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Next-generation Voltage Stability Control: Harnessing BESS Integration for Efficiency

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Abstract **– In the pursuit of grid modernization and enhanced renewable energy integration, voltage stability control plays a pivotal role in maintaining grid reliability. This paper presents a next-generation approach to voltage stability control by leveraging Battery Energy Storage Systems (BESS) integration. The integration of BESS offers a dynamic and flexible solution to address voltage fluctuations and maintain optimal grid performance. The proposed model combines advanced control algorithms with BESS integration to achieve efficient voltage stabilization. By dynamically adjusting the charging and discharging of batteries in response to grid voltage variations, the system ensures rapid and precise voltage regulation. Additionally, the model incorporates predictive analytics and real-time monitoring to anticipate voltage disturbances and proactively mitigate potential issues.**

Keywords **– Voltage Stability Control, Integration for Efficiency.**

I. Introduction

With the increasing penetration of renewable energy sources and the growing complexity of modern power systems, ensuring voltage stability has become a critical challenge for grid operators worldwide. Voltage fluctuations stemming from intermittent renewable generation and dynamic load variations necessitate innovative solutions to maintain grid reliability and efficiency. In this context, the integration of Battery Energy Storage Systems (BESS) emerges as a promising approach to enhance voltage stability control.

This paper introduces a next-generation model for voltage stability control that harnesses BESS integration to optimize grid performance and efficiency. Traditional voltage stability control methods often rely on reactive power compensation devices and conventional voltage regulation techniques, which may lack the flexibility and responsiveness required to address dynamic grid conditions effectively. By contrast, BESS integration offers a dynamic and adaptable solution that can rapidly respond to voltage fluctuations and maintain grid stability in real-time.

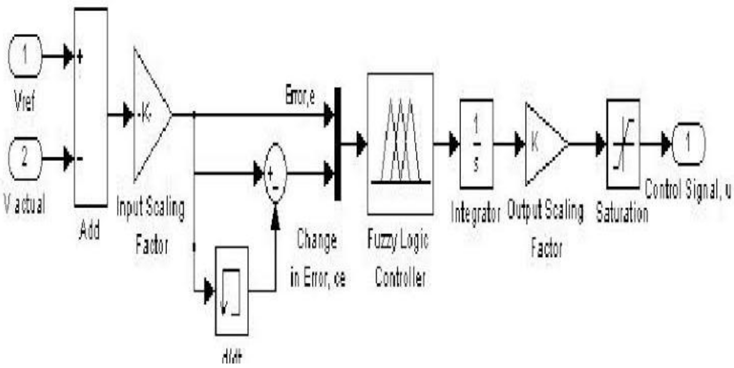


Fig: SIMULINK model of proposed FLC.

II. IMPORTANCE OF VOLTAGE STABILIZATION

Voltage stabilization is a critical aspect of power system operation, ensuring the reliability, efficiency, and safety of electrical grids. As power systems evolve to accommodate increasing levels of renewable energy integration and meet growing electricity demand, voltage stability becomes even more crucial. This paper highlights the importance of voltage stabilization in power systems and discusses the key reasons why it is essential for grid reliability and performance.

1. **Grid Reliability:** Voltage stability is essential for maintaining the integrity of the electrical grid and ensuring continuous power supply to consumers. Voltage fluctuations can lead to equipment failures, voltage sags, and even blackouts, resulting in significant disruptions to economic activities and quality of life. By stabilizing voltage levels, power systems can mitigate the risk of voltage-related disturbances and enhance grid reliability.

2. **Equipment Protection**: Voltage instability can cause stress on electrical equipment, including transformers, motors, and other devices connected to the grid. Overvoltage or undervoltage conditions can accelerate equipment degradation and reduce their operational lifespan, leading to increased maintenance costs and downtime. Voltage stabilization measures help protect equipment from voltage-related damage, thereby improving asset reliability and longevity.

3. **Renewable Energy Integration:** With the rapid growth of renewable energy sources such as solar and wind power, voltage stability becomes a more significant concern due to the variability and intermittency of these resources.

Integrating renewable energy into the grid requires robust voltage stabilization mechanisms to manage fluctuations in generation and maintain grid stability. Advanced control strategies, including the use of energy storage systems and grid-forming inverters, play a crucial role in stabilizing voltage levels and facilitating the seamless integration of renewables.

