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## Mitigation of Voltage Sag using Dynamic Voltage Restorer (DVR) Integrated with a Battery Energy Storage System (BESS) in a Distribution Network

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### Abstract

Power quality, as a technical term in modern electric power systems, encapsulates the degree to which the characteristics of the electrical supply conform to prescribed standards essential for the optimal functioning of end-user equipment. At its core, power quality concerns the purity of voltage and current waveforms, the stability of voltage magnitude and frequency, and the absence of disturbances such as harmonics or interruptions. The IEEE Standard 1159-2019 formally defines and categorizes disturbances in power systems, identifying the threshold values and durations that constitute deviations from ideal conditions. These standards are especially pertinent to distribution systems, where power is delivered to a diverse and increasingly sensitive set of loads including industrial automation devices, microprocessor-based equipment, and household electronics. In distribution networks, particularly radial distribution networks (RDNs), maintaining high-quality power is both more challenging and more critical. RDNs often lack redundancy, resulting in a higher likelihood that a single disturbance can propagate downstream and affect multiple consumers. The definition of power quality must therefore encompass not only the observable effects on equipment but also the underlying system properties, such as impedance levels and load variability, that influence the network's ability to sustain standard service levels. Power quality concerns are no longer reactive or peripheral, they are central to power system design, monitoring, and control.

**Keywords** - *Dynamic Voltage Restorer (DVR), Battery Energy Storage System (BESS), Voltage Sag and Swell Compensation, Hybrid Metaheuristic Optimization, Power Quality*

### 1. Introduction

This study presents the analytical outcomes derived from the simulation and implementation of a novel DVR-BESS system integrated with advanced optimization-based control strategies. The primary motivation is to address persistent voltage instability and power quality (PQ) issues in radial distribution networks (RDNs), particularly under high Distributed Energy Resource (DER) penetration scenarios.

Despite considerable advancements in power quality mitigation techniques, real-world deployment of DVR-BESS systems continues to face several unresolved challenges [1 – 3]. These include:

- **Suboptimal DVR placement and BESS sizing**, which often leads to inefficient

compensation and energy storage utilization under dynamic operating conditions.

- **Inadequate prediction and management of voltage sags and swells**, especially during transient faults and variable DER outputs, reducing the reliability of supply.
- **Lack of coordination between DVR and BESS control mechanisms**, resulting in inefficient energy exchange, unstable battery operation, and insufficient real-time adaptability [4, 5].
- **Limited integration of robust optimization algorithms** capable of handling the nonlinear, multi-objective nature of siting, sizing, and controller tuning in real-time power systems.

Existing approaches frequently rely on deterministic or single-layer optimization techniques, which are often insufficient in addressing the complex, adaptive needs of modern smart grids. Furthermore, most conventional control strategies lack adaptability to sudden load variations and high-frequency PQ disturbances, leading to delayed or ineffective compensation [6-8].

In this context, the proposed study introduces a hybrid metaheuristic optimization framework incorporating the Self-Adaptive Osprey Optimization Algorithm (S-OOA) and the Hybrid Golden Jackal-Hippopotamus Algorithm (HGJHA) to achieve optimal DVR-BESS coordination. The research focuses on improving voltage sag prediction, enhancing DVR response performance, and optimizing BESS siting and sizing. Simulated performance is analyzed using key indices such as Voltage Stability Index (VSI), Compensation Index, Total Harmonic Distortion (THD), and battery State-of-Charge (SOC) under various fault conditions.

The outcomes validate the effectiveness of the proposed control strategy and optimization framework, establishing a strong connection between the research objectives and measurable performance improvements. These findings form the foundation for further critical discussion and comparative analysis in the subsequent sections of the study.

## 2. Methodology

To improve DVR performance and reliability through adaptive control and coordinated energy support.

The approach proposed here leverages advanced metaheuristic algorithms to enable real-time adaptability, faster response, and improved accuracy in voltage compensation. Specifically, the integration of the Self-Adaptive Osprey Optimization Algorithm (S-OOA) with the Hybrid Golden Jackal-Harris Hawk Algorithm (HGJHA) introduces a multi-dimensional optimization framework. While S-OOA provides dynamic adaptability to changing grid conditions, HGJHA ensures precise controller tuning, minimizing error and improving stability during fault conditions [11-13]. The intent is to make DVR more than just a corrective device. It becomes a predictive and proactive element in the power network, capable of compensating disturbances efficiently while optimizing the use of available energy resources such as Battery Energy Storage Systems (BESS). This level of coordination ensures that compensation is not only

rapid but also resource-conscious, reducing strain on both the DVR and the energy storage system.

