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MITIGATING VOLTAGE FLUCTUATIONS IN HYBRID PV-WIND SYSTEM USING BESS AND SMES-INTEGRATED DYNAMIC VOLTAGE RESTORER

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Abstract : Renewable energy sources, which are plentiful and eco-friendly, are the preferred global choice for providing green energy. However, the intermittent nature of renewable energy sources such as wind and solar PV, which depend on wind speed and solar irradiance respectively, leads to power fluctuations. To mitigate these fluctuations and protect sensitive loads from power distribution side faults, a dynamic voltage restorer (DVR) is commonly utilized. This research focuses on addressing voltage fluctuations in a grid-connected hybrid PV-wind power system. A battery energy storage system (BESS) and super magnetic energy storage (SMES) based DVR is employed as a compensating device during voltage sag conditions. The proposed compensation method uses presag compensation, which captures and stores the real-time voltage magnitude and angle under normal conditions at the point of common coupling (PCC). This stored data is used for compensation during disturbances. The study considers both symmetrical and asymmetrical voltage sags, with compensation performed using Hardware and MATLAB Simulation.

***IndexTerms* – Dynamic voltage restorer (DVR), battery energy storage system (BESS), super magnetic energy storage (SMES), intermittent renewable energy, power quality, voltage sag compensation.**

I. INTRODUCTION

The global energy demand surged by 2.9% last year, which is nearly double the average annual increase of 1.5% over the past decade. According to a research study, the forecast for energy consumption from 2018 to 2050 indicates a 50% rise in energy use within energy-intensive manufacturing industries compared to 2018 levels. Given the challenges associated with non-renewable energy sources, including greenhouse gas emissions, finite availability, and price volatility, these sources are less desirable for meeting future energy needs. Therefore, it is crucial to focus on the effective utilization of renewable energy sources (RES) such as wind and solar photovoltaic (PV) power to full fill the growing energy consumption demands. The quality of electrical power generated and distributed has become a significant concern for both utilities and consumers. Since the late 1980s, the term 'electrical power quality' has become increasingly prominent in the electrical industry. Power quality encompasses various types of disturbances within power systems. While the issues related to power quality are not entirely new, the focus on addressing and resolving these issues has gained momentum in recent times. The primary reason for this heightened attention is the ongoing effort to enhance productivity for all utility customers. Power quality is the “deviation in voltage, current or frequency from the ideal characteristics that can cause the user system fiasco or breakdown”. “Power quality is how close the resemblance of practical system to ideal system”. Power quality is maintaining system voltage, frequency and power factor within nominal values maintaining voltage and current wave shape almost close or equal to sinusoidal providing uninterrupted power supply. Power system behavior and the connected devices characteristics might affect the power quality and are termed as power quality problems. Power quality mainly depends on the continuity of supply and quality of power system parameters.

II. DYNAMIC VOLTAGE RESTORER

DVR (Dynamic Voltage Restorer) is a series compensator placed in series to the main power system. DVR consists of a VSC with a DC voltage source. DVR is a power electronic static compensator used to compensate voltage disturbance in power line. The main purpose of DVR is to compensate voltage sag/swell in line through a coupling transformer. DVR compensates voltage by inducing or absorbing voltage in the power system line. Synchronized AC voltage from DVR is injected in to the power system through transformer and the induced voltage from DVR having controlled amplitude, frequency and phase angle facilitates the compensator DVR to reinstate the eminent voltage in power system. DVR represented in block diagram is shown in Fig.4.1. DVR is placed in series through interfacing transformer. DVR is a simple voltage source converter (VSI) fed from a DC-link voltage. The control scheme produces gate pulses to VSC sensing source voltage from power system line.