4. **Grid Resilience:** Voltage stability is fundamental to the resilience of power systems against external disturbances, such as faults, storms, and cyber-attacks. A stable voltage profile enables power systems to withstand unforeseen events and recover quickly from disruptions, minimizing the impact on customers and critical infrastructure. Proactive voltage stabilization measures enhance grid resilience by reducing vulnerability to external threats and ensuring continuity of service under adverse

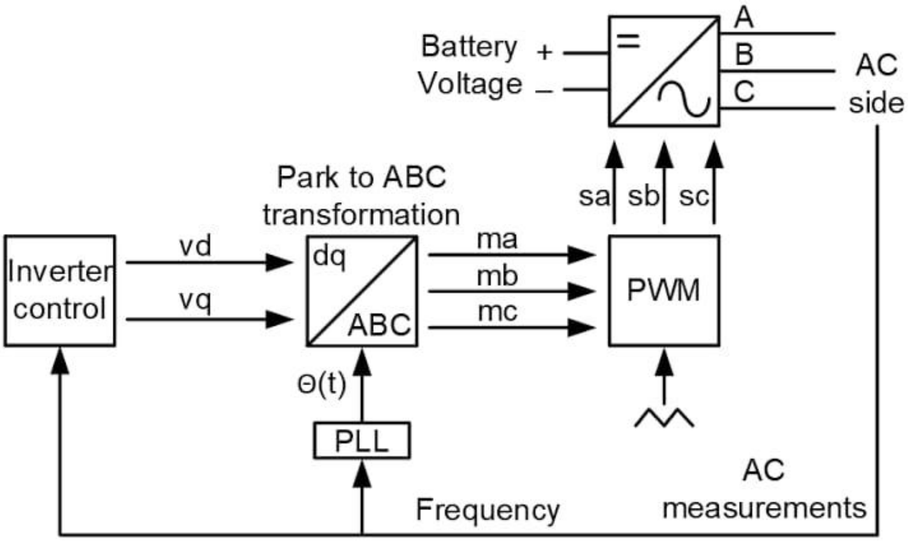


Fig: Basic Inverter control System

NEED FOR INNOVATION

voltage stability control arises from the evolving landscape of modern power systems, characterized by increasing complexity and the integration of renewable energy sources. Traditional voltage stability control methods, reliant on reactive power compensation devices and conventional regulation techniques, struggle to adapt to the dynamic nature of contemporary grids

Grid operators face mounting pressure to maintain grid reliability while accommodating these dynamic changes effectively. In this context, the integration of Battery Energy Storage Systems (BESS) presents a compelling opportunity for innovation. BESS offers a dynamic and flexible solution to address voltage fluctuations in real-time, mitigating the impact of intermittent renewable generation and dynamic load changes on grid stability.

By harnessing BESS integration, next-generation voltage stability control systems can dynamically adjust to changing grid conditions, ensuring optimal performance and efficiency. The ability of BESS to rapidly respond to voltage deviations enhances grid resilience and reliability, minimizing the risk of disruptions and blackouts. Additionally, BESS integration enables the seamless integration of renewable energy sources into the grid, unlocking their full potential while maintaining grid stability.

III. OPERATION OF DVR

The schematic of a DVR-connected system is shown in Fig. 1(a). The voltage Vinj is inserted such that the load voltage V load is constant in magnitude and is undistorted, although the supply voltage Vs is not constant in magnitude or is distorted. Fig. 1(b) shows the phasor diagram of different voltage injection schemes of the DVR. VL (pre−sag) is a voltage across the critical load prior to the voltage sag condition. During the voltage sag, the voltage is reduced to Vs with a phase lag angle of θ. Now, the DVR injects a voltage such that the load voltage supply is connected. In recent years, advancements in battery technology and falling costs have made BESS integration increasingly viable and attractive for utilities and grid operators. Lithium-ion batteries, in particular, have emerged as the dominant technology for BESS integration, thanks to their high energy density, rapid response times, and long cycle life. As a result, the deployment of BESS integration projects has been accelerating globally, with utilities and governments investing in large-scale installations to enhance grid resilience and support the transition to a cleaner, more sustainable energy future.

