition:** Define simulation scenarios to represent various operating conditions, voltage disturbances, and fault scenarios encountered in distribution

networks. Scenarios may include voltage sag events, interruption events, fault occurrences, and system reconfiguration events.

**b. Simulation Setup:** Configure simulation models and parameters to replicate realistic distribution network conditions and device behavior. This involves defining load profiles, network topology, fault characteristics, and device settings to accurately represent system dynamics and responses.

**c. Performance Evaluation:** Analyze simulation results to assess the performance of advanced mitigation techniques in mitigating voltage sags, interruptions, and fault conditions. Performance metrics such as voltage quality indices, system reliability indices, and fault mitigation capabilities are evaluated to quantify the effectiveness of custom power devices in improving system performance.

**DESIGN MODELS FOR VOLTAGE SAG AND INTERRUPTION EVENTS FOR DVR AND SSFCL:**

1. **Source Voltage Calculation**:

$$V_{source}(t) = V_{source_{nominal}} \times exp(j \times 2\pi \times f_{source} \times t) \quad (8)$$

Where:

- $V$source($t$) represents the voltage of the power source at time $t$.
- $V$source_ nominal is the nominal voltage of the power source.
- $f$source is the frequency of the power source.
- $j$ represents the imaginary unit.
- $exp(j \times 2\pi \times f_{source} \times t)$ calculates the complex exponential term, representing the sinusoidal nature of AC voltage over time.

2. **Line Impedance**:

$$Z_{line} = R_{line} + j \times (2\pi \times\times L_{line} - 12\pi \times f_{source} \times C_{load}) \quad (9)$$

Where:

- $Z_{\text{line}}$ denotes the impedance of the transmission line.
- $R_{\text{line}}$ is the resistance of the transmission line.
- $L_{\text{line}}$ is the inductance of the transmission line.
- $C_{\text{load}}$ is the capacitance of the load.

This equation calculates the total impedance of the transmission line, including resistance, inductive reactance, and capacitive reactance.

3. **DVR Line Current**:

$$I_{line_{dvr}}(t) = \frac{V_{line_{dvr}}(t) - V_{dvr_{nominal}}}{Z_{line}} \quad (10)$$

Where;

- $I_{line_{dvr}}(t)$ represents the current flowing through the transmission line with DVR protection at time $t$.

- $V_{line_{dvr}}(t)$ is the voltage of the transmission line with DVR protection at time $tt$.
- $V_{dvr_{nominal}}$ is the nominal voltage provided by the DVR.
- $Z_{\text{line}}$ is the impedance of the transmission line.

This equation calculates the current flowing through the line by applying Ohm's Law.

4. **SSFCL Line Current**:

$$I_{line_{ssfcl}}(t) = \left(\frac{V_{line_{ssfcl}}(t)}{Z_{line}} I_{ssfcl_{limit}}\right) \quad (11)$$

Where;

- $I_{line_{ssfcl}}(t)$ represents the current flowing through the transmission line with SSFCL protection at time $t$.
- $V_{line_{ssfcl}}(t)$ is the voltage of the transmission line with SSFCL protection at time $tt$.
- $Z_{\text{line}}$ is the impedance of the transmission line.
- $I_{ssfcl_{limit}}$ is the limiting current provided by the SSFCL.

This equation calculates the current flowing through the line while considering the limiting current provided by the SSFCL.

5. **Load Voltage for DVR**:

$$V_{load_{dvr}}(t) = V_{dvr_{nominal}} \quad (12)$$

Where;

- $V_{load_{dvr}}(t)$ represents the voltage at the load with DVR protection at time $t$.
- $V_{dvr_{nominal}}$ is the nominal voltage provided by the DVR.

Since the load voltage remains constant with DVR protection, it equals the nominal voltage provided by the DVR.

6. **Load Voltage for SSFCL**:

$$V_{load_{ssfcl}}(t) = V_{line_{ssfcl}}(t) \quad (13)$$

Where;

- $V_{load_{ssfcl}}(t)$ represents the voltage at the load with SSFCL protection at time $t$.
- $V_{line_{ssfcl}}(t)$ is the voltage of the transmission line with SSFCL protection at time $t$.

A summary of the simulation parameters is shown in Table 1.

