Rover Publications

United International Journal of Engineering and Sciences (UIJES)

An International Peer-Reviewed (Refereed) Engineering and Science Journal Impact Factor:7.984(SJIF) Volume-4, Special Issue-3; ISSN: :2582-5887

Fault Current Interruption by the Dynamic Voltage Restorer

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DOI:10.53414/UIJES:2024.43.337

***Abstract* -The dynamic voltage restorer (DVR) is a critical device employed in electrical distribution systems to mitigate voltage sags and maintain the quality of power supply. This paper presentation delves into the comprehensive understanding of DVR technology, its working principles, design considerations, control strategies, and applications in enhancing power quality. The discussion encompasses theoretical foundations, practical implementations, recent advancements, and future prospects of DVRs in modern power systems. Through an extensive review of literature, case studies, and simulation results, this paper aims to provide valuable insights into the role of DVRs in ensuring reliable and high-quality electricity supply.**

***Keywords* –Dynamic Voltage Restorer, Power Quality, Voltage Sag Mitigation, Distribution Systems, Control Strategies, Power Electronics**

I.INTRODUCTION

Overview of power quality issues in electrical distribution systems. Voltage sags are temporary reductions in voltage levels, typically lasting for a few cycles, caused by faults in the distribution network, starting of large loads, or switching operations. Voltage swells, on the other hand, are temporary increases in voltage levels, often resulting from load shedding or capacitor switching. Interruptions are complete cessations of voltage supply, which can occur due to faults or system maintenance. Voltage flicker refers to rapid variations in voltage magnitude, primarily caused by fluctuating loads like arc furnaces or welding equipment. These power quality issues can have detrimental effects on sensitive equipment and processes, necessitating effective mitigation strategies.

Importance of voltage regulation and mitigation of voltage sags[1]. Voltage regulation is essential to meet the power quality requirements of modern electrical systems. Stable and well-regulated voltage levels are necessary for the proper operation of sensitive electronic equipment, motors, and appliances. Voltage variations, such as sags, can result in significant financial losses due to equipment damage, downtime, and productivity losses. Moreover, voltage fluctuations can compromise the reliability and lifespan of electrical devices, leading to increased maintenance costs and decreased operational efficiency.

Introduction to the dynamic voltage restorer (DVR) as a solution. DVRs employ advanced power electronics and control algorithms to provide fast and accurate voltage regulation capabilities. Key features of DVRs for voltage sag mitigation include[3]:

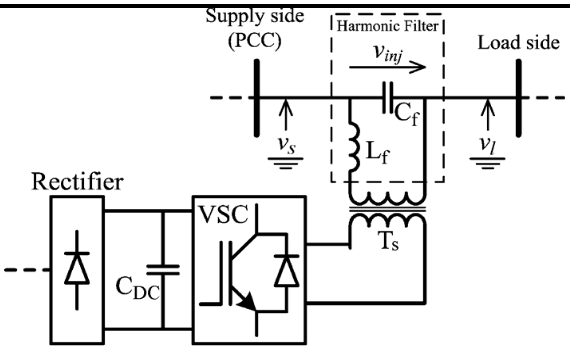


Fig. 1. Schematic diagram of a DVR with a line-side harmonic filter

1. Real-time Voltage Monitoring: DVRs continuously monitor the voltage profile at critical load points to detect deviations from the desired voltage levels.[3]
2. Fast Response Time: DVRs respond rapidly to voltage sags, injecting compensating voltages within milliseconds to restore voltage levels and mitigate the impact of disturbances.
3. Precision Control: DVRs employ sophisticated control algorithms, such as PI controllers and fuzzy logic systems, to ensure precise voltage regulation and optimal performance under varying operating conditions.[3]
4. Energy Storage Integration: DVRs utilize energy storage devices, such as capacitors or batteries, to store and discharge energy during voltage sag events, enabling seamless compensation and voltage restoration

II. Fundamentals of Dynamic Voltage Restorer

A. Basic principles and operation of DVRs

Voltage Detection: DVR continuously monitors the voltage levels at critical load points using voltage sensors. When a voltage disturbance, such as a sag, is detected, the control system initiates the compensation process.[3]

Energy Storage: Upon detecting a voltage sag, the control system activates the energy storage device (e.g., capacitors) to discharge stored energy. This energy is utilized to generate compensating voltages and restore the voltage profile at the load.