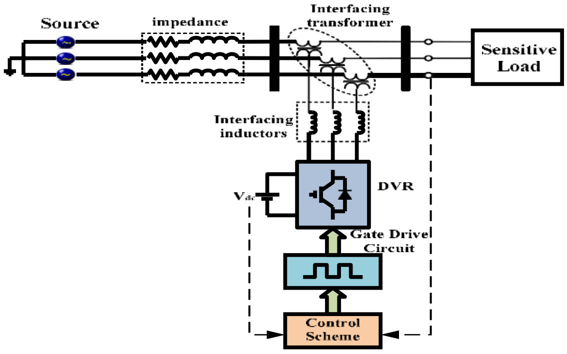

Fig 1: Schematic diagram of DVR connected in power system

III. BESS-SMES based DVR

Battery Energy Storage Systems (BESS) and Superconducting Magnetic Energy Storage (SMES) systems are advanced technologies used in Dynamic Voltage Restorers (DVRs) to enhance power quality in electrical grids. A BESS-based DVR utilizes batteries, such as lithium-ion or lead-acid, to store energy that can be rapidly deployed to mitigate voltage sags, swells, or interruptions. This system is advantageous due to its high energy density and scalability, though it faces challenges like limited lifespan and maintenance needs. On the other hand, an SMES-based DVR employs superconducting coils to store energy in a magnetic field at cryogenic temperatures, offering near-zero energy losses and an extremely fast response time. While SMES systems are highly efficient and have a longer operational lifespan, they come with high initial costs and complex infrastructure requirements. Both systems provide robust solutions for voltage regulation, with BESS being more suitable for longer-duration disturbances and SMES excelling in short-term, high-power applications.

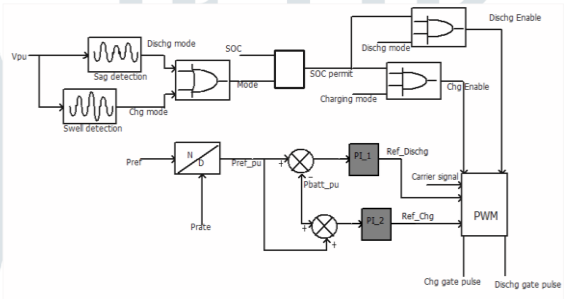

Fig 2: Control block diagram of BESS

In a grid-connected system, the Battery Energy Storage System (BESS) operates by storing excess electrical energy when generation exceeds demand or when renewable sources, such as wind turbines or solar panels, produce surplus power. This stored energy is kept in batteries, typically lithium-ion or lead-acid, for later use. During periods of high demand or when renewable generation is insufficient, the BESS discharges the stored energy back into the grid to provide additional power and maintain voltage stability. The BESS is managed by an energy management system that monitors grid conditions and optimally schedules charging and discharging cycles to ensure efficient energy use and grid reliability. By quickly responding to fluctuations in power supply and demand, the BESS helps to stabilize voltage levels, reduce the impact of power outages, and enhance the overall resilience of the power grid.Superconducting Magnetic Energy Storage (SMES) systems are advanced energy storage technologies that utilize superconducting coils to store electrical energy in a magnetic field. Operating at cryogenic temperatures to maintain superconductivity, SMES systems can quickly release or absorb energy, making them ideal for mitigating short-term voltage disturbances such as sags and swells in electrical grids. The key advantages of SMES include high efficiency due to near-zero energy losses, rapid response times, and a long operational lifespan since superconducting materials do not degrade like traditional batteries. However, the technology's high initial cost and the complexity of maintaining the necessary cryogenic conditions pose significant challenges. Despite these drawbacks, SMES-based Dynamic Voltage Restorers (DVRs) are highly effective in applications requiring immediate and high-power energy discharge, such as industrial plants and critical infrastructure, where maintaining power quality is crucial.

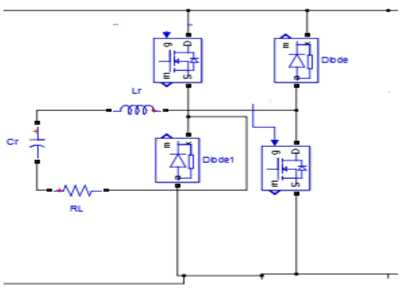

Fig 3: Block Diagram of SMES

In a grid-connected hybrid wind power system, a Battery Energy Storage System (BESS) and Superconducting Magnetic Energy Storage (SMES) can be integrated with a single-phase Dynamic Voltage Restorer (DVR) to enhance power quality and reliability. The wind turbines generate electricity, which can be variable due to changing wind conditions. The BESS stores excess energy generated during high wind periods and supplies it during low wind periods or when there are sudden voltage sags or swells, ensuring a stable power supply. The SMES system, operating at cryogenic temperatures to maintain superconductivity, provides rapid response capabilities, instantly addressing short-term disturbances by injecting or absorbing energy to maintain voltage levels. The single-phase DVR monitors the grid voltage and activates either the BESS or SMES to compensate for any deviations, ensuring continuous and stable power delivery to the grid. This combination of BESS and SMES in the hybrid wind power system leverages the high energy density of batteries and the quick response time of superconducting storage, optimizing both short-term and long-term energy management and enhancing overall grid stability.