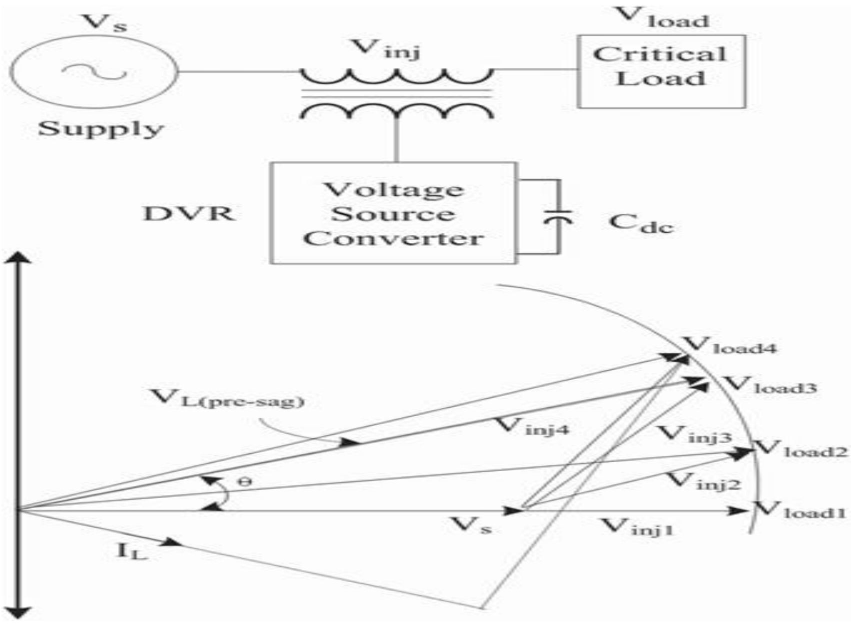
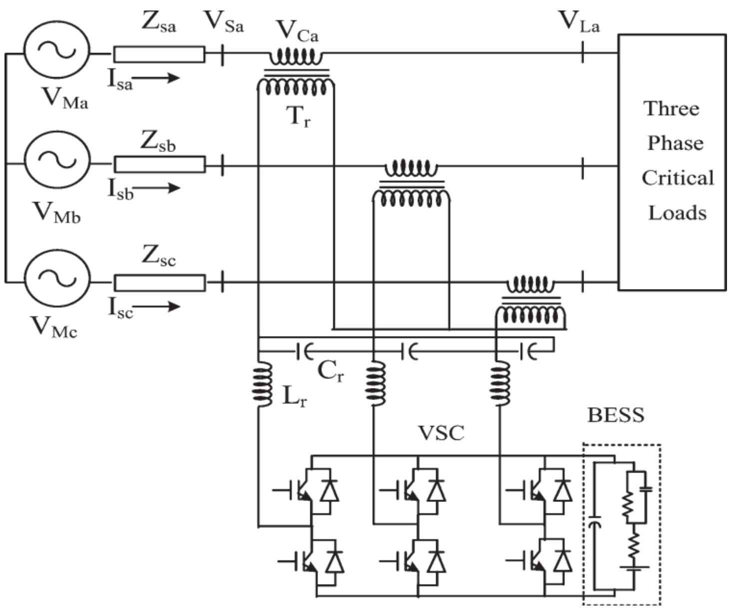


Fig. 1. (a) Basic circuit of DVR. (b) Phasor diagram of the DVR voltage injection schemes

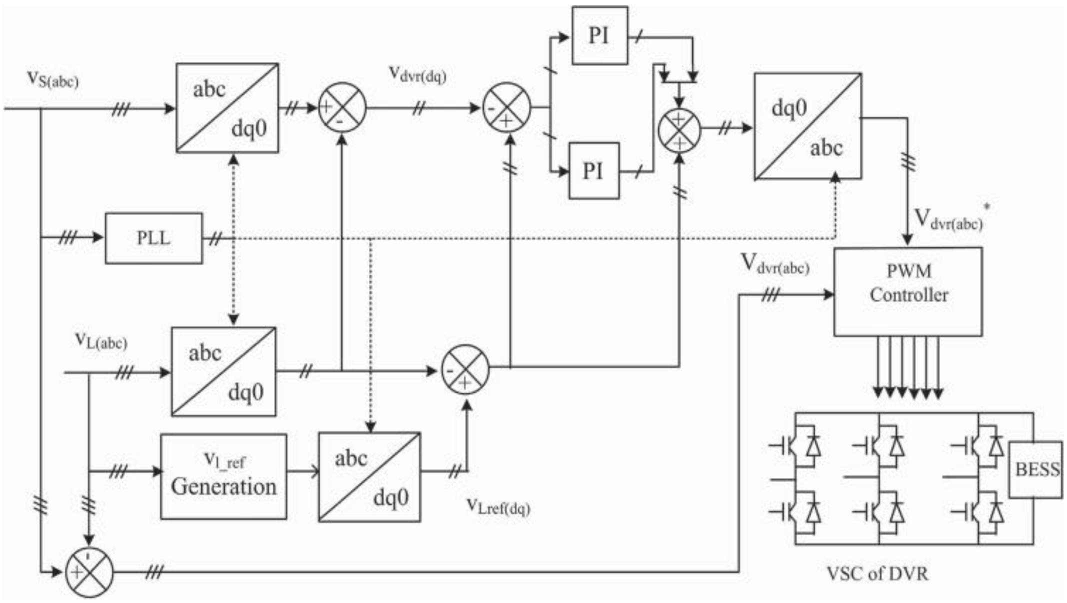
Vinj1 represents the voltage- injected in-phase with the supply voltage. With the injection of Vinj2, the load voltage magnitude remains same but it leads Vs by a small angle. In Vinj3, the load voltage retains the same phase as that of the pre-sag condition, which may be an optimum angle considering the energy source [10]. Vinj4 is the condition where the injected voltage is in quadrature with the current, and this case is suitable for a capacitor-supported DVR as this injection involves no active power [17]. However, a minimum possible rating of the converter is achieved by Vinj1.The DVR is operated in this scheme with a battery energy storage system (BESS).The injection schemes of the DVR. VL(pre−sag) is a voltage across the critical load prior to the voltage sag condition. During the voltage sag, the voltage is reduced to Vs with a phase lag angle of θ. Now, the DVR injects a voltage such that the load voltage.