Voltage Injection: The power electronic converter (VSI) generates compensating voltages based on the detected voltage deviation and the control algorithm. These compensating voltages are injected into the distribution system to counteract the effects of the voltage sag and maintain the desired voltage levels at the load.[3]

Real-Time Control: DVRs employ real-time control algorithms to ensure fast and accurate compensation for voltage disturbances. The control system continuously adjusts the output voltage of the VSI to match the desired voltage profile and minimize the impact of voltage fluctuations on connected equipment.

B.Components and configurations of DVR systems

Voltage Sensors: Voltage sensors are essential components of DVR systems, responsible for continuously monitoring the voltage levels at critical load points.These sensors detect voltage deviations, such as sags and swells, and provide real-time feedback to the control system for appropriate action.

Energy Storage Device:DVR systems incorporate energy storage devices, such as capacitors or batteries, to store and release energy during voltage disturbance events.Energy storage devices ensure rapid response and effective compensation for voltage fluctuations, helping to maintain stable voltage levels at the load.

Power Electronic Converters: Power electronic converters, typically voltage source inverters (VSIs), are integral to DVR systems for generating compensating voltages.[3]These converters interface between the grid and the load, allowing bidirectional power flow and precise voltage control.

Control System: The control system of DVRs plays a crucial role in coordinating the operation of various components and implementing control strategies for voltage regulation.Advanced control algorithms, such as proportional-integral (PI) control, hysteresis control, and pulse width modulation (PWM), are employed to regulate the output voltage and ensure accurate compensation.

C. Configurations of DVR Systems:

Series Configuration: In the series configuration, the DVR is connected in series with the distribution feeder and the critical load.During a voltage sag event, the DVR injects compensating voltages in series with the load, effectively boosting the voltage levels and mitigating the impact of the disturbance.

Shunt Configuration: In the shunt configuration, the DVR is connected in parallel with the distribution feeder and the critical load.The DVR continuously monitors the voltage profile and injects compensating currents into the distribution system to regulate voltage levels at the load.

Combined Series-Shunt Configuration: Some DVR systems utilize a combined series-shunt configuration, where DVR units are deployed both in series and shunt with the load.This configuration provides enhanced voltage regulation capabilities, allowing for effective compensation of voltage sags and swells in the distribution system.

Multiple DVR Configuration: In large-scale distribution systems or networks with multiple critical loads, multiple DVR units may be deployed at different locations to provide comprehensive voltage regulation coverage.Coordinated operation and communication between multiple DVR units ensure synchronized compensation and optimal voltage regulation across the entire distribution network.

III. Power Electronics in DVR Design

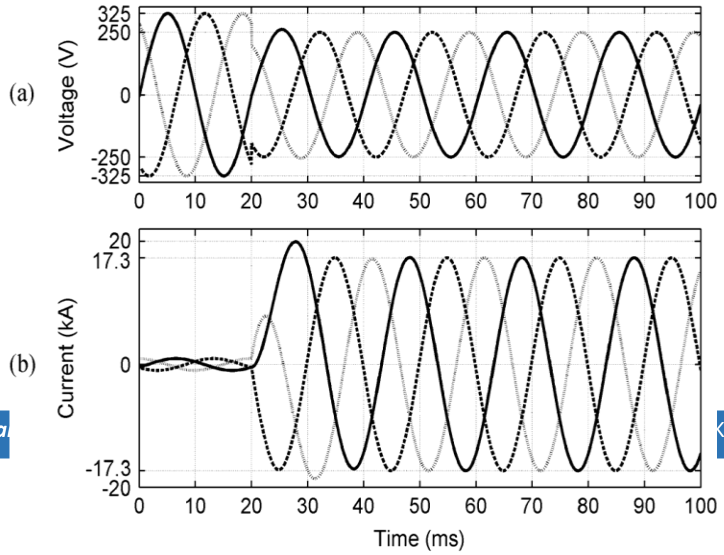
A. Power converter topologies used in DVRs

Voltage Source Inverter (VSI): The Voltage Source Inverter (VSI) is one of the most commonly used converter topologies in DVR systems. It converts DC voltage from an energy storage device (e.g., capacitor) into AC voltage, which is injected into the distribution system to mitigate voltage sags and swells. VSIs offer precise voltage control and fast response times, making them suitable for real-time compensation of voltage disturbances. They can operate in both grid-connected and islanded modes, providing flexibility and versatility in DVR applications.