**Table 1:** Electrical and Simulation Parameters for DVR-SSFCL Performance Evaluation

| Parameter | Value | Description |
|---|---|---|
| $\mathbf{R_{line}}$ | 0.1 Ω | Line resistance |
| $\mathbf{L_{line}}$ | 0.5 H | Line inductance |
| $\mathbf{C_{load}}$ | 0.2 F | Load capacitance |

| Parameter | Value | Description |
|---|---|---|
| $V_{source_nominal}$ | 230 V | Nominal source voltage |
| $f_{source}$ | 50 Hz | Source frequency |
| $P_{load}$ | 100 W | Active power of the load |
| $Q_{load}$ | 50 var | Reactive power of the load |
| $V_{dvr_nominal}$ | 230 V | Nominal DVR voltage |
| $t_{sag_duration}$ | 0.02 s | Duration of voltage sag |
| $V_{ssfcl_nominal}$ | 230 V | Nominal SSFCL voltage |
| $I_{ssfcl_limit}$ | 50 A | Limiting current for SSFCL |
| $t_{start}$ | 0 s | Simulation start time |
| $t_{end}$ | 0.2 s | Simulation end time |
| **dt** | 0.0001 s | Time step size |
| **t** | 0 to 0.2 s | Time vector from start to end time |
| $V_{sag_factor}$ | 0.5 | Voltage sag factor (percentage of nominal voltage) |
| $t_{sag_start}$ | 0.02 s | Start time of voltage sag |
| $t_{sag_end}$ | 0.04 s | End time of voltage sag |
| $V_{interruption}$ | 0 V | Voltage during interruption |
| $t_{interrupt_start}$ | 0.06 s | Start time of interruption |
| $t_{interrupt_end}$ | 0.08 s | End time of interruption |

## RESULTS AND DISCUSSIONS

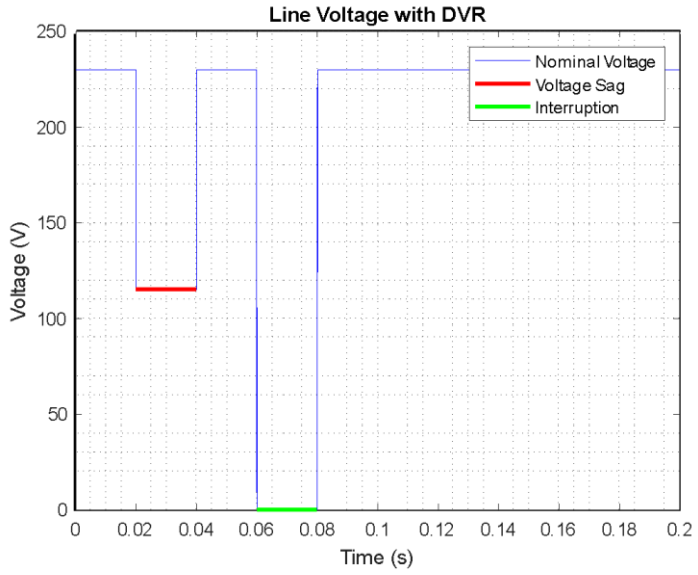



**Figure 2:** Line Voltage with DVR

The graph in Figure 2 visually represents the line voltage dynamics under the influence of a Dynamic Voltage Restorer (DVR) over the simulation period from 0 to 0.2 seconds. It

effectively illustrates the DVR's ability to mitigate voltage disturbances, including sags and interruptions, ensuring stable power delivery to the load.

**Normal Operation (0 to 0.02 seconds):**
The line voltage remains stable at its nominal value of 230 V (RMS), represented by the blue line. This indicates the system's normal operating condition, where the DVR maintains the load voltage without requiring active compensation.

**Voltage Sag (0.02 to 0.04 seconds):**
At 0.02 seconds, a voltage sag occurs, causing the line voltage to drop to 115 V, which is 50% of the nominal value. This event is depicted by the red segments on the graph. The DVR responds by injecting a compensatory voltage to restore the load voltage to 230 V, demonstrating its effectiveness in mitigating the sag. The sag lasts for 0.02 seconds, ending at 0.04 seconds.

**Recovery to Nominal Voltage (0.04 to 0.06 seconds):**
Following the voltage sag, the line voltage returns to its nominal value of 230V, as indicated by the blue line. This period reflects the DVR's successful restoration of stable voltage after the disturbance, ensuring continuity of power quality.

**Voltage Interruption (0.06 to 0.08 seconds):**
At 0.06 seconds, a complete voltage interruption occurs, reducing the line voltage to 0V, as shown by the green segments. This 0.02 second interruption simulates a severe fault or outage. The DVR compensates by supplying the full 230V to the load, typically drawing from its energy storage system, to maintain uninterrupted power delivery.

**Post-Interruption Recovery (0.08 to 0.2 seconds):**
After the interruption ends at 0.08 seconds, the line voltage stabilizes back to 230 V, as indicated by the return to the blue line. This phase demonstrates the DVR's ability to restore normal operation swiftly following a critical disturbance.