IV. CONTROL OF DVR

The below figure shows the DVR connected to restore the voltage of a three-phase critical load.



The compensation for voltage sags using a DVR can be performed by injecting or absorbing the reactive power or the real power . When the injected voltage is in quadrature with the current at the fundamental frequency, the compensation is made by injecting reactive power and the DVR is with a self-supported dc bus. However, if the injected voltage is in-phase with the current, DVR injects real power, and hence, a battery is required at the dc bus of the VSC. The control technique adopted should consider the limitations such as the voltage injection capability (converter and transformer rating) and optimization of the size of energy storage.Control of DVR With BESS for Voltage Sag, Swell, and Harmonics



Compensation

Fig. 3 shows a control block of the DVR in which the SRF theory is used for reference signal estimation.

The voltages at the PCC vS and at the load terminal vL are sensed for deriving the IGBTs' gate signals. The reference load voltage

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V ∗ is extracted using the derived unit vector [23]. Load volt- ages (VLa, VLb, VLc) are converted to the rotating reference frame using abc−dqo conversion using Park's transformation with unit vectors (sin, θ, cos, θ) derived using a phase-locked loop as future.

vLq cos θ cos ¡θ− 2π ¢ cos ¡θ+ 2π ¢‖vLaref]

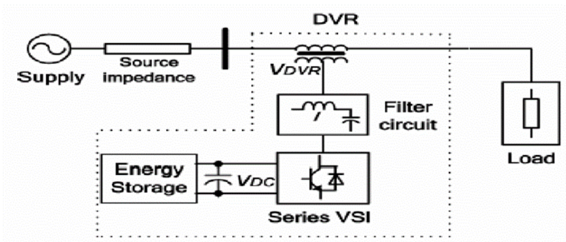
Similarly, reference load voltages (V ∗ ,V ∗ ,V ∗) and voltage PCCv.

BESS Integration : The primary objective of BESS integration is to enhance grid flexibility and resilience, enabling power systems to adapt to dynamic changes in supply and demand. By storing surplus energy when generation exceeds consumption and releasing stored energy during periods of high demand, BESS integration helps to balance the grid and minimize fluctuations in voltage and frequency. This contributes to improved grid stability and reliability, reducing the risk of blackouts and ensuring uninterrupted power supply to consumers.

One of the key advantages of BESS integration is its ability to support the integration of renewable energy sources, such as solar and wind power, into the grid. Renewables are inherently intermittent, generating electricity only when the sun is shining or the wind is blowing. BESS can smooth out the variability of renewable generation by storing excess energy when it is abundant and dispatching it when needed, thus enabling a more reliable and consistent supply of renewable energy.

Furthermore, BESS integration offers opportunities for optimizing grid operations and reducing overall system costs. By providing fast-response ancillary services such as frequency regulation and voltage support, BESS can improve grid efficiency and reduce the need for costly infrastructure upgrades. Additionally, BESS integration can help utilities to defer investments in peaking power plants and transmission lines, resulting in cost savings and improved resource utilization.