Current Source Inverter (CSI): The Current Source Inverter (CSI) is another converter topology employed in DVR systems. Unlike VSIs, CSIs control the output voltage by regulating the output current, making them suitable for applications requiring robust current control. CSIs utilize inductive energy storage devices, such as reactors or chokes, to maintain a constant output current, thereby providing inherent short-circuit protection and improved fault tolerance. However, CSIs may have slower response times compared to VSIs due to the additional energy storage element.

B . Control strategies for DVR operation

1. **Proportional-Integral (PI) Control:** PI control is one of the most commonly used control strategies in DVRs.[1]It relies on feedback from voltage sensors to continuously adjust the output voltage of the DVR in proportion to the voltage deviation (proportional control) and over time to eliminate steady-state errors (integral control).[1]PI controllers are widely employed due to their simplicity, stability, and effectiveness in regulating voltage levels.
2. **Hysteresis Control:**Hysteresis control is a robust control strategy that sets predefined voltage thresholds (hysteresis bands) within which the DVR operates.[1]When the voltage deviates outside the hysteresis band, the control system triggers the DVR to inject compensating voltages until the voltage is restored within the band.Hysteresis control offers fast response times and is less sensitive to parameter variations and disturbances compared to other control strategies.



3. **Pulse Width Modulation (PWM):** PWM control involves modulating the width of the output voltage pulses generated by the DVR's power electronic converter (e.g., voltage source inverter).[2]By varying the pulse width in proportion to the voltage deviation, PWM control achieves precise voltage regulation and harmonic suppression.[2] PWM control is widely used in DVRs to ensure accurate compensation for voltage disturbances while minimizing harmonic distortion in the output voltage waveform.
4. **Fuzzy Logic Control:** Fuzzy logic control employs fuzzy inference systems to mimic human reasoning and decision-making processes. By using linguistic variables and fuzzy rules, fuzzy logic controllers adaptively adjust the output voltage of the DVR based on input parameters such as voltage deviation, load conditions, and system dynamics. Fuzzy logic control offers flexibility and robustness in handling nonlinearities and uncertainties in the system, making it suitable for DVR operation in dynamic and changing environments.
5. **Model Predictive Control (MPC):** MPC is an advanced control strategy that utilizes dynamic models of the electrical distribution system to predict future system behavior and optimize control actions.By solving optimization problems iteratively, MPC determines the optimal control inputs (compensating voltages) to minimize voltage deviations and meet performance objectives. MPC offers superior performance in terms of accuracy, robustness, and adaptability, but it requires computational resources and accurate system models for implementation.

C. Active and reactive power injection capabilities of DVRs

ACTIVE POWER INJECTION: Active power injection refers to the capability of DVRs to inject real power into the distribution system.[2] This feature enables DVRs to compensate for active power losses associated with voltage disturbances and to provide additional power support during peak demand periods. The active power injection capability of DVRs contributes to voltage regulation, load balancing, and overall system efficiency.

REACTIVE POWER INJECTION: Reactive power injection involves the generation or absorption of reactive power by DVRs to regulate voltage levels and improve power factor.[2] Reactive power injection is particularly beneficial for addressing voltage fluctuations, enhancing voltage stability, and reducing system losses.

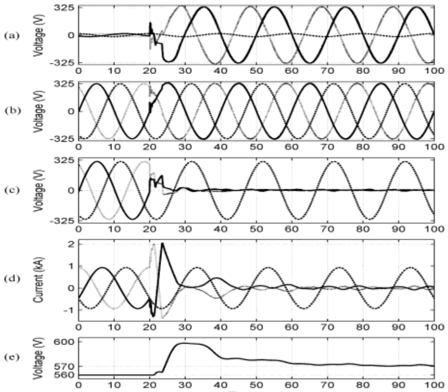


Fig. 3. (a) Injected voltages. (b) Source voltages. (c) Load voltages. (d) Line currents. (e) DC-link voltage, during the three-phase downstream fault.

Voltage sag mitigation using Dynamic Voltage Restorer (DVR) systems is a critical aspect of ensuring power quality in electrical distribution networks. Voltage sags, characterized by short-term reductions in voltage levels, can result from various factors such as network faults, switching operations, or sudden changes in load demand. These disturbances can have detrimental effects on sensitive equipment, leading to operational disruptions, equipment damage, and financial losses.