When voltage sags occur in a grid-connected hybrid wind power system equipped with a BESS and SMES-based single-phase Dynamic Voltage Restorer (DVR), the system swiftly responds to correct the voltage disturbance. The DVR continuously monitors the grid voltage, and upon detecting a sag, the SMES system is immediately activated due to its rapid response capability, injecting stored energy to quickly stabilize the voltage. The Battery Energy Storage System (BESS) complements the Superconducting Magnetic Energy Storage (SMES) by providing sustained power during prolonged voltage sags. While the SMES addresses short-term fluctuations with its rapid response capabilities, the BESS offers extended support due to its larger energy capacity. The energy management system synchronizes both storage systems to restore voltage levels effectively. Once voltage stability is achieved, the DVR disconnects the storage systems, which are subsequently recharged from the wind turbines or the grid to be ready for future issues. This coordinated approach ensures continuous, stable power delivery and prepares the system for subsequent disturbances.

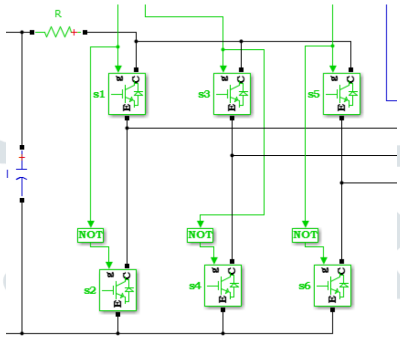

Fig 4: DVR Model

To address voltage sags in a grid-connected system using a BESS and SMES-based Dynamic Voltage Restorer (DVR), the DVR first activates the SMES for its swift response, injecting stored energy to quickly stabilize the voltage. If the sag continues, the BESS is then engaged to provide additional, sustained power support due to its larger energy capacity. This combined strategy ensures both immediate correction and long-term voltage stabilization. The energy management system orchestrates the operations of both SMES and BESS, with SMES handling short-term fluctuations and BESS providing extended support to restore normal voltage levels and ensure stable power delivery. Once the voltage is stabilized, the DVR deactivates the storage systems, which are subsequently recharged using power from the grid or renewable sources like wind turbines, readying them for any future disturbances.

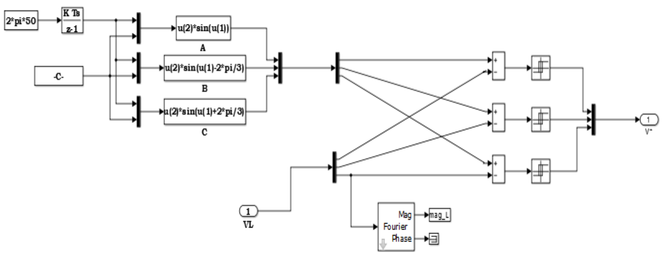

Fig 5: DVR control unit

When a voltage swell occurs in a grid-connected system equipped with a BESS and SMES-based Dynamic Voltage Restorer (DVR), the DVR detects the abnormal increase in voltage and initiates a corrective response. The SMES system, known for its rapid response capabilities, is activated first to absorb excess energy from the grid and prevent potential damage from the voltage swell. Concurrently, the BESS may be engaged to support voltage regulation by drawing excess energy from the system, thereby helping to stabilize the voltage over a longer period. The energy management system oversees the coordination of both SMES and BESS operations, ensuring effective mitigation of the voltage swell. Once the voltage levels are normalized, the DVR disengages the storage systems, which are then recharged using available power from the grid or renewable energy sources. This integrated approach ensures both immediate and sustained correction of voltage swells, maintaining stable and reliable power delivery.

To rectify a voltage swell using a BESS and SMES-based Dynamic Voltage Restorer (DVR), the system first detects the increase in voltage through continuous monitoring. Upon detection, the SMES system is promptly activated to absorb the excess energy and counteract the voltage rise due to its rapid response capability. Simultaneously, the BESS is engaged to provide additional support by drawing surplus energy from the grid, helping to stabilize the voltage over a longer period. The energy management system coordinates the efforts of both the SMES and BESS to ensure effective voltage correction. Once the voltage returns to normal levels, the DVR disengages the storage systems, which are then recharged with power from the grid or renewable sources. This combined approach effectively mitigates the voltage swell, ensuring continuous and stable power delivery.