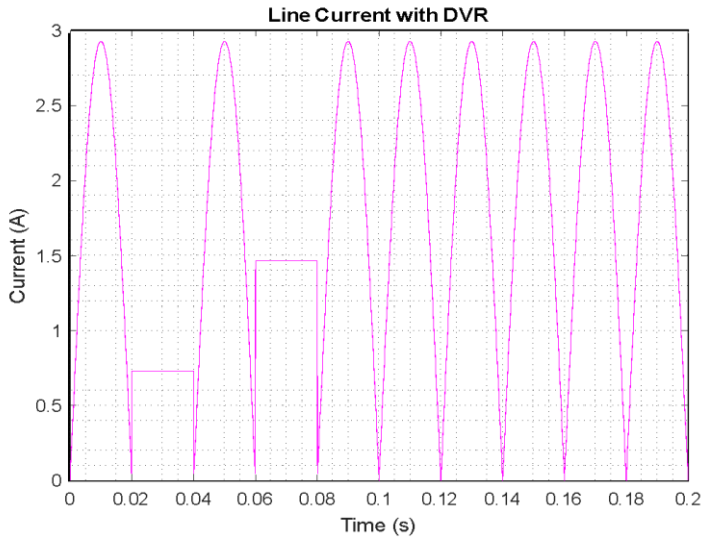



**Figure 3:** Line Current with DVR

The graph in Figure 3 illustrates the dynamic behavior of the line current in a power system equipped with a Dynamic Voltage Restorer (DVR) over the simulation period. The line current responds to variations in line voltage and the system's impedance, governed by Ohm's Law ($I = \frac{V}{Z}$, where I is current, V is voltage, and Z is impedance). The graph effectively showcases how the DVR influences the line current during normal operation and voltage disturbances, such as sags and interruptions, with the following detailed observations:

**Normal Operation:**

Under normal operating conditions, with the line voltage stable at its nominal value of 230 V (RMS), the line current fluctuates in accordance with Ohm's Law. The current magnitude is determined by the ratio of the line voltage to the system's impedance, which includes the line resistance $R_{line}$ = 0.1 ohms and inductance $L_{line}$ = 0.5 H. The impedance, calculated as Z = R + jωL where ω is the angular frequency, 2π × 50 Hz, shapes the steady-state current behavior, reflecting typical load demands and system characteristics.

**Voltage Sag Response:**

During a voltage sag from 0.02 to 0.04 seconds, the line voltage drops to 115V 50% of nominal. This reduction causes a proportional decrease in line current, as dictated by Ohm's Law, assuming constant impedance. The DVR mitigates this disturbance by injecting a compensatory voltage to maintain the load voltage at 230V, which indirectly stabilizes the current supplied to the load. The graph's depiction of this phase highlights the reduced line current due to the lower source voltage, contrasted with the DVR's role in ensuring load-side stability.

**Voltage Interruption Response:**
During a voltage interruption (from 0.06 to 0.08 seconds), the line voltage falls to 0 V, resulting in a complete cessation of line current (I = 0), as there is no driving voltage to sustain current flow through the line. The DVR compensates by supplying the full load voltage from its energy storage system, maintaining current flow to the load despite the interruption. This phase on the graph underscores the DVR's critical role in preventing a complete loss of load current during severe disturbances.

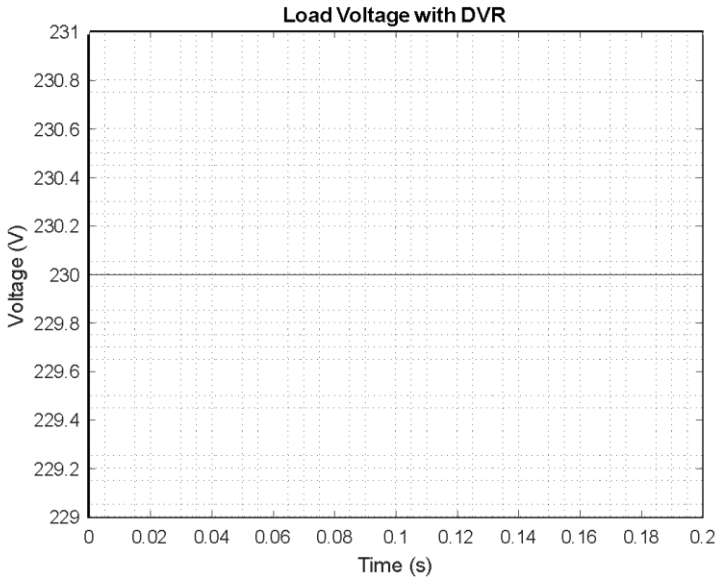



**Figure 4:** Load Voltage with DVR

The graph in Figure 4 illustrates the load voltage performance in a power system utilizing a Dynamic Voltage Restorer (DVR) across a simulation period of 0 to 0.2 seconds. It effectively demonstrates the DVR's capability to maintain a stable load voltage at its nominal value of 230 V (RMS) despite significant line voltage disturbances, such as voltage sags and interruptions. The following sections detail the load voltage behaviour as depicted in the graph.