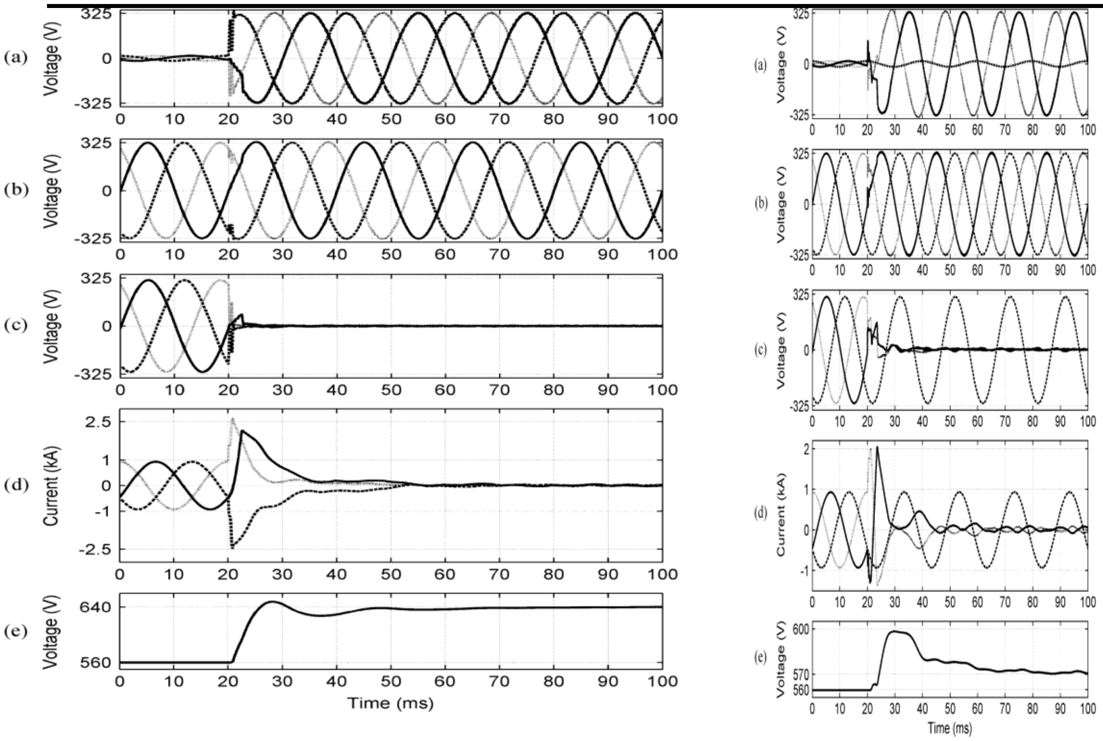


Fig. 4. (a) Injected voltages. (b) Source voltages. (c) Load voltages. (d) Line currents. (e) DC-link voltage, during the three-phase downstream fault.

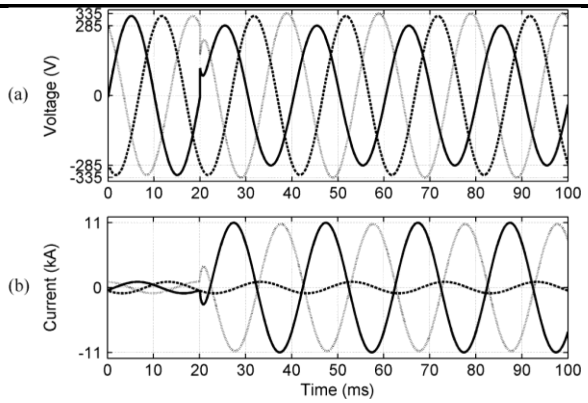


Fig. 5. (a) Voltages at , (b) Fault currents, during downstream phase-to- phase fault when the DVR is inactive (bypassed).

A.Phase-to-Phase Downstream Faults

The system of Fig. 4 is subjected to a phase-A to phase-C fault with the resistance of 0.05 at 10% of the cable length connecting to, at 20 m s. When the DVR is inactive (bypassed) during the fault (Fig. 7), the PCC voltage drops to 0.88 p.u., and the fault current increases to about 11 times the rated load current.