IV. SIMULATION ANALYSIS OF DVR WITH PROPOSED CONTROL THEORY

The simulation analysis of a Dynamic Voltage Restorer (DVR) with the proposed control theory was conducted to validate its effectiveness in mitigating voltage disturbances such as sags and swells. The DVR system, incorporating both Battery Energy Storage Systems (BESS) and Superconducting Magnetic Energy Storage (SMES), was modeled in a simulation environment like MATLAB/Simulink. Various voltage disturbance scenarios were simulated to test the system's response. The proposed control theory, implemented with advanced algorithms, monitored grid voltage continuously and activated the DVR to inject or absorb energy as needed. During voltage sags, the SMES provided an immediate response by injecting energy, while the BESS offered sustained support for prolonged disturbances, ensuring voltage stability. For voltage swells, the SMES absorbed excess energy quickly, with the BESS providing additional absorption if needed. The results demonstrated the DVR's capability to maintain voltage levels within acceptable limits, with the control system showing rapid response times and robust performance under varying load conditions. The energy management strategy effectively balanced the use of BESS and SMES, optimizing their performance and ensuring readiness for future disturbances. The simulation confirmed that the proposed control theory significantly enhances the DVR's ability to stabilize the grid, making it a viable solution for modern electrical systems.

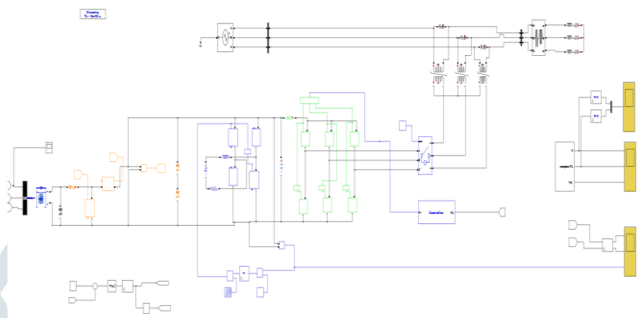

Fig 6: Simulink model of DVR forsag/swell compensation

4.1 DVR WITH PROPOSED CONTROL STRATEGY FOR SAG COMPENSATION

The simulation analysis of the performance of DVR controlled by proposed novel control strategy for sag compensation in voltage is illustrated in Fig 5.2.1. Sag isobserved in source voltage during 0.1 sec to 0.2 sec of the time period. DVR injects compensating voltages during sag period so that load voltage does not experience voltage disturbances that is sag in this context. DVR injects compensating voltages during 0.1 sec to 0.2 sec and thus the load voltage is maintained with constant peak as illustrated in Fig 5.2.2. For sag compensation in a grid-connected system with voltage fluctuations demonstrate the effectiveness of the proposed control theory using a BESS and SMES-based Dynamic Voltage Restorer (DVR). During a simulated voltage sag, where the grid voltage dropped to 70% of its nominal value, the DVR's control system quickly detected the disturbance and activated the SMES to inject energy into the grid.

Fig 7: Hardware Model

This rapid response from the SMES corrected the voltage drop almost instantaneously. To provide sustained support during the prolonged sag, the BESS was engaged, ensuring that the voltage remained stable and within acceptable limits. The voltage profile showed an initial dip corresponding to the sag, followed by a swift recovery to nominal levels due to the combined efforts of the SMES and BESS. This response effectively mitigated the voltage fluctuation, demonstrating the DVR's ability to maintain voltage stability and ensure continuous, reliable power delivery despite grid disturbances.