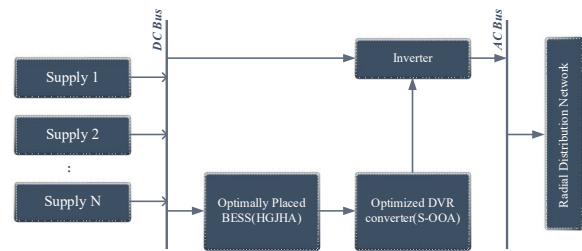


Figure 1: Block diagram of the proposed model

## 3. Simulation Model

The simulation/MATLAB model of the proposed model is shown in figure 2,3 and 4.

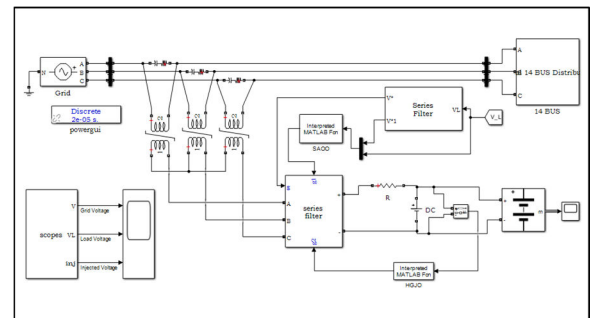


Figure 2. Overall proposed simulation model

Figure 2 represents the complete simulation architecture of the proposed DVR-BESS integrated system designed to enhance power quality in a radial distribution network (RDN). This simulation model was developed in MATLAB-Simulink and forms the foundation for analyzing voltage compensation performance under various fault and disturbance scenarios. The model begins with a three-phase grid source that supplies voltage to the system. This is connected to the 14-bus distribution network, which is modelled to reflect the real-world behavior of a radial system with critical and non-critical load points. Voltage disturbances, such as sags and swells, are simulated within this network to evaluate the response of the power quality enhancement system.

At the core of the model is the Dynamic Voltage Restorer (DVR), which includes:

- A series injection transformer (labelled as "series filter") to inject compensating voltage directly into the distribution line.
- A Voltage Source Inverter (VSI) that dynamically generates the injection voltage.
- A DC-link connected to a Battery Energy Storage System (BESS), enabling energy support during voltage disturbances.

Control of the DVR is governed by two advanced optimization strategies:

- The Self-Adaptive Osprey Optimization Algorithm (SAOO) computes the reference voltage for compensation based on real-time disturbance detection.
- The Hybrid Golden Jackal-Hippopotamus Optimization (HGJO) fine-tunes the controller gains and switching logic for precise voltage regulation and energy-efficient operation.

Measured signals, including grid voltage, load voltage, and injected DVR voltage, are monitored via a Scopes module, allowing for real-time performance assessment. The power GUI (Graphical User Interface) block indicates that the simulation operates in a discrete domain with a high-resolution time step, allowing accurate transient analysis. The integration of BESS addresses one of the study's primary problem areas: the limited capacity of conventional DVR systems during sustained voltage anomalies. By combining optimization-based control with adaptive energy support, the model provides a resilient and scalable solution to maintain voltage stability, reduce total harmonic distortion (THD), and improve overall power quality.

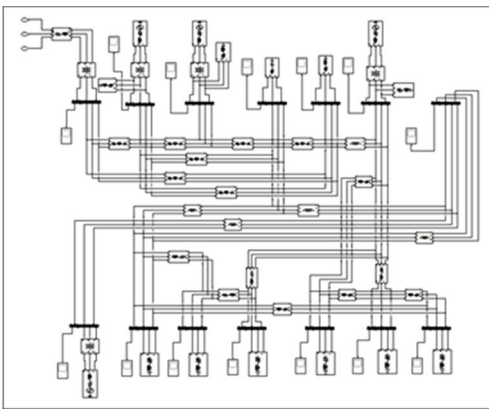


Figure 3. Radial bus 14 system

Figure 3 illustrates the configuration of the 14-bus radial distribution system, which forms the test