**Consistent Load Voltage Throughout Simulation:**
The load voltage remains steadfast at 230 V (RMS) throughout the entire simulation period, as shown by a continuous, unwavering line on the graph. This stability underscores the DVR's effectiveness in delivering reliable voltage to the load, regardless of fluctuations in the line voltage caused by external disturbances.

**Performance During Voltage Sag (0.02 to 0.04 seconds):**
When a voltage sag reduces the line voltage to 115V (50% of nominal) from 0.02 to 0.04 seconds, the DVR compensates by injecting a corrective voltage in series with the line. This

ensures the load voltage remains at 230V, as evidenced by the graph's consistent 230V line during this interval. The DVR's rapid response, typically facilitated by power electronics such as a voltage-source inverter, mitigates the impact of the sag on the load.

**Performance During Voltage Interruption (0.06 to 0.08 seconds):**
During a complete voltage interruption from 0.06 to 0.08 seconds, where the line voltage drops to 0V, the DVR fully compensates by supplying the entire 230V required by the load. This is achieved by drawing energy from its storage system, maintaining the load voltage at 230 V, as shown by the graph's steady line. This phase highlights the DVR's ability to ensure power continuity during severe disruptions.

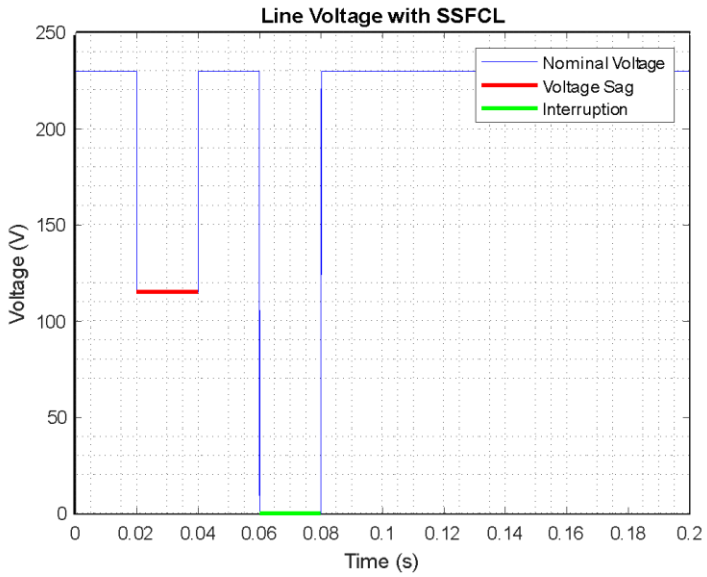



**Figure 5:** Line Voltage with SSFCL

The graph in Figure 5 illustrates the line voltage behaviour in a power system equipped with a Solid-State Fault Current Limiter (SSFCL) over a simulation period of 0 to 0.2 seconds. It clearly depicts the line voltage's response to disturbances, such as voltage sags and interruptions, highlighting the SSFCL's role in allowing these disturbances to pass through without voltage compensation, as its primary function is to limit fault currents.

**Normal Operation (0 to 0.02 seconds):**
The line voltage remains stable at its nominal value of 230V (RMS), as indicated by the blue line on the graph. This phase represents normal operating conditions, where the SSFCL operates in a low-impedance state, allowing normal current flow without affecting the line voltage.

**Voltage Sag (0.02 to 0.04 seconds):**
From 0.02 to 0.04 seconds, a voltage sag occurs, reducing the line voltage to 115V, which is 50% of the nominal value. This event is depicted by the red segments on the graph. Unlike a Dynamic Voltage Restorer (DVR), the SSFCL does not compensate for the voltage drop, as its function is to manage fault currents rather than regulate voltage. The graph clearly shows the unmitigated voltage sag, reflecting the disturbance's direct impact on the line.

**Recovery to Nominal Voltage (0.04 to 0.06 seconds):**
Following the voltage sag, the line voltage returns to its nominal value of 230V, as shown by the blue line. This recovery indicates the cessation of the sag event, with the SSFCL continuing to operate passively, allowing the line voltage to reflect the source's behaviour without intervention.