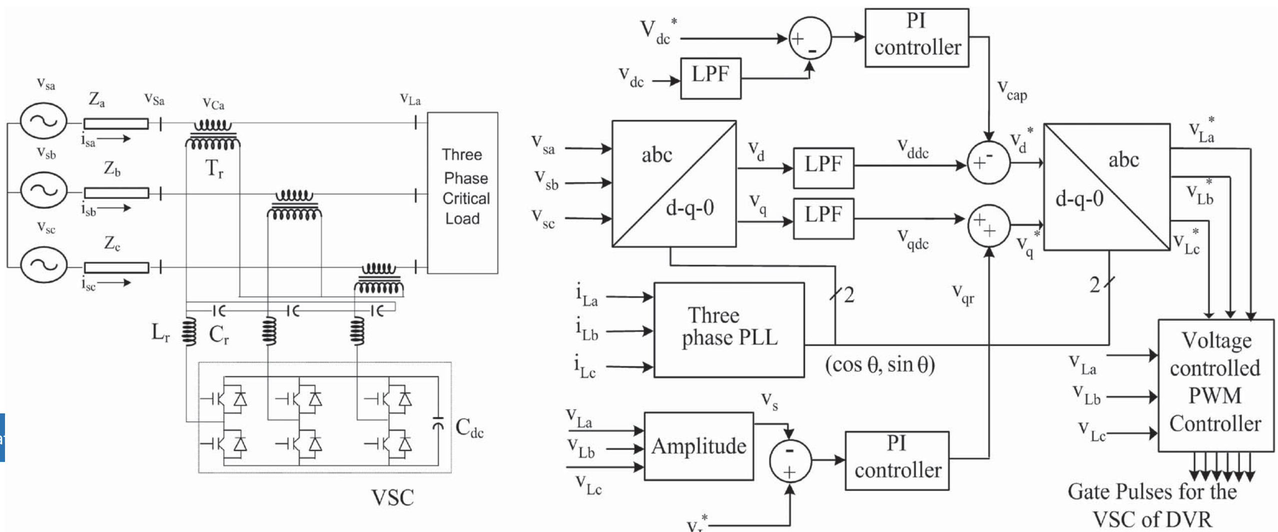
In recent years, advancements in battery technology and falling costs have made BESS integration increasingly viable and attractive for utilities and grid operators. Lithium-ion batteries, in particular, have emerged as the dominant technology for BESS integration, thanks to their high energy density, rapid response times, and long cycle life. As a result, the deployment of BESS integration projects has been accelerating globally, with utilities and governments investing in large-scale installations to enhance grid resilience and support the transition to a cleaner, more sustainable



energy future.

Fig : The basic function of the DVR is to inject a dynamically controlled voltage V DVR generated

V. OPERATIONAL PRINCIPLES OF BESS INTEGRATION



(a) (b)

Fig. 4. (a) Schematic of the self-supported DVR. (b) Control block of the DVR that uses the SRF method of control.

This operation encompasses various stages, from energy storage and management to grid interaction and control. Below is an overview of the key aspects of BESS operation:

1. Energy Storage: At the core of BESS operation is the storage of electrical energy. BESS units store energy during periods of low demand or high renewable energy generation, converting electrical energy into chemical energy for later use. This process involves charging the batteries by capturing surplus energy from the grid or renewable sources such as solar panels or wind turbines.
2. Energy Management: BESS integration requires sophisticated energy management systems (EMS) to optimize the utilization of stored energy. EMS algorithms determine when to charge or discharge the batteries based on factors such as grid demand, energy prices, and renewable energy availability. By analyzing real-time data and forecasting future energy trends, EMS ensures that BESS operates efficiently and effectively to meet grid requirements.
3. Grid Interaction: BESS units interact with the grid through various control mechanisms to provide grid support services and enhance stability. Grid interaction includes functions such as frequency regulation, voltage support, and peak shaving
4. Ancillary Services: BESS integration enables the provision of ancillary services to the grid, including frequency regulation, voltage control, and grid balancing. BESS units can respond rapidly to changes in grid conditions, providing fast-response ancillary services to support grid operation and reliability

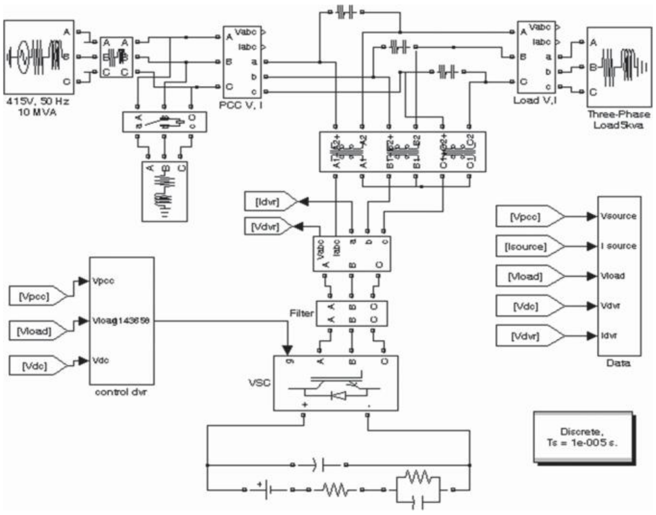


Fig. 5. MATLAB-based model of the BESS-supported DVR-connected system.