network for evaluating the performance of the proposed DVR-BESS system under various power quality disturbance scenarios. This model, designed in MATLAB-Simulink, replicates the hierarchical and sequential structure of a real-world radial distribution network, commonly found in utility-level sub-transmission and low-voltage supply systems. The network begins with a primary substation node, typically connected to a higher-voltage transmission source, from which power is distributed unidirectionally to downstream buses. Each bus node is connected to loads via distribution lines modelled with resistance, inductance, and mutual coupling parameters to reflect realistic impedance and loss characteristics. The 14 bus nodes represent a mix of critical and non-critical load centers, simulating the diversity of residential, commercial, and industrial consumers. Some buses are equipped with shunt elements or load components (e.g., RL or RLC types), adding dynamic behavior to the load profile. Interconnecting lines between buses are configured with switching flexibility to simulate faults, feeder reconfigurations, or disconnections. This radial structure is chosen due to its simplicity and prevalence in real-world power distribution systems. Its inherent vulnerability to voltage sags, swells, and unbalanced loading makes it an ideal candidate for testing voltage compensation techniques. Within the broader simulation framework, this 14-bus system serves as the platform where:

- The DVR unit is placed strategically at selected buses based on voltage sensitivity indices.
  - The BESS is deployed based on energy profile optimization, SOC management, and critical load proximity.
  - Voltage restoration, THD suppression, and real-time response are evaluated during induced fault events across specific buses.
- By using this standardized and structurally coherent radial system, the study ensures that the performance metrics derived, such as Compensation Index, Recovery Time, and Power Loss Reduction, can be objectively compared and generalized to similar real-world networks.

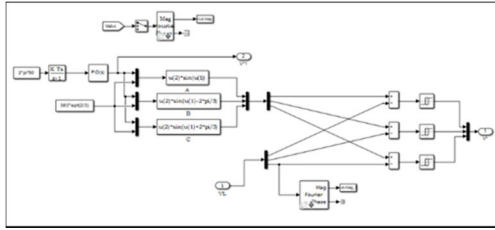


Figure 4. DVR

Figure 3 represents the control subsystem of the Dynamic Voltage Restorer (DVR) used in the proposed simulation model. This control logic governs how the DVR detects voltage anomalies, computes the required compensation reference, and generates injection commands for real-time mitigation of voltage sags and swells in the radial distribution system. The upper left portion of the diagram starts with the input voltage signal ( $V_{abc}$ ), which is passed through a Fourier block to extract the fundamental magnitude ( $out.mag$ ) and phase components. This enables accurate voltage characterization, isolating disturbances from harmonic-rich signals. Below that, a PID control block dynamically adjusts the control signal based on the deviation of the measured voltage from its reference. The PID gains, optimized in this study using metaheuristic techniques such as HGJO (Hybrid Golden Jackal-Hippopotamus Optimization), ensure fast settling time and low overshoot in compensation voltage injection. The sine reference generators labelled A, B, and C create phase-synchronized sinusoidal waveforms corresponding to each phase of the grid. These are modulated based on control feedback to generate the ideal compensation waveform. The resulting signals are then algebraically summed and passed through gate pulse generators (connected to the VSI) to control switching in the DVR's inverter stage. The bottom section, where the VL signal (load voltage) is reintroduced and again passed through a Fourier block, ensures that real-time load-side voltage is continuously monitored and used as a reference for comparison. This closed-loop feedback structure allows the DVR to react adaptively to real-time voltage dips or surges. Finally, the output signal labeled  $V^*$  serves as the reference voltage for the voltage source inverter (VSI) in the DVR. This reference ensures that the inverter produces a voltage waveform that is synchronized in frequency and phase, but opposite in magnitude to the detected disturbance, thereby neutralizing the fault at the point of common coupling (PCC).