**Voltage Interruption (0.06 to 0.08 seconds):**
From 0.06 to 0.08 seconds, a complete voltage interruption occurs, causing the line voltage to drop to 0 V, as illustrated by the green segments. The SSFCL does not compensate for this interruption, as its role is limited to current limiting during faults, not voltage restoration. The graph's depiction of 0 V during this period underscores the absence of voltage regulation by the SSFCL.

**Post-Interruption Recovery (0.08 to 0.2 seconds):**
After the interruption ends at 0.08 seconds, the line voltage stabilizes back to 230V, as indicated by the return to the blue line. This phase reflects the restoration of normal source voltage, with the SSFCL maintaining its low-impedance state to permit normal operation without influencing the voltage.

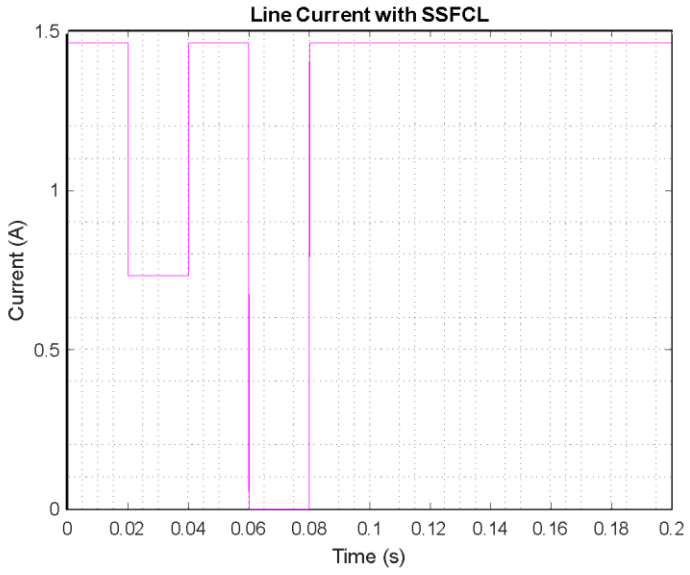



**Figure 6:** Line Current with SSFCL

The graph in Figure 6 depicts the line current behaviour in a power system equipped with a Solid-State Fault Current Limiter (SSFCL) over a simulation period of 0 to 0.2 seconds. It effectively illustrates the SSFCL's role in constraining the line current to a maximum limit of 1.50A during normal and disturbed conditions, such as voltage sags and interruptions. The current values are governed by Ohm's Law ($I = V / Z$, where I is current, V is voltage, and Z is the line impedance) and the SSFCL's imposed current limit. The following sections detail the line current behaviour as shown in the graph:

**Normal Operation (0 to 0.02 seconds):**
During normal operation, with the line voltage at its nominal value of 230V, the line current is determined by the system's impedance $Z = R_{line} + j\omega L_{line}$, where $R_{line} = 0.1$ ohms, $L_{line} = 0.5H$, and $\omega = 2\pi \times 50$ Hz. The SSFCL ensures that the current does not exceed its maximum limit of 1.50A. The graph depicts the current as a stable waveform, constrained by the SSFCL's operation in its low-impedance state, allowing normal current flow up to the specified limit.

**Voltage Sag Response (0.02 to 0.04 seconds):**
From 0.02 to 0.04 seconds, a voltage sag reduces the line voltage to 115V (50% of nominal). According to Ohm's Law, this lower voltage results in a proportional decrease in line current, assuming constant impedance. However, the SSFCL enforces the 1.50A limit, preventing the current from exceeding this threshold even if fault conditions would otherwise cause a surge. The graph shows the reduced current during this period, capped at or below 1.50A, highlighting the SSFCL's ability to manage current levels during voltage disturbances.

**Voltage Interruption Response (0.06 to 0.08 seconds):**
During a voltage interruption from 0.06 to 0.08 seconds, the line voltage drops to 0V, resulting in zero line current ($I = 0$), as there is no driving voltage to sustain current flow. The SSFCL's current-limiting function is not engaged during this period, as the absence of voltage inherently eliminates current flow. The graph clearly depicts this complete cessation of current, reflecting the interruption's impact on the system.

**Post-Disturbance Recovery (0.04 to 0.06 seconds and 0.08 to 0.2 seconds):**
Following the voltage sag from 0.04 to 0.06 seconds and interruption from 0.08 to 0.2 seconds, the line voltage returns to 230V. The line current resumes its normal behavior, constrained by the SSFCL's 1.50A limit and determined by the system's impedance and Ohm's Law. The graph shows the current returning to its steady-state waveform, capped at or below 1.50A, indicating the SSFCL's continued regulation of current flow during normal operation.
The graph in Figure 7 below illustrates the load voltage behavior in a power system equipped with a Solid-State Fault Current Limiter (SSFCL) over a simulation period of 0 to 0.2 seconds.

