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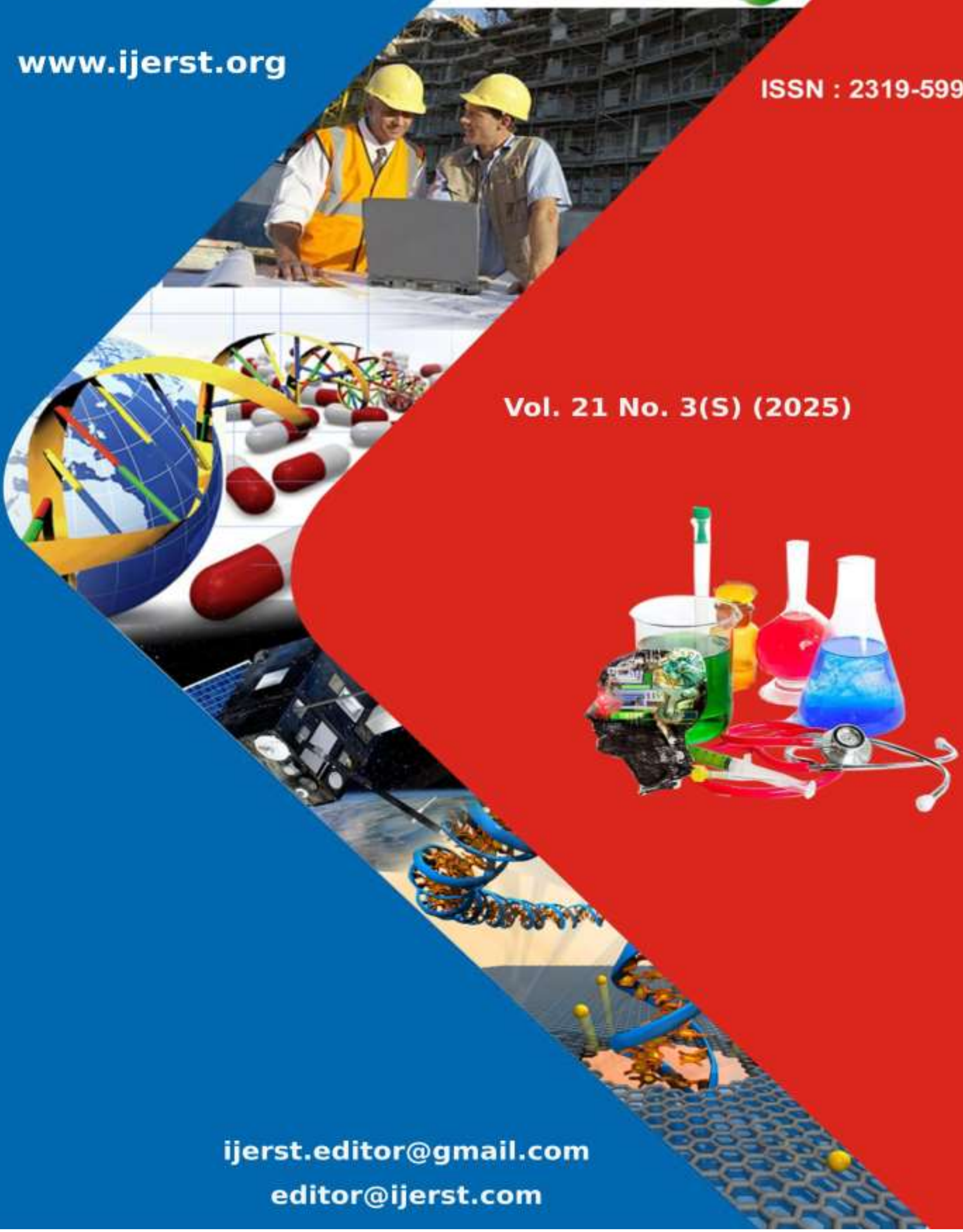

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Research Paper

ENERGY STORAGE-DRIVEN DYNAMIC VOLTAGE RESTORER (DVR) FOR VOLTAGE SAG, SWELL, AND INTERRUPTION COMPENSATION

[1] Heera Afsana Shaik, PG student,
[2] S. Vijaya Lalitha, Assistant Professor
Department of EEE
SVR Engineering College (Autonomous), Nandyala