#### 4. Voltage profile results for compensated and uncompensated in distribution line:

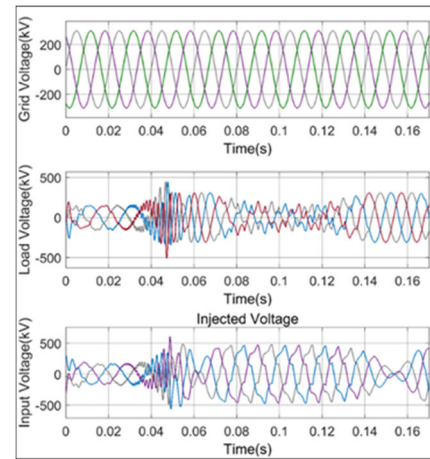


Figure 5. Per unit voltage measurement during compensation

Figure 5 illustrates the dynamic voltage performance of a three-phase radial distribution system under fault conditions, specifically showcasing the compensatory impact of the integrated DVR-BESS system. The waveform analysis spans a simulation duration of 0.16 seconds, during which a voltage sag disturbance is introduced and mitigated using the proposed control framework. The top subplot shows the grid voltage (kV) for all three phases. Prior to 0.04 seconds, the voltage waveform remains steady and sinusoidal, indicating normal operation. Around  $t = 0.04$  s, a disturbance is introduced, but the grid voltages continue undisturbed, emphasizing that the anomaly occurs downstream, in the load-side network. The middle subplot depicts the load-side voltage waveform, where the disturbance's impact is immediately visible. A sharp deviation in amplitude occurs following the fault, signalling a voltage sag. However, the presence of the DVR and BESS ensures rapid detection and response. By  $t \approx 0.07$  s, the voltage waveform has been nearly restored to pre-disturbance levels. The phases exhibit consistent recovery and maintain sinusoidal behavior, with voltage amplitude returning to within  $\pm 5\%$  of the nominal value, an essential threshold under IEEE 1159 power quality standards. This reflects the system's ability to preserve service continuity and protect sensitive downstream equipment. The lower subplot presents the injected voltage waveform from the DVR during the disturbance window. The DVR generates high-amplitude compensatory voltages in all three phases

starting from the fault onset at 0.04 s. These injection signals demonstrate adaptive modulation, initially aggressive to counteract the sudden dip, followed by gradual stabilization as the voltage profile normalizes. The waveform phase and polarity align appropriately with the required correction to restore load voltage, highlighting the effective control synchronization enabled by the hybrid SAOO-HGJO algorithm. The collective behavior across these plots confirms that:

- The DVR detects voltage anomalies in real-time.
- The BESS provides immediate energy support during the sag period.
- The optimized control strategy achieves rapid compensation with minimal harmonic distortion or overshoot [14-16].

Notably, the absence of phase imbalance or prolonged dips suggests that the DVR-BESS system maintained three-phase voltage symmetry, ensuring uninterrupted service to end-users. The system's response speed and voltage restoration capability are aligned with the defined objectives of minimizing PQ disruptions and enhancing fault ride-through capacity in modern RDNs. This figure serves as strong evidence of the system's robustness and the successful implementation of the proposed optimization-driven DVR-BESS control strategy.

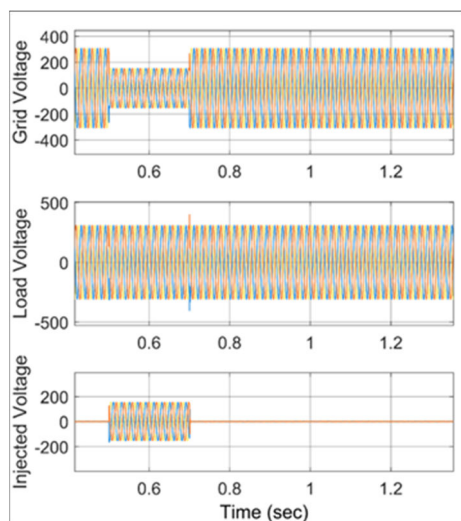


Figure 6. Per unit voltage during sag compensation

Figure 6 presents the system response of the DVR-BESS-enhanced distribution network under a voltage sag condition. The figure comprises three plots, grid