VI. L-PERFORMANCE OF THE DVR SYSTEM

The performance of the DVR is demonstrated for different supply voltage disturbances such as voltage sag and swell. Fig. 6 shows the transient performance of the system under voltage sag and voltage swell conditions. At 0.2 s, a sag in supply voltage is created for five cycles, and at 0.4 s, a swell in the supply voltages is created for five cycles. It is observed that the load voltage is regulated to constant amplitude under both sag and swell conditions. PCC voltages vS, load voltages vL, DVR voltages vC, amplitude of load voltage VL and PCC voltage Vs, source currents iS, reference load voltages vLref, and dc bus voltage vdc are also depicted in Fig. 6. The load and PCC voltages of phase A are shown in Fig. 7, which shows the in-phase injection of voltage by the DVR. The compensation of harmonics in the supply voltages is demonstrated in Fig. 8. At 0.2 s, the supply voltage is distorted and continued for five cycles. The load voltage is maintained sinusoidal by injecting proper compensation voltage by the DVR. The total harmonics distortions (THDs) of the voltage at the PCC, supply current and load voltage are shown in Figs. 9–11, respectively. It is observed that the load voltage THD is reduced to a level of 0.66% from PCC voltage of 6.34%.

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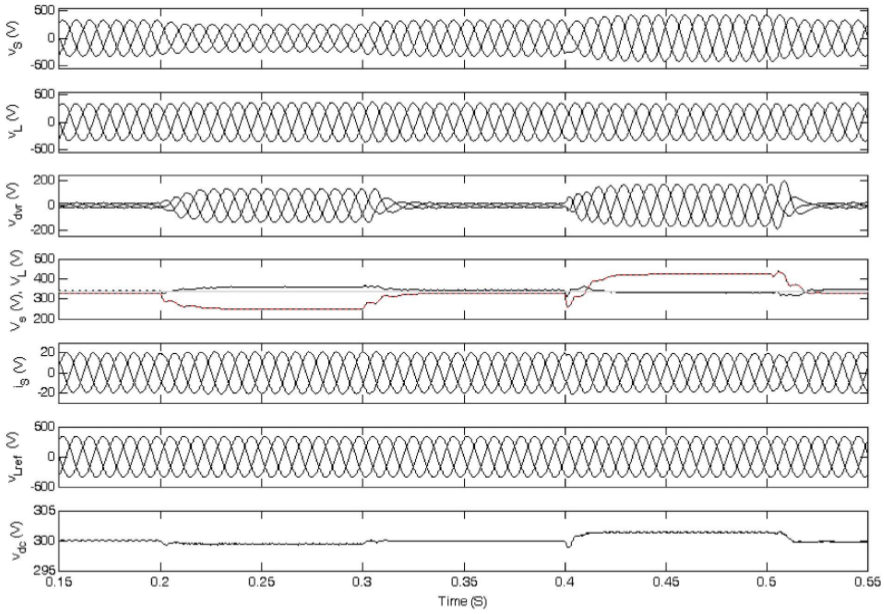

Fig. 8. PCC voltage and harmonic spectrum during the disturbance.

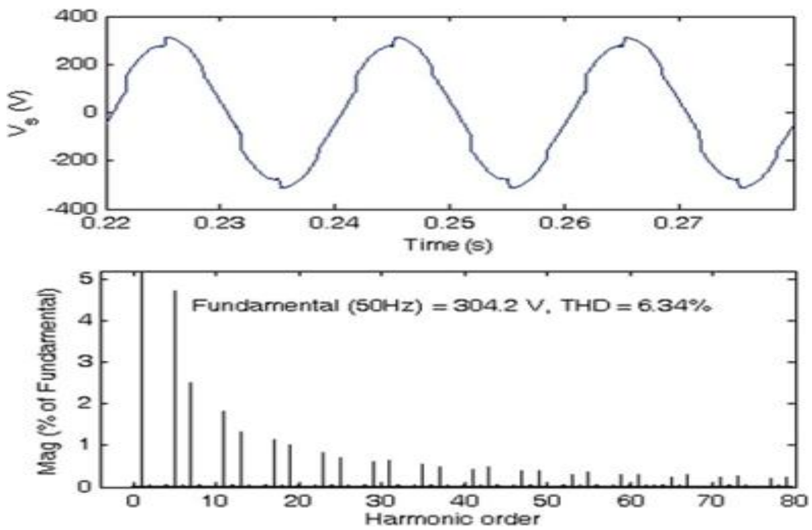

Fig. 9. Dynamic performance of DVR during harmonics in supply voltage applied to critical load.