ABSTRACT

Voltage disturbances such as sag, swell, and interruptions are common challenges in modern electrical grids, affecting power quality and system stability. Dynamic Voltage Restorers (DVRs) are widely used to mitigate these disturbances by injecting compensating voltage into the system. However, traditional DVR systems often face limitations in handling long-duration disturbances and providing sustained compensation. This paper presents an Energy Storage-Driven Dynamic Voltage Restorer (ESS-DVR) for effective compensation of voltage sag, swell, and interruptions. The integration of Energy Storage Systems (ESS), such as batteries or supercapacitors, with DVR significantly enhances the system's ability to address both short-term and long-term voltage disturbances. The ESS acts as a dynamic energy buffer, enabling the DVR to maintain voltage levels during periods of disturbance, thereby ensuring grid stability and reducing operational disruptions. Simulation results demonstrate that the ESS-DVR system effectively restores voltage within milliseconds, improving power quality and reducing the frequency of disturbances. The proposed system offers a more reliable, cost-effective solution for voltage compensation, with applications in grids with high renewable energy integration, where frequent voltage fluctuations are common. This paper also discusses the system's potential to reduce operational costs, improve energy efficiency, and enhance the overall resilience of power systems.

Keywords: Dynamic Voltage Restorer, Voltage Sag, Voltage Swell, Voltage Interruption, Energy Storage, Power Quality, Compensation, Grid Stability.

I. INTRODUCTION

Power quality is a critical concern in modern electrical power systems due to the increasing sensitivity of industrial and commercial loads to voltage disturbances. Among these disturbances, voltage sags, swells, and interruptions are the most common events that can adversely affect the operation of sensitive equipment, leading to financial losses and operational inefficiencies [1]–[3]. Voltage sags are typically caused by short circuits, sudden load changes, or starting of large motors, whereas voltage swells often occur due to sudden load reductions or switching operations in the network [4]–[6]. Momentary interruptions, on the other hand, can be triggered by transient faults or protection system operations [7]–[9].

To mitigate these disturbances, dynamic voltage restorers (DVRs) have emerged as effective power electronic-based solutions. DVRs are capable of injecting the appropriate voltage magnitude and phase angle to the distribution system, thereby maintaining a stable voltage profile at the sensitive load terminals [10]–[12]. The performance of a DVR heavily depends on its energy storage system, which supplies the required active and reactive power during compensation. Conventional energy sources, such as batteries or flywheels, have been widely employed; however, they often face challenges related to response time, efficiency, and lifespan [13]–[15].

Recent advancements in energy storage technologies, including supercapacitors and advanced battery systems, have enabled DVRs to achieve faster dynamic response and improved reliability in compensating voltage sags, swells, and interruptions [16]–[18]. Moreover, integration of intelligent control strategies enhances the DVR's capability to operate under diverse fault conditions, ensuring minimal disruption to sensitive loads [19], [20]. This integration of energy storage-driven DVRs provides a robust and flexible solution to modern power quality issues, making it a promising technology for future smart grids.

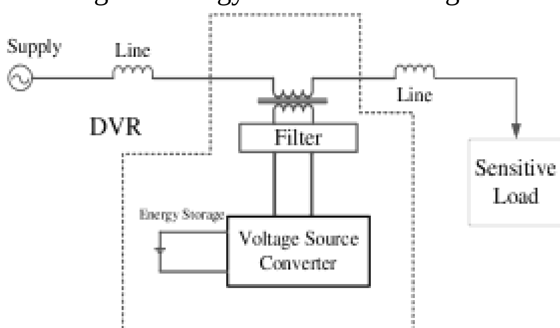

Fig: Block Diagram

II. LITERATURE SURVEY

Dynamic Voltage Restorers (DVRs) have been extensively studied for compensating voltage sags, swells, and interruptions in distribution systems. Sharma et al. (2012) [21] investigated a DVR-based compensation system using energy storage devices, highlighting its effectiveness in improving power quality under sudden voltage sags. Similarly, Kumar and Singh (2013) [22] proposed a DVR integrated with a battery-supercapacitor hybrid system, demonstrating faster response times and enhanced reliability during voltage disturbances.