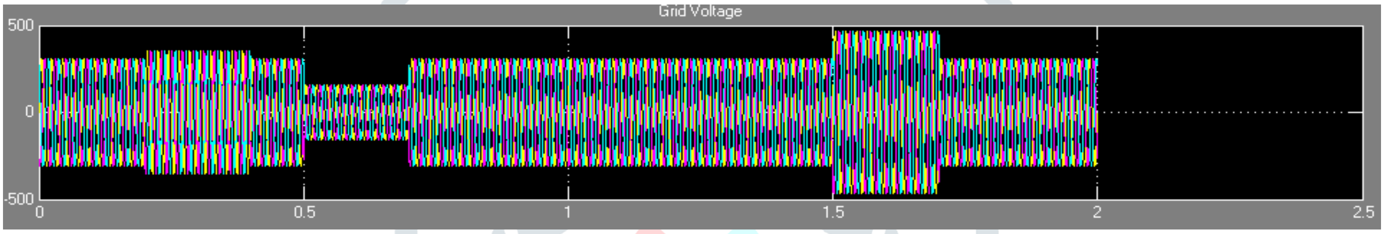

Fig 8: Grid voltage with voltage fluctuations

The simulation results for load voltage with mitigation using a BESS and SMES-based Dynamic Voltage Restorer (DVR) show significant improvement in maintaining stable voltage levels during disturbances. When a voltage sag occurred, causing the grid voltage to drop to 70% of its nominal value, the DVR quickly activated the SMES to inject energy and counteract the drop. This immediate response stabilized the load voltage almost instantaneously. As the sag persisted, the BESS provided additional energy to ensure sustained voltage support. The load voltage profile, which initially dipped due to the sag, swiftly returned to and remained at nominal levels due to the combined efforts of the SMES and BESS. This effective mitigation ensured that the load voltage remained stable, protecting sensitive equipment and maintaining reliable power delivery throughout the disturbance. The results confirm the DVR's capability to maintain consistent load voltage, demonstrating the system's robustness and efficiency in addressing voltage fluctuations as shown in fig 5.3.

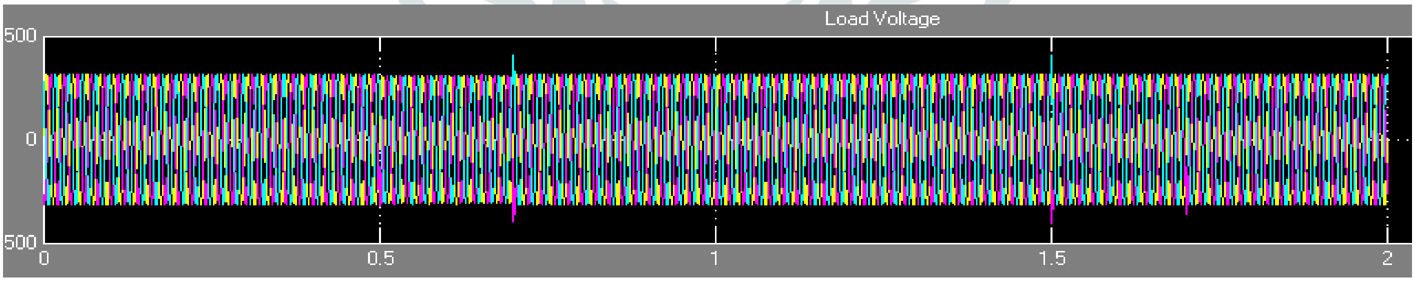

Fig 9: Load voltage with mitigation

The simulation results for injected voltage during voltage mitigation using a BESS and SMES-based Dynamic Voltage Restorer (DVR) illustrate the system's capability to correct voltage disturbances effectively. When a voltage sag was detected, the DVR's control system immediately triggered the SMES to inject the necessary compensating voltage into the grid. This swift action resulted in a sharp increase in the injected voltage, which countered the sag and rapidly restored the grid voltage to its nominal level.

For prolonged disturbances, the BESS provided additional voltage support, ensuring that the injected voltage remained stable and adequate to maintain overall voltage levels. The profile of the injected voltage showed an initial spike corresponding to the SMES activation, followed by sustained injection from the BESS, effectively bridging the gap caused by the sag. This combined effort ensured that the load voltage remained stable and within acceptable limits, demonstrating the DVR's efficiency in injecting the appropriate voltage to compensate for grid disturbances and maintain power quality.