Fig. 8 illustrates that when the DVR is in service, the pro- posed FCI control successfully interrupts the fault current and DVRs offer an effective solution for mitigating voltage sags by injecting compensating voltages to restore the voltage profile at critical load points. This section delves into the key aspects of voltage sag mitigation using DVR systems:

1. Real-Time Voltage Monitoring: DVR systems continuously monitor the voltage profile at critical load points using voltage sensors. Real-time monitoring enables the timely detection of voltage sags and facilitates rapid response to disturbances.

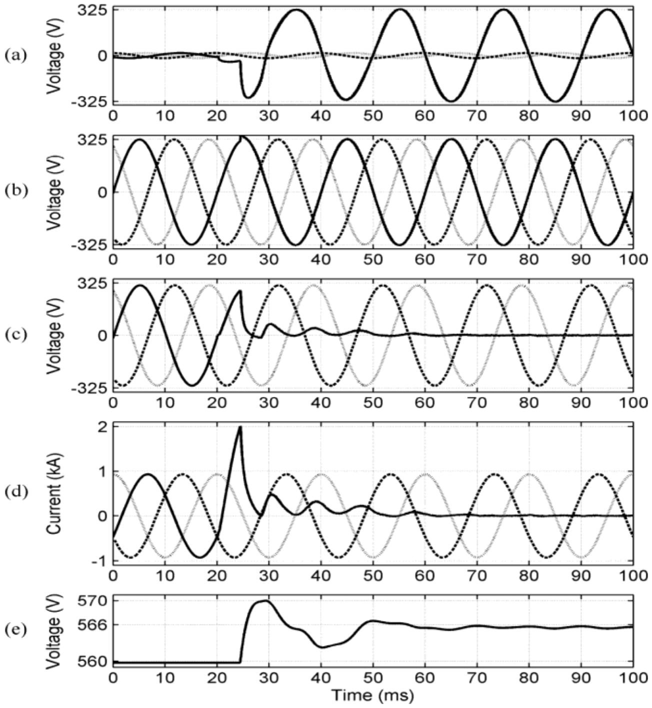


Fig. 6 . (a) Injected voltages. (b) Source voltages. (c) Load voltages. (d) Line currents. (e) DC-link voltage, during the single-phase-to-ground downstream fault.

2. Fast Response Time: DVRs are designed to respond rapidly to voltage sags, typically within milliseconds. This fast response time ensures that compensating voltages are injected promptly to mitigate the impact of voltage disturbances on connected equipment.
3. Compensation Techniques: DVR systems employ various compensation techniques to mitigate voltage sags effectively. These techniques include injecting compensating voltages in series or parallel with the existing supply to restore the voltage levels at the load.
4. Energy Storage Integration: DVRs utilize energy storage devices, such as capacitors or batteries, to store and discharge energy during voltage sag events. Energy storage integration enhances the performance of DVR systems by providing the necessary power for compensating voltage injection.
5. Power Electronics and Control: The heart of DVR systems lies in their power electronic converters and control algorithms. Voltage source inverters (VSIs) are commonly used to generate compensating voltages, while sophisticated control strategies such as pulse width modulation (PWM) and proportional-integral (PI) control ensure accurate voltage regulation.
6. Placement and Configuration: The placement and configuration of DVR systems are crucial for effective voltage sag mitigation. DVRs are typically installed close to critical loads to minimize the impact of voltage disturbances. Optimal placement and configuration ensure efficient operation and maximum coverage of sensitive equipment.
7. System Coordination and Integration: DVR systems can be integrated with other power quality enhancement devices and control systems to achieve comprehensive voltage regulation and power quality improvement. Coordination with distribution automation systems and smart grid technologies enables seamless integration and enhances overall system reliability.
8. Benefits of Voltage Sag Mitigation: Mitigating voltage sags using DVR systems offers several benefits, including:

- Protection of sensitive equipment and appliances from damage.
- Reduction in downtime and operational disruptions.
- Improvement in power quality and system reliability.
- Minimization of financial losses associated with equipment failures and productivity interruptions.

IV. VOLTAGE STABILITY IMPROVEMENT IN DISTRIBUTION NETWORKS

Voltage stability is essential for ensuring the reliable operation of electrical distribution networks. However, distribution systems often face challenges such as voltage sags, swells, and fluctuations, which can compromise voltage stability and affect the quality of power delivered to consumers. [3]Dynamic Voltage Restorers (DVRs) have emerged as effective devices for enhancing voltage stability in distribution networks. This section explores the role of DVR systems in improving voltage stability and discusses their key features and benefits.