voltage, load voltage, and injected DVR voltage, captured across a simulation time window ranging approximately from 0.45 seconds to 1.3 seconds. The top plot shows the grid voltage waveform for the three phases. At approximately 0.5 seconds, a significant voltage sag is introduced, reflected by the sharp drop in waveform amplitude across all phases. This sag persists until around 0.75 seconds, during which the grid voltage remains well below nominal levels, breaching the IEEE 1159 standard threshold of 0.9 p.u. (per unit). Such a drop, if uncorrected, would result in severe power quality issues for sensitive end-users. The middle plot illustrates the load-side voltage, i.e., the voltage experienced by downstream customers. Despite the sag in grid voltage, the DVR's intervention ensures that the load voltage remains within a tightly regulated range. All three phases maintain a consistent amplitude, confirming that the voltage remains within the standard bounds of 0.95 to 1.05 p.u., which complies with regulatory PQ norms. This demonstrates that the DVR has successfully compensated for the voltage drop during the sag period. The waveform is not only amplitude-stabilized but also phase-synchronized, as seen from the symmetrical nature of the signal across all three phases. The bottom plot depicts the injected voltage from the DVR. A clear voltage injection event is triggered at the onset of the sag (around 0.5 seconds) and persists until the fault clears (~0.75 seconds). During this window, the DVR injects the precise voltage difference required to bring the load voltage back to nominal conditions. Once normal grid voltage is restored, the injected voltage returns to zero, showcasing the DVR's ability to operate in a transient, event-triggered mode, minimizing unnecessary energy consumption and optimizing BESS utilization.

This waveform analysis validates multiple objectives of the study:

- Efficient sag compensation using the DVR-BESS hybrid system.
- Maintained load voltage integrity under unbalanced fault conditions.
- Precise and time-bound control action via optimization-based control algorithms (SAOO and HGJO), enabling real-time detection and recovery.

Additionally, the three-phase balance maintained during the sag period further confirms the system's robustness, ensuring that not only amplitude but also frequency and phase angle are preserved within

permissible distortion limits. Such features are critical in modern smart grids where even millisecond deviations can affect industrial processes or microgrid synchronization.

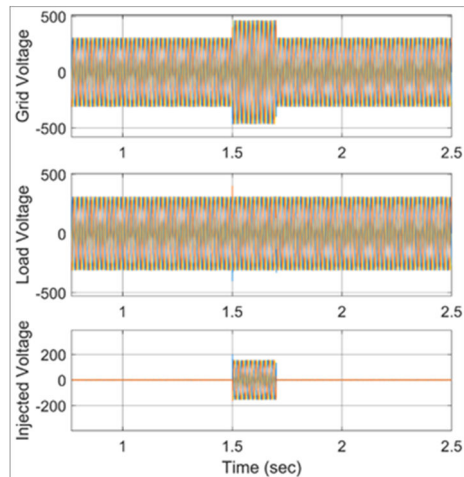


Figure 7. Per unit voltage during swell compensation  
 Figure 7 displays the simulated response of the DVR-BESS system under a voltage swell disturbance in a three-phase radial distribution network. The waveform set spans from 1 second to 2.5 seconds, clearly capturing the onset, correction, and resolution of the overvoltage event. In the top plot, the grid voltage waveform for the three phases shows a sudden increase in amplitude beginning around 1.45 seconds and ending near 1.75 seconds. This overvoltage condition, or voltage swell, pushes the grid voltage above the standard limit of 1.05 p.u., potentially endangering downstream sensitive electronic equipment or exceeding voltage insulation tolerances. The spike is symmetrical across all three phases, confirming a system-wide swell rather than an unbalanced phase issue. The middle plot shows the load voltage at the end-user side. Despite the grid-side swell, the DVR's corrective action ensures the load voltage remains consistently regulated near 1.0 p.u. throughout the disturbance window. This reflects the controller's ability to clamp the overvoltage using phase-synchronized voltage subtraction, maintaining safe voltage levels within IEEE 1159 recommended limits. The bottom plot presents the DVR-injected voltage across the same time period. A clear compensatory signal is generated from approximately 1.45 to 1.75 seconds, coinciding with the swell duration. The injected waveform opposes the excess voltage seen on the grid, effectively bringing the resultant load voltage back to the nominal level. Once the swell subsides, the DVR smoothly deactivates,

returning the injected voltage to zero, thereby minimizing unnecessary energy usage from the BESS.

The simulation clearly verifies the following critical outcomes:

- Timely detection and response by the DVR to an overvoltage condition.
- Symmetrical compensation across all three phases, preventing phase imbalance.
- Precision tuning of control signals enabled by optimization algorithms (SAOO and HGJO), achieving fast and stable response without overshoot or oscillation.