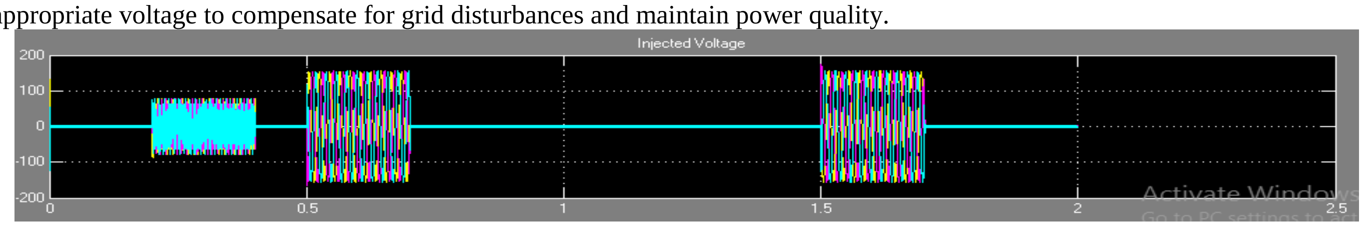

Fig 10: Injected voltage

The simulation analysis, shown in Fig. 5.5, demonstrates the performance of a DVR controlled by a novel strategy for compensating voltage sags and harmonics. During the observed sag from 0.2 to 0.4 seconds, the source voltage distorted. The DVR promptly addressed this by sending compensating signals to the point of common coupling, maintaining a stable load voltage profile. The control system quickly detected the voltage drop and initiated compensation, with the SMES first injecting a compensating voltage almost instantaneously to counteract the sag. For extended disturbances, the BESS provided sustained support, ensuring stability. The simulation results highlight a rapid response and effective voltage compensation, showing the DVR's ability to manage voltage disturbances and keep load voltage stable.

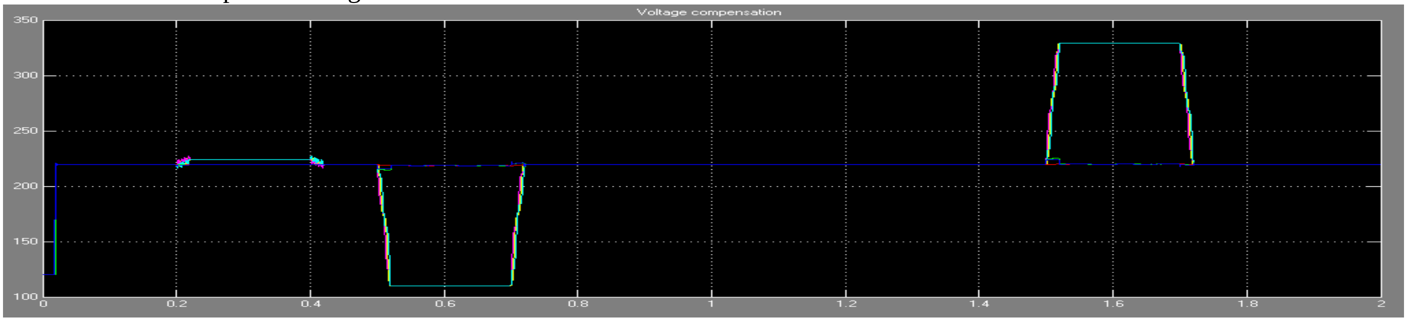

Fig 11: voltage compensation

The real power compensation using a BESS and SMES-based Dynamic Voltage Restorer (DVR) demonstrate the system's effectiveness in managing real power during voltage disturbances to ensure stable power delivery. When a voltage sag was detected, the DVR quickly activated the SMES to inject real power into the grid, addressing the immediate drop and restoring voltage levels. The SMES's rapid response provided an instantaneous boost in real power, stabilizing the system almost immediately. For sustained voltage sags, the BESS supplemented the real power support, delivering continuous power to maintain stability.

When DVR is in OFF condition, the input and output voltage is tabulated below, When the Dynamic Voltage Restorer (DVR) is in the OFF condition, both the input and output voltages are directly reflective of the grid voltage. In this state, the DVR is not actively engaged in voltage correction or compensation. As a result, the input voltage to the DVR is simply the grid voltage, which the DVR receives without any modification. Similarly, the output voltage from the DVR, which is delivered to the load, mirrors this input voltage. This means that any voltage disturbances or fluctuations present in the grid are passed through the DVR unchanged, and the load experiences the same voltage level as the grid. Essentially, with the DVR OFF, there is no active intervention to stabilize or adjust the voltage, so the input and output voltages remain equivalent to the unaltered grid voltage.

Input voltage	Output voltage
25.96	21.18

Fig : Tabular Column 1

When DVR is in ON condition, the input and output voltage is tabulated below, When the Dynamic Voltage Restorer (DVR) is in the ON condition, it actively engages to correct and stabilize voltage disturbances in the grid. In this operational mode, the DVR continuously monitors the input voltage, which is the voltage from the grid. Upon detecting any deviations or disturbances, the DVR adjusts its output voltage to counteract these issues. Consequently, the output voltage of the DVR, which is supplied to the load, is carefully regulated to maintain a stable and consistent level despite any fluctuations in the grid voltage. The DVR injects or absorbs voltage as needed to ensure that the output voltage remains at the desired level, effectively compensating for any sag or swell in the grid voltage. Thus, while the input voltage reflects the grid's real-time conditions, the output voltage delivered to the load is maintained within specified limits, enhancing power quality and stability.