Voltage Stability Challenges in Distribution Networks: Voltage instability can result from various factors, including changes in load demand, network faults, and the integration of renewable energy sources.[2] Voltage sags and swells, in particular, can disrupt sensitive equipment and affect the performance of electrical appliances, leading to operational inefficiencies and financial losses for consumers and utilities alike.

Role of DVR Systems in Voltage Stability Improvement: DVR systems play a crucial role in improving voltage stability by mitigating voltage disturbances and maintaining stable voltage levels at critical load points. These systems operate based on real-time monitoring of voltage variations and employ advanced control algorithms to inject compensating voltages and restore the voltage profile to desired levels. By providing rapid and accurate voltage regulation, DVRs help mitigate the impact of voltage fluctuations and enhance the stability and reliability of distribution networks.

V. CONCLUSION

- **Summary of key findings and contributions**

Dynamic Voltage Restorer (DVR) systems have emerged as vital solutions for mitigating voltage disturbances and ensuring the stability and reliability of electrical distribution networks. Over the years, extensive research and development efforts have been dedicated to enhancing the performance and effectiveness of DVR technology. Here, we summarize the key findings and contributions of DVR systems based on existing literature and practical implementations:

1. Voltage Regulation and Power Quality Enhancement:

- DVRs play a crucial role in maintaining voltage stability and improving power quality by mitigating voltage sags, swells, and interruptions.
- Research studies have demonstrated the effectiveness of DVRs in reducing voltage variations and enhancing the reliability of electrical distribution systems, thereby minimizing equipment downtime and operational disruptions.

2. Fast and Accurate Compensation:

- DVRs offer rapid response times, typically in the order of milliseconds, enabling quick detection and mitigation of voltage disturbances.
- Advanced control algorithms and real-time monitoring techniques ensure precise compensation, minimizing the impact of voltage fluctuations on connected loads and sensitive equipment.

3. Flexibility and Adaptability:

- DVRs are highly flexible and adaptable to various grid configurations and operating conditions.
- They can be easily integrated into existing distribution systems, offering seamless voltage regulation capabilities without significant modifications to the infrastructure.

4. Cost-Effectiveness and Efficiency:

- Studies have highlighted the cost-effectiveness of DVRs compared to alternative voltage regulation solutions, such as static compensators (STATCOMs) or traditional voltage regulators.
- DVRs utilize energy storage devices efficiently, minimizing energy losses and optimizing system performance during voltage sag events.

5. Applications across Diverse Sectors:

- DVR technology finds applications across diverse sectors, including industrial, commercial, and residential environments.
- Case studies and field trials have demonstrated the efficacy of DVRs in protecting critical equipment, enhancing productivity, and improving customer satisfaction.
- Importance of DVRs in enhancing power quality

Power quality is a critical aspect of electrical distribution systems, ensuring that voltage levels remain within specified tolerances and that disturbances such as voltage sags, swells, and interruptions are mitigated effectively. Dynamic Voltage Restorers (DVRs) have emerged as indispensable tools for enhancing power quality by swiftly correcting voltage deviations and maintaining stable voltage levels at critical load points. This section explores the significance of DVRs in improving power quality within dynamic voltage restorer systems.

1. Mitigation of Voltage Disturbances: Voltage sags, one of the most prevalent disturbances in power systems, can lead to equipment malfunction, productivity losses, and operational disruptions. DVRs offer rapid response capabilities, detecting voltage sags in real-time and injecting compensating voltages to restore the voltage profile at affected load points. By mitigating voltage disturbances, DVRs ensure uninterrupted operation of sensitive equipment and minimize the impact of voltage fluctuations on connected loads.
2. Voltage Regulation and Stability: DVRs play a crucial role in regulating voltage levels and maintaining system stability, particularly in scenarios where voltage fluctuations are common due to varying load conditions or the integration of renewable energy sources. By dynamically adjusting output voltages in response to changes in grid conditions, DVRs help stabilize the voltage profile and ensure consistent voltage levels within acceptable limits. This enhances the reliability and resilience of electrical distribution systems, reducing the risk of equipment damage and service interruptions.
3. Protection of Sensitive Equipment: Sensitive electronic devices, motors, and appliances are vulnerable to damage or malfunction caused by voltage variations beyond specified tolerances. DVRs provide an effective barrier against voltage disturbances, safeguarding connected equipment from the adverse effects of voltage sags, swells, and other transient events. By maintaining stable voltage levels, DVRs prolong the lifespan of equipment, reduce maintenance costs, and enhance overall system reliability.