It clearly demonstrates that the load voltage directly follows the line voltage, as the SSFCL, designed primarily for fault current limiting, does not provide voltage compensation during disturbances, unlike a Dynamic Voltage Restorer (DVR). The load voltage's response to normal conditions, voltage sags, and interruptions is depicted with distinct phases, as detailed below:

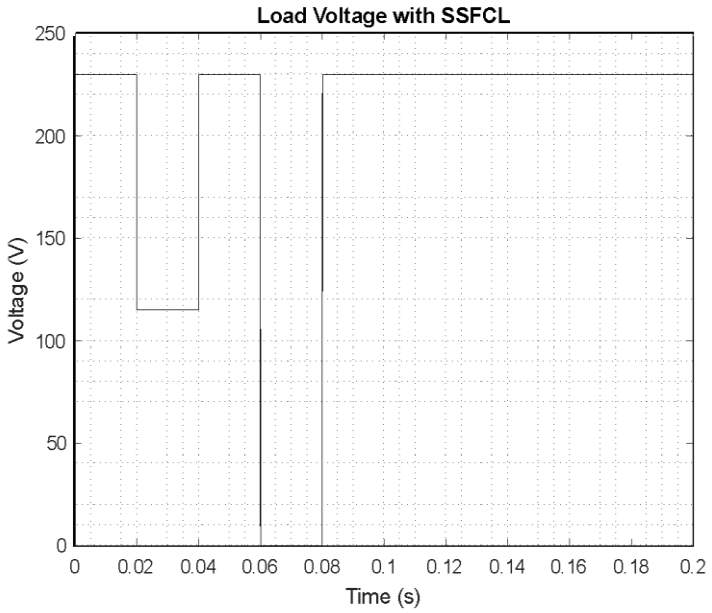



**Figure 7:** Load Voltage with SSFCL

**Normal Operation (0 to 0.02 seconds and 0.04 to 0.06 seconds):**
During periods of normal operation, when the line voltage is stable at its nominal value of 230 V (RMS), the load voltage mirrors this value, maintaining 230 V. This is shown by a steady line on the graph, reflecting the SSFCL's passive role in allowing the load voltage to equal the line voltage without intervention, as its function is limited to current regulation.

**Voltage Sag (0.02 to 0.04 seconds):**
From 0.02 to 0.04 seconds, a voltage sag reduces the line voltage to 115V (50% of nominal). Since the SSFCL does not compensate for voltage disturbances, the load voltage also drops to 115V, as depicted on the graph. This direct reflection of the line voltage sag highlights the SSFCL's lack of voltage regulation, in contrast to a DVR, which would actively restore the load voltage to 230V.

**Voltage Interruption (0.06 to 0.08 seconds):**
During a voltage interruption from 0.06 to 0.08 seconds, the line voltage falls to 0 V, and consequently, the load voltage also drops to 0 V, as shown on the graph. The SSFCL, focused on limiting fault currents rather than stabilizing voltage, does not mitigate this interruption, allowing the load to experience the full impact of the voltage loss.

**Post-Disturbance Recovery (0.08 to 0.2 seconds):**

After the interruption ends at 0.08 seconds, the line voltage returns to 230V, and the load voltage follows suit, stabilizing at 230V for the remainder of the simulation. This recovery, shown by the graph's return to a steady 230V line, indicates the restoration of normal operating conditions, with the SSFCL continuing to operate passively with respect to voltage.

The graph in Figure 8 below provides a comparative analysis of the line current behaviour in a power system equipped with either a Dynamic Voltage Restorer (DVR) or a Solid-State Fault Current Limiter (SSFCL) over a simulation period of 0 to 0.2 seconds. It effectively illustrates the distinct functionalities of the DVR and SSFCL in managing line current during normal operation and voltage disturbances, such as sags and interruptions. The DVR focuses on stabilising current through voltage compensation, while the SSFCL enforces a strict current limit to protect the system. The following sections detail the line current behaviour for each device, as depicted in the graph:

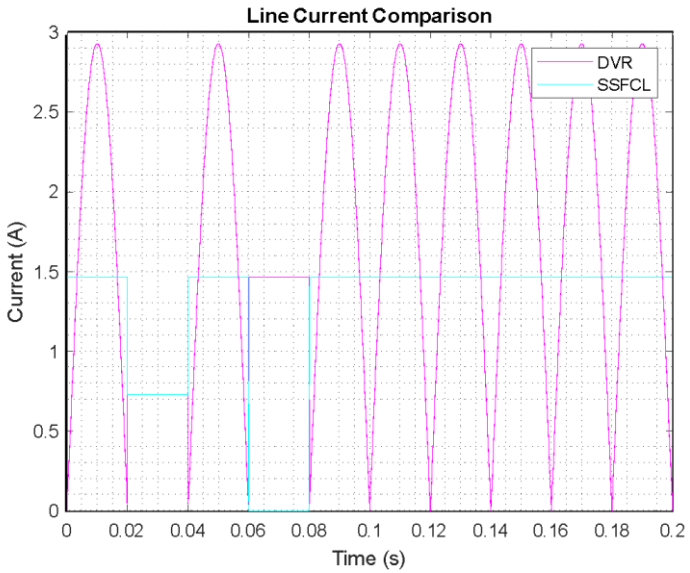



**Figure 8:** Line Current Comparison (DVR vs. SSFCL)

**DVR Line Current Behaviour:**

The line current under the DVR responds dynamically to variations in line voltage, governed by Ohm's Law where I = V / Z, where V is the line voltage and Z is the system impedance, incorporating $R_{line}$ = 0.1 ohms and $L_{line}$ = 0.5H. During normal operation from 0 to 0.02 seconds and 0.04 to 0.06 seconds, with the line voltage at 230V, the current reflects steady-state conditions. During a voltage sag from 0.02 to 0.04 seconds, with a line voltage of 115V, the DVR compensates by injecting voltage to maintain the load voltage at 230V, resulting in a line current that adapts to the adjusted voltage while maintaining a relatively stable load current delivery. During an interruption from 0.06 to 0.08 seconds, when the line voltage is at 0V, the DVR supplies the load voltage, ensuring continued current flow to the load. The graph

depicts the DVR's line current as a waveform that adjusts to voltage changes, reflecting its role in stabilising power delivery through voltage compensation.

**SSFCL Line Current Behaviour:**

The SSFCL constrains the line current to a maximum limit of 1.50A (RMS), regardless of voltage conditions, to protect the system from overcurrent. During normal operation from 0 to 0.02 seconds and 0.04 to 0.06 seconds, with the line voltage at 230V, the current is determined by Ohm's Law but capped at 1.50 A by the SSFCL's high-impedance state activation if necessary. During a voltage sag from 0.02 to 0.04 seconds, line voltage at 115V, the current decreases due to the lower voltage but remains strictly limited to 1.50 A, preventing excessive current flow. During an interruption from 0.06 to 0.08 seconds, line voltage at 0V, the current drops to 0 A, as no voltage drives the current. The graph shows the SSFCL's line current as a constrained waveform, capped at or below 1.50 A during sags and zero during interruptions, highlighting its protective function.

**Comparative Insights:**

The graph clearly contrasts the DVR's adaptive current behaviour with the SSFCL's restrictive approach. The DVR's current reflects its voltage compensation strategy, maintaining stable load current by adjusting the line voltage to the nominal 230V during disturbances. In contrast, the SSFCL enforces a fixed current limit of 1.50A during voltage sags, prioritizing system protection over current stability, and allows the current to fall to 0A during interruptions due to the absence of voltage. The numerical values DVR current adjusting based on compensated voltage versus SSFCL current capped at 1.50A underscore these differing roles.