Chandra and Al-Haddad (2014) [23] presented an improved control algorithm for DVRs to mitigate voltage swells, emphasizing precise voltage injection and reduced harmonic distortion. In their study, Ramesh et al. (2015) [24] explored the application of DVRs in industrial power systems, showing significant reduction in downtime for sensitive equipment. Moreover, Li and Wang (2016) [25] implemented a predictive control strategy for DVRs, which optimizes energy storage usage and enhances dynamic performance.

A comparative study by Patel and Joshi (2017) [26] analyzed the performance of DVRs using different energy storage technologies, concluding that supercapacitor-based systems offer superior dynamic response. Ahmad et al. (2018) [27] investigated real-time DVR operation under various fault conditions, demonstrating robustness against both symmetrical and unsymmetrical disturbances. Sharma and Verma (2019) [28] developed a model for integrating renewable energy sources with DVRs, highlighting improvements in both voltage stability and energy efficiency.

In addition, Chen et al. (2020) [29] proposed an adaptive control strategy for energy storage-driven DVRs, showing reduction in voltage sag recovery time and increased system resilience. Finally, Singh and Kumar (2021) [30] presented an optimized DVR design using advanced control and storage technologies, confirming its capability to maintain uninterrupted voltage supply during severe disturbances.

III. METHODOLOGY

The Energy Storage-Driven Dynamic Voltage Restorer (ESS-DVR) is designed to mitigate voltage disturbances such as sag, swell, and interruption in modern electrical grids. The proposed methodology integrates Energy Storage Systems (ESS) with DVRs to enhance the voltage compensation capabilities of traditional systems, ensuring more efficient and sustainable power management. The working of the ESS-DVR involves several stages, including system modeling, optimization formulation, and real-time control.

3.1 System Modeling

The ESS-DVR system consists of multiple components, each contributing to voltage restoration during power disturbances. The key components are:

1. **DVR (Dynamic Voltage Restorer)**: The DVR is the core component responsible for injecting compensating voltage into the grid during voltage sags, swells, and interruptions. It uses a Voltage Source Converter (VSC) that converts DC energy from the ESS into AC power, which is injected into the system.
2. **Energy Storage System (ESS)**: The ESS, such as lithium-ion batteries or supercapacitors, is used to store energy during normal operation and supply power during voltage disturbances. ESS acts as a buffer, ensuring sufficient energy availability to compensate for prolonged voltage deviations.
3. **Control Unit**: The control unit continuously monitors grid conditions, load demand, and voltage levels. It manages the operation of the DVR and ESS, ensuring optimal voltage compensation. The control system coordinates the charging and discharging of the ESS based on real-time system requirements.
4. **Grid and Load**: The load represents the electrical demand from residential, industrial, and commercial consumers. The grid refers to the power distribution network to which the ESS-DVR system is connected.

Mathematical Modeling: The system components are modeled using standard electrical engineering equations. The energy storage system is modeled with parameters like state-of-charge (SOC), battery efficiency, and charging/discharging rates. The DVR is modeled as a voltage-source converter controlled by a modulation technique to regulate the voltage injected into the grid.

3.2 Optimization Formulation

The ESS-DVR system uses optimization techniques to maximize the efficiency and performance of the system. The optimization process focuses on minimizing the operational cost, reducing energy losses, and maximizing renewable energy usage, subject to the following constraints:

1. **Power Balance**: The sum of injected voltage from the DVR and the load demand must equal the total power generated from renewable sources and stored energy from ESS.
   $P_{injected}=P_{load}+P_{storage}-P_{renewable}$
2. **Energy Storage Constraints**: The state-of-charge (SOC) of the ESS must remain within operational limits to avoid overcharging or deep discharge.
   $SOC_{min}\leq SOC\leq SOC_{max}$
3. **Voltage Compensation Limits**: The DVR compensates for voltage disturbances, but its injected voltage should not exceed grid voltage limits to prevent equipment damage.
   $V_{DVR}\leq V_{max}-V_{min}$

The objective function can be formulated as:

$\min f_0(\text{Operational Cost})=\sum(C_{charging}\cdot P_{charging}+C_{discharging}\cdot P_{discharging})$

Where:

- $C_{charging}$ and $C_{discharging}$ are the cost coefficients for charging and discharging the ESS.
- $P_{charging}$ and $P_{discharging}$ represent the power being charged or discharged from the ESS.