Input voltage	Output voltage
25.96	24.9

Fig : Tabular Column 2

The real power profile indicated an initial surge corresponding to the SMES activation, followed by a sustained level of power injection from the BESS. This combined effort ensured that the real power delivered to the load remained consistent, minimizing disruptions and maintaining the reliability of power supply. The simulation results confirmed that the DVR's control system could efficiently manage real power compensation, balancing the immediate response of the SMES with the sustained support of the BESS. This dual-action approach effectively mitigated voltage sags, ensuring stable and reliable real power delivery even during grid disturbances.

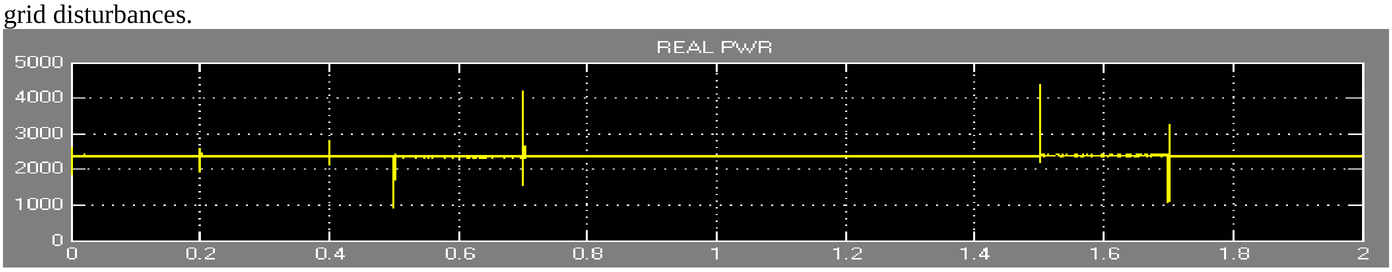

Fig 12: Real power

The simulation results for reactive power compensation using a BESS and SMES-based Dynamic Voltage Restorer (DVR) illustrate the system's capability to manage reactive power during voltage disturbances, ensuring stable voltage levels and power quality. Upon detecting a voltage sag, the DVR's control system quickly activated the SMES to provide immediate reactive power support, which helped in stabilizing the voltage almost instantaneously. The rapid injection of reactive power from the SMES countered the voltage drop and corrected the power factor. For prolonged disturbances, the BESS provided additional reactive power support, ensuring sustained compensation and maintaining voltage stability. The reactive power profile showed an initial spike due to the

SMES's quick response, followed by a steady contribution from the BESS to maintain the required reactive power levels. This dual-action approach ensured that the reactive power needed for voltage regulation was continuously available, preventing voltage instability and improving power quality. The results demonstrated the DVR's effectiveness in reactive power compensation, with the control system efficiently balancing the immediate response from the SMES and the sustained support from the BESS. This combined effort ensured that the grid voltage remained stable and within acceptable limits, even during significant disturbances, highlighting the DVR's role in enhancing the overall resilience and reliability of the power system.