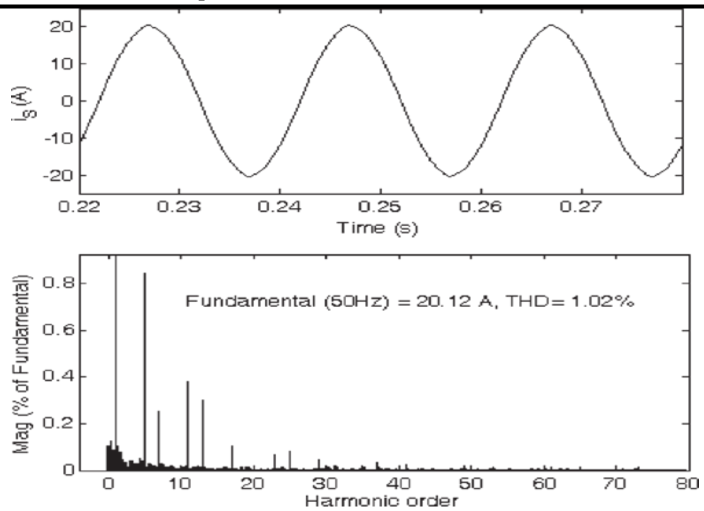

Fig. 10. Supply current and harmonic spectrum during the disturbance.

The L-performance of a Dynamic Voltage Restorer (DVR) system refers to its ability to effectively mitigate voltage sags and maintain power quality within acceptable limits. The performance of a DVR system is typically evaluated based on several key metrics, including its response time, compensation capability, and overall effectiveness in restoring voltage to the desired level during disturbances.

1. Response Time: The response time of a DVR system is crucial for ensuring timely voltage restoration during transient disturbances such as voltage sags. A high-performance DVR should have a fast response time, typically in the order of milliseconds, to quickly detect voltage deviations and inject compensating voltage to stabilize the grid.

2. Compensation Capability: The compensation capability of a DVR system refers to its ability to provide sufficient voltage support to mitigate voltage sags and maintain power quality. This includes the magnitude and duration of the voltage sag that the DVR can effectively compensate for, as well as its ability to handle multiple and simultaneous disturbances.

3. Voltage Regulation: The primary function of a DVR system is to regulate voltage and maintain it within acceptable limits during disturbances. The L-performance of the DVR system is determined by its ability to restore voltage to the desired level with minimal deviation and ensure stable operation of sensitive loads connected to the grid.

4. Reliability and Availability: The reliability and availability of a DVR system are essential factors in assessing its performance. A high-performance DVR should be robust and reliable, capable of operating continuously with minimal downtime or maintenance requirements to ensure uninterrupted voltage support to critical loads.

5. Efficiency and Energy Consumption: The efficiency of a DVR system, measured by its energy consumption and losses, also impacts its L-performance. A well-designed DVR should minimize energy losses and consumption while providing effective voltage support, ensuring optimal utilization of resources and cost-effectiveness.

6. Control and Monitoring: The control and monitoring capabilities of a DVR system play a crucial role in its performance. Advanced control algorithms and real-time monitoring systems enable precise voltage regulation and adaptive response to changing grid conditions, enhancing the overall effectiveness of the DVR in maintaining power quality

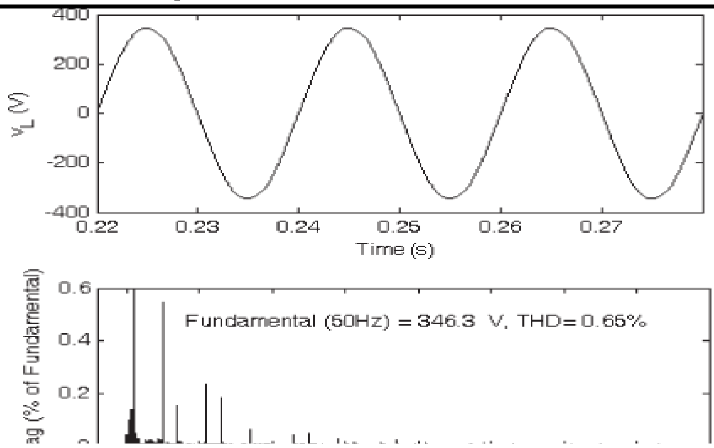

Fig. 11. Load voltage and harmonic spectrum during the disturbance.

VII. COMPARISON OF DVR RATING FOR SAG MITIGATION

Capacity: The capacity of a DVR determines its ability to mitigate voltage sags and support critical loads during disturbances. Higher-rated DVRs can provide more significant voltage support and accommodate larger loads.

Cost: The cost of a DVR is influenced by its rating, with higher-rated DVRs generally being more expensive due to the larger capacity and additional features.

Installation Requirements: The installation requirements, including physical footprint, cooling requirements, and infrastructure upgrades, vary depending on the rating of the DVR.

Performance: The performance characteristics, such as response time, efficiency, and reliability, also with vary DVR rating and can impact its effectiveness in mitigating voltage sags.