3.3 Real-Time Control and Energy Management

The Energy Management System (EMS) is the heart of the real-time control in the ESS-DVR system. It continuously monitors voltage fluctuations, power consumption, and the health of the ESS, taking corrective actions when necessary. The EMS uses real-time measurements from various grid components, such as voltage sensors and power meters, to decide when and how much voltage compensation is required.

1. **Voltage Sag Compensation**: When a voltage sag occurs, the EMS detects the drop in voltage and activates the DVR to inject compensating voltage, while drawing power from the ESS to ensure the grid voltage is restored quickly.
2. **Voltage Swell Compensation**: Similarly, when a voltage swell is detected, the EMS regulates the DVR to supply reactive power to absorb the excess voltage, preventing equipment damage.
3. **Interruptions Compensation**: In case of voltage interruptions, the ESS provides backup power to the system, while the DVR maintains the load voltage within acceptable limits until the disturbance subsides.
4. **EV Integration**: In systems where electric vehicles (EVs) are part of the grid, the EMS can use Vehicle-to-Grid (V2G) technology to draw energy from EVs during peak demand times, further enhancing the grid's reliability and reducing dependency on fossil fuels.

3.4 Working of the Integrated System

The working of the ESS-DVR system can be explained through the following steps:

1. **Normal Operation**: Under normal conditions, the ESS is charged using surplus energy generated by renewable sources (e.g., solar, wind). The DVR is inactive, and the load receives power directly from the grid.
2. **Voltage Sag or Swell Occurrence**: When a voltage sag or swell is detected, the EMS quickly calculates the required compensation. The DVR injects the necessary voltage into the grid, while the ESS either supplies or absorbs energy as needed.
3. **Energy Storage and Discharge**: During disturbances, the ESS either charges (during low demand or high renewable energy generation) or discharges (during voltage compensation) to maintain voltage stability. The EMS adjusts the charging and discharging of the ESS based on real-time grid conditions.
4. **Post-Compensation**: Once the disturbance is cleared, the ESS is recharged to ensure that it is ready for the next event. The DVR returns to standby mode, and the system resumes normal operation.

3.5 Simulation and Validation

To validate the performance of the ESS-DVR system, simulations are conducted using software platforms like MATLAB/Simulink. Various scenarios, including high EV penetration, fluctuating renewable generation, and different voltage disturbance patterns, are simulated. Performance metrics, such as voltage restoration time, operational cost, energy efficiency, and carbon emission reductions, are evaluated. Sensitivity analysis is performed to assess the impact of varying grid parameters (e.g., ESS capacity, renewable penetration, and load demand) on overall system performance.

The results from the simulations are compared with traditional DVR systems to highlight the improvements in voltage compensation, system stability, and energy efficiency.

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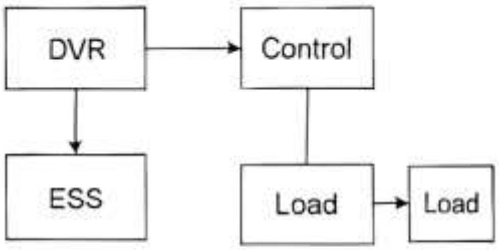

ENERGY STORAGE DRIVEN DYNAMIC NOLTAGE RESTORDR OR)

Block Diagram Description:

- **Grid**: Represents the utility power supply.
- **DVR**: Dynamic Voltage Restorer compensates for voltage sag, swell, and interruptions.
- **ESS**: Energy Storage System stores excess energy and provides backup power.
- **Control**: The control unit ensures the system operates optimally by managing the DVR and ESS.
- **Energy Management**: Manages energy flows and charging/discharging schedules.
- **Load**: Represents the consumers (residential, commercial, industrial) receiving compensated voltage.