- **Future outlook and potential advancements in DVR technology**

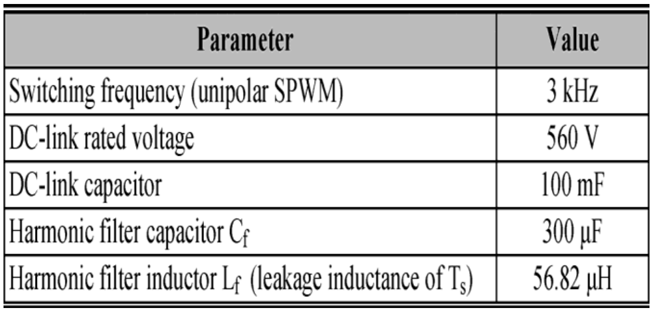
1. Advanced Control Algorithms: Future DVR systems are expected to leverage advanced control algorithms to enhance their response to voltage disturbances. Machine learning techniques, such as artificial neural networks and reinforcement learning, can optimize control strategies and adapt dynamically to changing operating conditions, improving the overall efficiency and effectiveness of DVRs.

2. Integration with Smart Grids: Integration of DVRs with smart grid infrastructure is anticipated to enable enhanced communication, coordination, and interoperability with other grid devices and systems. By leveraging real-time data and grid analytics, smart DVRs can anticipate voltage disturbances and proactively mitigate them, thereby improving power quality and grid stability.
3. Energy Storage Technologies: Advancements in energy storage technologies, such as supercapacitors, advanced batteries, and hybrid energy storage systems, offer opportunities to enhance the energy storage capacity and efficiency of DVRs. By increasing energy density and reducing charging/discharging times, these technologies can improve the responsiveness and performance of DVRs in mitigating voltage disturbances.
4. Modular and Scalable Designs: Future DVR systems may adopt modular and scalable designs to accommodate varying system requirements and load profiles. Modular architectures enable flexible configuration and expansion of DVRs, allowing utilities and end-users to tailor the system capacity and functionality according to specific needs, thereby enhancing cost-effectiveness and scalability.
5. Multi-Functionality: Future DVR systems may incorporate multi-functionality to address a broader range of power quality issues and grid challenges. Integrated devices capable of mitigating multiple types of disturbances, such as voltage sags, swells, harmonics, and flicker, offer enhanced versatility and efficiency, simplifying system integration and deployment.

In conclusion, the utilization of Dynamic Voltage Restorers (DVRs) for fault current interruption presents a promising solution to enhance power system reliability and stability. By swiftly detecting and mitigating fault currents, DVRs can prevent voltage sags and disturbances, thereby maintaining the quality of power supply to critical loads. The integration of advanced control algorithms and switching devices enables DVRs to respond rapidly to fault conditions, minimizing downtime and potential damage to sensitive equipment. Additionally, their ability to inject compensating voltages allows for seamless restoration of voltage profiles post-fault. While challenges such as cost-effectiveness and coordination with existing protection schemes remain, ongoing research and development efforts are poised to further optimize the performance and deployment of DVRs in modern power systems, ensuring efficient fault current interruption and sustained reliability.

Table I: Transformer Parameters

Transformer	**T_1, T_2**	**T_3**	**T_s**
Rated Power (MVA)	90	2	0.175
No load losses (p.u.)	0.001	0.00205	0.003
Copper losses (p.u.)	0.0048	0.0097	0.02
Leakage reactance (p.u.)	0.237	0.06	0.05
Primary voltage rating (kV)	230	20	0.4
Secondary voltage rating (kV)	20	0.4	0.245
Winding connection type	YnD	DYn	---



Parameter	Value
Switching frequency (unipolar SPWM)	3 kHz
DC-link rated voltage	560 V
DC-link capacitor	100 mF
Harmonic filter capacitor C_f	300 μF
Harmonic filter inductor L_f (leakage inductance of T_s)	56.82 μH

Table II: VSC Parameters

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