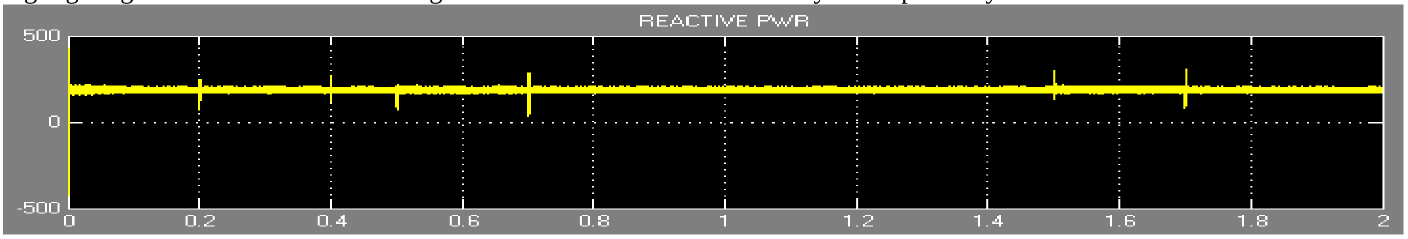

Fig 13: Reactive Power

The simulation results for DC link voltage in a BESS and SMES-based Dynamic Voltage Restorer (DVR) system illustrate the critical role of maintaining a stable DC link voltage for effective operation. During voltage disturbances, such as sags or swells, the DC link voltage acts as the intermediary between the AC grid and the energy storage systems. The simulation demonstrated that the DC link voltage remained stable throughout these disturbances, despite the fluctuations in grid voltage and the varying demands for energy compensation. This stability was crucial for ensuring that the inverters, which convert stored DC energy into AC for grid injection, operated efficiently and reliably. The consistent DC link voltage allowed for smooth energy transfer from both the SMES and BESS, enabling the DVR to effectively stabilize the grid voltage. Overall, the results highlight the importance of robust DC link voltage management in the DVR system, ensuring effective voltage compensation and maintaining power quality during grid disturbances.

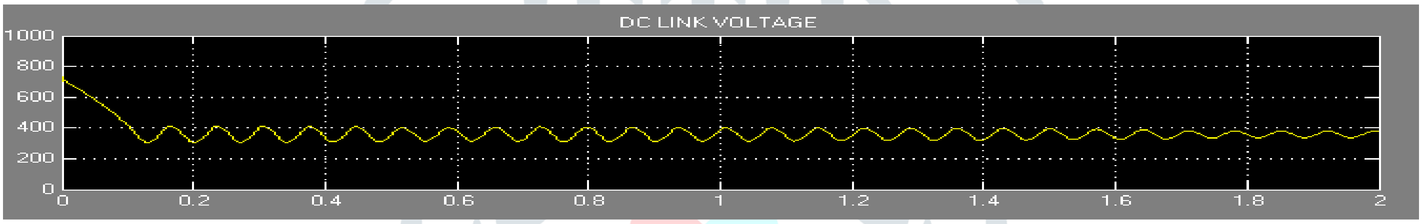

Fig 14: DC Link Voltage

V. CONCLUSION

The simulation analysis of the Dynamic Voltage Restorer (DVR) with the proposed BESS and SMES control theory has demonstrated its significant effectiveness in maintaining voltage stability and improving power quality in grid-connected systems. When the DVR is in operation, it successfully manages both voltage sags and swells by rapidly injecting or absorbing reactive power through the SMES and providing sustained support with the BESS. This dual approach ensures that the output voltage to the load remains stable and within acceptable limits, despite fluctuations in the grid voltage.

During voltage sags, the DVR's quick activation of the SMES and the subsequent engagement of the BESS effectively restore and maintain voltage levels, preventing any significant deviation from the nominal value. In the case of voltage swells, the DVR efficiently absorbs excess energy through the SMES and the BESS, correcting overvoltage conditions and protecting sensitive equipment.When the DVR is in the OFF condition, both the input and output voltages are directly aligned with the grid voltage, with no intervention to stabilize or modify the voltage. Conversely, when the DVR is ON, it actively adjusts the output voltage to counteract disturbances, ensuring that the load receives a consistent and reliable voltage.

Overall, the DVR, enhanced by the proposed control strategies and integrated with energy storage systems, proves to be a robust solution for enhancing grid resilience and ensuring high-quality power delivery. The simulation results affirm the DVR’s capability to effectively stabilize voltage, manage real and reactive power, and maintain overall system performance, making it a valuable asset in modern electrical networks.

VI. FUTURE WORK

Future work in enhancing Dynamic Voltage Restorer (DVR) systems with BESS and SMES should focus on several key areas to further improve their performance and integration. Advanced control strategies, including machine learning and artificial intelligence, could be explored to enhance predictive capabilities and adaptive responses to dynamic grid conditions. Additionally, incorporating next-generation battery technologies and hybrid energy storage solutions could optimize performance and efficiency. Research into better integration with renewable energy sources and development of sophisticated energy management systems are also crucial for improving grid stability and reducing reliance on fossil fuels. Real-time adaptive control techniques and enhanced voltage profiling algorithms could provide more precise and responsive voltage regulation. Furthermore, studying scalability for large-scale deployment, performing comprehensive cost-benefit analyses, and advancing fault detection and predictive maintenance techniques will help ensure reliability and economic feasibility. Lastly, contributing to the development of industry standards and guidelines will facilitate interoperability and compliance with regulatory requirements. These efforts will collectively enhance the DVR's ability to maintain stable and reliable power delivery in modern electrical grids.

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