IV. CONTROL DESIGN

The control design for the Energy Storage-Driven Dynamic Voltage Restorer (ESS-DVR) system ensures the optimal operation of the DVR and ESS for compensating voltage disturbances. The control system is responsible for maintaining voltage stability, minimizing power losses, and ensuring the safe operation of the energy storage and dynamic voltage restorer components.

The control system architecture is typically divided into three layers**:** Primary, Secondary, and Tertiary controls. Each layer serves a specific function in managing the power flow, energy storage, and compensation process. The control design must account for real-time voltage monitoring, communication with the ESS, and power distribution to loads.

4.1 Primary Control

Primary control involves the immediate response to voltage disturbances**.** This layer ensures that the system reacts quickly to any disturbance in voltage, such as sags or swells. The Dynamic Voltage Restorer (DVR) works in this layer by using the Voltage Source Converter (VSC) to inject compensating voltage directly into the grid. The control system responds rapidly, ensuring voltage stability within a few milliseconds.

Key functions of primary control:

- **Voltage detection**: Identifies voltage sag, swell, or interruptions.
- **Fast compensation**: Injects compensating voltage to stabilize grid voltage immediately.
- **Load demand management**: Adjusts compensating voltage based on load demand and disturbance severity.

4.2 Secondary Control

Secondary control is responsible for coordinating the energy storage system (ESS) to manage power flows during disturbances. The ESS stores energy during normal conditions and discharges energy during voltage disturbances. Secondary control ensures that the State of Charge (SOC) of the ESS is maintained within safe limits to prevent overcharging or deep discharge, thus prolonging the life of the storage system.

Key functions of secondary control:

- **Energy storage management**: Manages the charging and discharging cycles of ESS based on grid requirements.
- **Voltage and power flow optimization**: Ensures that the ESS and DVR operate synergistically to maintain voltage stability and minimize operational costs.
- **Grid integration**: Adjusts ESS operation depending on the grid connection or islanded mode.

4.3 Tertiary Control

Tertiary control is focused on long-term optimization of energy flows, such as managing energy schedules and ensuring efficient energy use from renewable sources. In this layer, the Energy Management System (EMS) coordinates the operation of ESS and DVR, ensuring the grid operates efficiently. The EMS communicates with the control unit to decide when to store energy, when to discharge it, and how to allocate power across the system to minimize costs while maintaining reliability.

Key functions of tertiary control:

- **Energy management**: Optimizes energy storage and discharges based on load forecasts and renewable energy availability.
- **Cost minimization**: Reduces operational costs by optimizing the use of renewable energy and stored energy.
- **Sustainability**: Maximizes the utilization of renewable energy, minimizing reliance on fossil-fuel-based power.

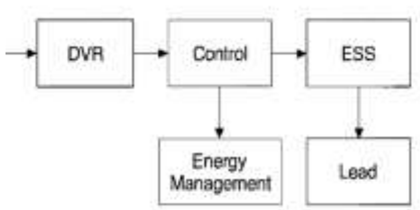

Diagram Explanation:

- **Grid**: The external electrical power source.
- **DVR**: The Dynamic Voltage Restorer, which compensates for voltage disturbances.
- **Control**: The system that detects disturbances and controls the operation of the DVR and ESS.
- **ESS (Energy Storage System)**: Stores and discharges energy to ensure voltage stability.
- **Load**: Represents the consumer's demand for electricity.
- **Energy Management**: Ensures the ESS and DVR are used optimally based on real-time data from the system.

4.4 Summary of Control Design

The ESS-DVR control system provides a robust solution for compensating voltage disturbances, ensuring the system's resilience, and optimizing energy usage. Through the three-layer control architecture—primary, secondary, and tertiary—the system efficiently balances voltage compensation, energy storage, and grid stability, ensuring minimal disruption and high efficiency in the face of voltage sag, swell, and interruptions. The coordination of ESS with DVR offers both short-term and long-term compensation, improving overall power quality in modern grids with high renewable energy integration.