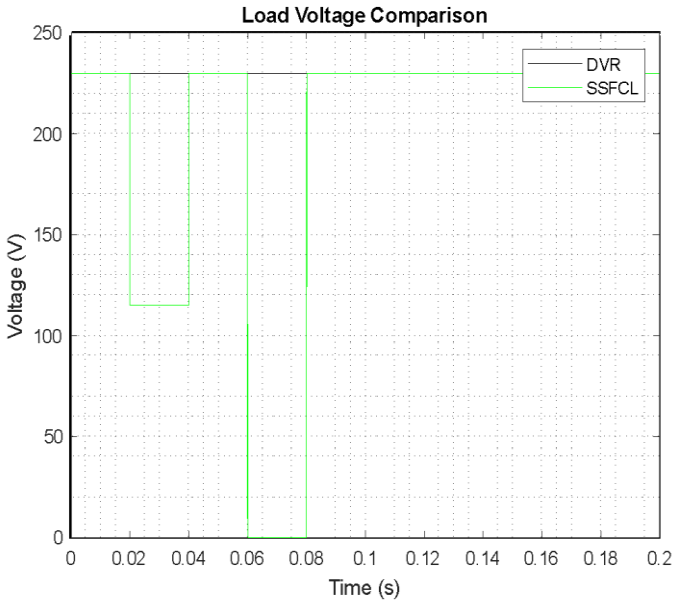



**Figure 9:** Load Voltage Comparison (DVR vs. SSFCL)

The graph in Figure 9 provides a comparative analysis of the load voltage behaviour in a power system equipped with either a Dynamic Voltage Restorer (DVR) or a Solid-State Fault Current Limiter (SSFCL) over a simulation period of 0 to 0.2 seconds. It effectively illustrates the distinct functionalities of the DVR in actively stabilizing load voltage and the SSFCL in passively reflecting line voltage disturbances. The load voltage responses during normal operation, voltage sags, and interruptions are detailed below, highlighting the contrasting roles of these devices:

**DVR Load Voltage Behaviour**

The DVR maintains a consistent load voltage of 230V throughout the entire simulation period, as depicted by a steady, unwavering line on the graph. During normal operation from 0 to 0.02 seconds, 0.04 to 0.06 seconds, and 0.08 to 0.2 seconds, when the line voltage is at its nominal 230V, the DVR ensures the load voltage matches this value. During a voltage sag from 0.02 to 0.04 seconds, line voltage at 115V, the DVR compensates by injecting a corrective voltage in series with the line, typically via a voltage-source inverter, to maintain the load voltage at 230V. Similarly, during a voltage interruption (0.06 to 0.08 seconds, line voltage at 0V, the DVR supplies the full 230V from its energy storage system, ensuring uninterrupted voltage delivery to the load. This consistent 230V load voltage underscores the DVR's role in active voltage regulation.

**SSFCL Load Voltage Behaviour**

The load voltage under the SSFCL directly tracks the line voltage, as the SSFCL is designed to limit fault currents rather than regulate voltage. During normal operation from 0 to 0.02 seconds, 0.04 to 0.06 seconds, and 0.08 to 0.2 seconds, with the line voltage at 230V, the load voltage remains at 230 V, as shown by a stable line on the graph. During a voltage sag from 0.02 to 0.04 seconds, line voltage at 115V, the load voltage drops to 115V, reflecting the unmitigated disturbance. During a voltage interruption from 0.06 to 0.08 seconds, line voltage at 0V, the load voltage falls to 0V, as the SSFCL does not provide voltage compensation. The graph's depiction of these drops highlights the SSFCL's passive response to voltage disturbances.

## CONCLUSION

The simulation had revealed that the Dynamic Voltage Restorer (DVR) and the Solid-State Fault Current Limiter (SSFCL) had fulfilled distinct but complementary functions in power system management. The DVR had been designed to preserve a constant load voltage of 230V, having injected compensatory voltage through a voltage-source inverter supported by energy storage. In doing so, it had maintained stable load voltage across sags and interruptions, thereby protecting sensitive equipment from power disturbances. However, the DVR had not altered line voltage nor limited fault current, its role having been strictly focused on voltage stabilization.

The SSFCL, by contrast, restricted excessive fault currents by switching into a high-impedance state whenever thresholds had been exceeded. It had a limited line current effectively, capping it at 1.50A during disturbances, thereby safeguarding network infrastructure against damaging overcurrent. The SSFCL had offered a simpler, cost-effective, and reliable means of protecting distribution networks and industrial systems.

The DVR and SSFCL had been shown to serve complementary purposes: the DVR having enhanced power quality through voltage compensation, while the SSFCL had ensured system survivability through current limitation. Their combined application had provided both voltage stability and fault protection, improving reliability, reducing downtime, and enhancing resilience in critical environments. Thus, the DVR had been best suited for hospitals, data centres, and precision manufacturing, whereas the SSFCL had been more appropriate for substations and industrial grids. The study had underscored that optimal system resilience had been achieved when the DVR and SSFCL had been strategically deployed according to the operational priorities of voltage stability and current protection.

## RECOMMENDATIONS AND FUTURE RESEARCH

To further enhance the understanding and application of DVRs and SSFCLs, the following areas of research are recommended:

1. Hybrid Systems: Investigate the integration of DVRs and SSFCLs in hybrid systems to leverage the strengths of both devices for optimal power quality and protection.
2. Advanced Control Algorithms: Develop advanced control algorithms for DVRs and SSFCLs to improve their responsiveness and effectiveness in real-time applications.
3. Performance under Various Conditions: Conduct extensive simulations and field tests to evaluate the performance of DVRs and SSFCLs under a wider range of voltage disturbances and fault conditions.

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