	Scheme-1	Scheme-2	Scheme-3	Scheme-4
Phase Voltage (V)	90	100	121	135
Phase Current (A)	13	13	13	13
VA per phase	1170	1300	1573	1755
KVA (% of Load)	37.5%	41.67%	50.42%	56.25%

Table: DVR RATING FOR SAG MITIGATION

- LV-DVRs are designed for applications where voltage sags occur frequently and are of relatively low magnitude.
- LV-DVRs are suitable for protecting sensitive loads in residential, commercial, and small industrial settings where voltage sags are common but not severe.
- Medium Voltage DVR (MV-DVR):
- MV-DVRs are designed for applications where voltage sags are less frequent but can be of moderate to high magnitude.
- These DVRs have higher ratings compared to LV-DVRs, typically ranging from tens of kVA to hundreds of kVA.
- HV-DVRs are designed for applications where voltage sags are infrequent but can be severe and have a widespread impact on the grid.

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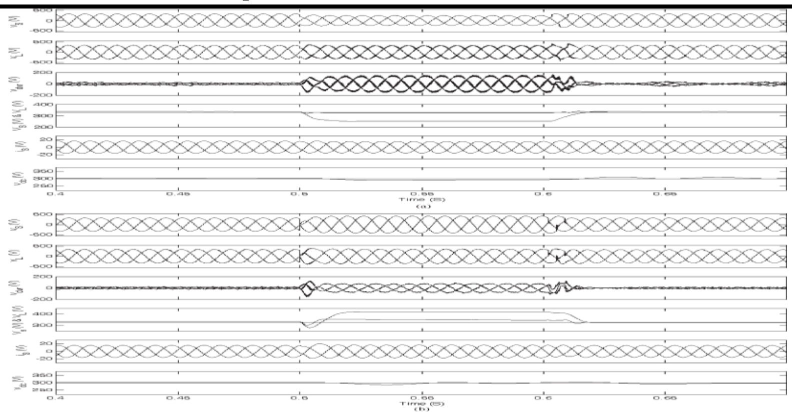

Fig. 12. Dynamic performance of the capacitor-supported DVR during (a) voltage sag and (b) voltage swell applied to critical load.

Capacitor-supported DVRs enhance the performance of traditional DVR systems by integrating energy storage capacitors, allowing for faster response times and improved voltage support capabilities.

Advantages of DVR:

1. Enhanced Response Time: The integration of energy storage capacitors enables capacitor-supported DVRs to achieve significantly faster response times compared to conventional DVR systems. This rapid response is critical for quickly injecting compensating voltage into the grid during transient voltage sags, thereby minimizing the impact on sensitive loads and ensuring uninterrupted operation.
2. Increased Compensation Capability: Capacitor-supported DVRs possess enhanced compensation capabilities due to the additional energy stored in the capacitors. This increased energy reservoir allows the DVR to provide higher levels of voltage support for longer durations, effectively mitigating deeper and more prolonged voltage sags in the grid.
3. Improved Voltage Regulation: The dynamic performance of capacitor-supported DVRs is characterized by improved voltage regulation capabilities. By rapidly injecting or absorbing reactive power from the energy storage capacitors, these DVRs can stabilize grid voltage and maintain it within acceptable limits, even under fluctuating load conditions or varying grid disturbances.

VI. CONCLUSION

The operation of a DVR has been demonstrated with a new control technique using various voltage injection schemes. A comparison of the performance of the DVR with different schemes has been performed with a reduced-rating VSC, including a capacitor-supported DVR. The reference load voltage has been estimated using the method of unit vectors, and the control of DVR has been achieved, which minimizes the error of voltage injection. The SRF theory has been used for estimating the reference DVR voltages. It is concluded that the voltage injection in-phase with the PCC voltage results in minimum rating of DVR but at the cost of an energy source at its dc bus.

Future outlook and potential advancements in DVR technology :

BESS integration facilitates the seamless integration of renewable energy sources into the grid, maximizing their utilization while maintaining grid stability. The operational flexibility and scalability of BESS integration make it well-suited for various grid environments and renewable energy integration scenarios

- Advanced Control Algorithms: Future BESS-equipped DVR systems may leverage advanced control algorithms, including predictive control and real-time optimization techniques. These algorithms can help anticipate voltage fluctuations and proactively adjust energy storage parameters to maintain grid stability.
- Integration with Renewable Energy Sources: As the penetration of renewable energy sources increases, BESS-equipped DVR systems can play a crucial role in integrating intermittent renewable generation into the grid. Future expansions may involve closer integration between BESS, renewable energy sources (such as solar and wind), and grid infrastructure to provide seamless voltage support.
- Scalability and Modularity: Future BESS-equipped DVR systems may emphasize scalability and modularity to accommodate varying grid requirements and evolving energy storage needs. This could involve the deployment of modular BESS units that can be easily expanded or reconfigured based on demand.

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