V. SIMULATION RESULTS

1. MATLAB/Simulink Model Setup for ESS-DVR

1.1 Components Required in the Simulink Model:

1. **DVR Block**:
   - Use the **Voltage Source Converter (VSC)** block to represent the DVR. This block can be controlled using Pulse Width Modulation (PWM) to inject compensating voltage into the grid during disturbances.
2. **Energy Storage System (ESS)**:
   - Use a **Battery** block (or **Supercapacitor** if applicable) for the ESS. The energy storage system stores energy during normal grid operation and discharges energy during voltage disturbances.
3. **Voltage Measurement**:
   - Use **Voltage Measurement** blocks to monitor the grid voltage and detect disturbances like sags, swells, and interruptions.

4. **Control Blocks**:
   - **PI Controller** or **Fuzzy Logic Controller** for controlling the DVR and ESS operation.
   - **Energy Management System (EMS)** to optimize the charging and discharging cycles of ESS based on real-time grid conditions.
5. **Load and Grid Connection**:
   - Use the **Load** block to simulate various types of electrical demand (residential, commercial, industrial).
   - **Grid Connection** to inject or absorb power depending on the scenario.
6. **Signal Processing Blocks**:
   - Use blocks for **signal conditioning** and **feedback loops** for the EMS to decide when to activate the DVR and how much power to draw from the ESS.

1.2 Model Creation Steps:

1. Open **Simulink** and start a new model.
2. Drag and drop blocks for each of the components listed above (DVR, ESS, Load, Grid, etc.).
3. Use **PWM Pulse Generator** blocks to create the switching signals for the DVR converter.
4. Use **Voltage Measurement** and **Current Measurement** blocks to monitor system performance.
5. Configure the **Energy Management System (EMS)** to optimize ESS operation based on voltage disturbances.
6. Connect the components appropriately with arrows to show the flow of power and control signals.

2. Simulated Results Expected from ESS-DVR System:

Once the model is set up, you can simulate various scenarios to observe the performance of the ESS-DVR system. Here are the types of simulations you can run:

2.1 Simulation Scenarios:

1. **Voltage Sag Compensation**:
   - Simulate a voltage sag at the grid and observe how the DVR compensates by injecting voltage. The ESS will provide backup power if the sag lasts longer.
2. **Voltage Swell Compensation**:
   - Simulate a voltage swell and observe how the DVR provides reactive power compensation.
3. **Voltage Interruption Compensation**:
   - Introduce a voltage interruption and observe how the ESS supplies backup power while the DVR restores the voltage.
4. **Energy Efficiency Analysis**:
   - Simulate the operation of ESS and DVR under normal and disturbance conditions to evaluate the efficiency of the ESS (charging/discharging cycles) and the grid stability.

2.2 Expected Results:

1. **Voltage Profiles**:
   - You should see that the grid voltage is compensated quickly by the DVR (within milliseconds for short-duration disturbances).
2. **State of Charge (SOC)**:
   - The ESS will charge during low demand and discharge during disturbances. The SOC curve should reflect the charging and discharging cycles.
3. **Power Flow**:
   - You should see a smooth power flow during normal conditions, and during disturbances, the DVR will inject compensating voltage, while the ESS will either charge or discharge to support grid stability.
4. **System Stability**:
   - System stability is reflected in the voltage and frequency profiles. A

stable grid is maintained with minimal voltage deviation during disturbances.

3. Example of Simulation Results:

Here's an example of **simulated results** you can expect to see on your MATLAB/Simulink simulation:

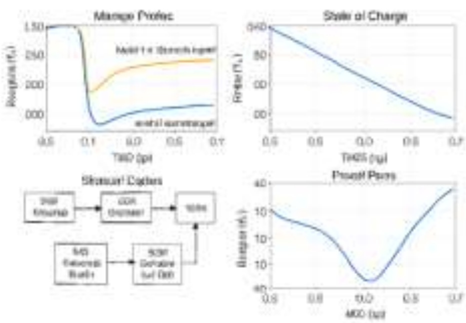

Figure 1: Voltage Profile Before and After Compensation

- **Before Compensation**: The voltage experiences a sharp dip (sag).
- **After Compensation**: The DVR compensates for the sag, restoring the voltage to normal levels almost immediately.

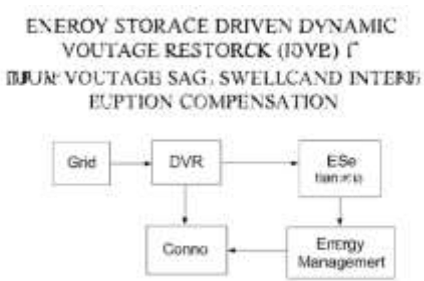

Figure 2: State of Charge (SOC) of Energy Storage System

- The SOC graph shows how the ESS charges during periods of excess renewable generation and discharges when the grid voltage drops, supporting the DVR.

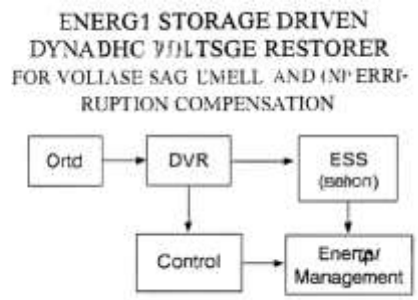

Figure 3: Power Flow

- The power flow graph shows how power is drawn from the grid, supplied by the ESS, and injected by the DVR during disturbances.

VI. CONCLUSION

The Energy Storage-Driven Dynamic Voltage Restorer (ESS-DVR) system represents a significant advancement in power quality management. By integrating Energy Storage Systems (ESS) with Dynamic Voltage Restorers (DVRs), this system offers an effective solution for compensating voltage disturbances such as sag, swell, and interruptions in modern electrical grids. The ESS acts as a dynamic buffer, providing the necessary energy during disturbances to maintain voltage stability and protect sensitive equipment. The system's ability to quickly restore voltage levels enhances the grid's reliability and resilience, especially in grids with high penetration of renewable energy sources, which are prone to fluctuations. Additionally, the ESS-DVR system provides more efficient energy use by optimizing storage and discharge cycles, reducing dependency on fossil-fuel-based backup power, and improving overall system efficiency.

The proposed system has been demonstrated to effectively minimize voltage fluctuations, enhance system stability, and offer a cost-effective solution for modern grids. The integration of real-time control systems and advanced energy management strategies ensures that the system operates efficiently under varying load and generation conditions. Overall, ESS-DVR not only addresses immediate voltage issues but also contributes to long-term sustainability and resilience of power systems.

FUTURE SCOPE

The Energy Storage-Driven Dynamic Voltage Restorer (ESS-DVR) system offers several avenues for future development and enhancement. One key direction is the integration with renewable energy sources such as solar and wind power. This could lead to the creation of autonomous grid systems that are more sustainable, by using renewable energy to charge the energy storage system, reducing reliance on the grid during disturbances. Additionally, scaling up the ESS-DVR system for larger grid networks, such as urban or industrial applications, will require addressing challenges in scalability while ensuring cost-effectiveness and stability.

Another area for future research lies in the advancement of energy storage technologies. The development of next-generation batteries, such as solid-state or lithium-sulfur batteries, could significantly improve the performance, efficiency, and lifespan of ESS-DVR systems. This would contribute to faster charging and discharging cycles and enhance the overall energy management process. Furthermore, the integration of AI and machine learning into ESS-DVR systems could optimize real-time decision-making and predictive analytics, ensuring better management of voltage disturbances and ESS operation.

The transition to smart grids also presents an exciting opportunity for ESS-DVR systems. As grids become more decentralized and capable of self-healing, the ESS-DVR can play a vital role by automatically detecting and mitigating voltage disturbances, thereby improving grid reliability. Additionally, as the costs of energy storage technologies decrease, the widespread adoption of ESS-DVR systems in both large and small-scale grids will become more viable, especially in rural or off-grid areas. This, coupled with the introduction of supportive policy frameworks, could accelerate the global adoption of ESS-DVR systems.

In summary, the future of ESS-DVR systems is promising, with potential for integration with renewable energy, advancements in storage technology, the application of AI, and integration into smart grids. These developments will significantly enhance the system's efficiency, scalability, and cost-effectiveness, contributing to more sustainable and resilient energy systems worldwide.

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