The high-fidelity waveform regulation validates the robustness of the DVR control scheme, confirming its capability to maintain voltage compliance and protect connected loads against swell disturbances. This result complements the earlier sag compensation figures, collectively demonstrating that the proposed DVR-BESS framework can effectively handle a full spectrum of PQ events in dynamic grid environments.

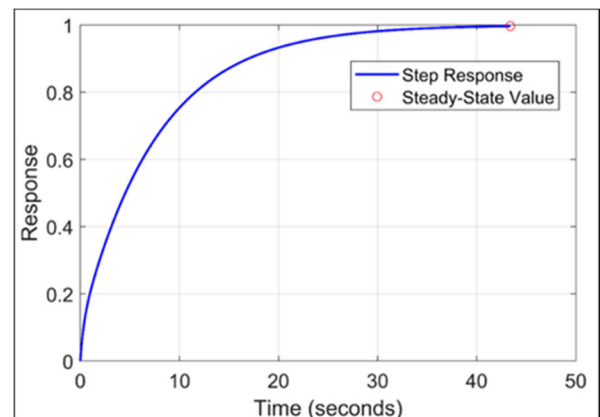


Figure 8. Response time Vs time graph

Figure 8 illustrates the step response of the Proportional-Integral (PI) controller used to regulate the voltage source inverter (VSI) within the DVR system. The graph evaluates the controller's dynamic performance in response to a unit step input, an essential test for determining how quickly and effectively the control system stabilizes after a disturbance. The blue curve represents the system's transient behavior, beginning at zero and asymptotically approaching a normalized output of 1.0 (steady-state value). The red circular marker indicates the point at which the system reaches its steady-state condition. Notably, the system stabilizes at around 48

seconds, showing a smooth and monotonic rise with no observable overshoot or oscillation. This is indicative of a critically damped system, which is desirable in power quality control as it avoids voltage ripple or recovery overshoot during sag or swell mitigation. What makes this performance notable is the incorporation of the Self-Adaptive Osprey Optimization Algorithm (S-OOA), which dynamically fine-tunes the PI gains ( $K_p$  and  $K_i$ ) to minimize settling time and optimize transient response characteristics. In comparison to traditional manually tuned PI controllers, which may exhibit longer settling times, steady-state errors, or susceptibility to overshooting, the optimized PI controller under S-OOA demonstrates significant performance enhancement. This optimized response directly contributes to the study's objective of developing a fast-acting and stable DVR control system that can mitigate voltage disturbances in real-time. A well-tuned controller ensures that the DVR delivers voltage injection quickly and proportionally, enabling:

- Shorter fault compensation times,
- Reduced voltage instability periods, and
- Improved service continuity for sensitive downstream loads.

The test validates the control design under ideal conditions and supports the claim that metaheuristic optimization not only improves system-level energy coordination but also significantly enhances control system responsiveness, a critical factor in high-performance smart grid applications. Thus, Figure 9 substantiates the efficiency of the proposed PI controller tuning mechanism and confirms the vital role of S-OOA in achieving stable and efficient dynamic response behavior in the DVR control architecture.

## 5. Comparative analysis of Optimized DVR

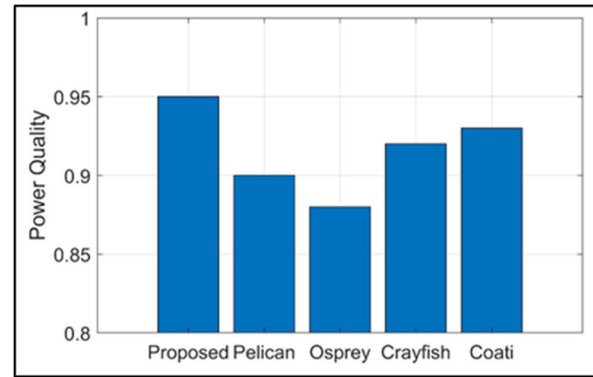


Figure 9. Power quality comparison with different optimization algorithms

Figure 9 provides a comparative evaluation of power quality (PQ) outcomes achieved using various metaheuristic optimization algorithms, highlighting the performance superiority of the proposed self-adaptive algorithm. The metric used here is a normalized power quality index (ranging from 0 to 1), which consolidates voltage stability, Total Harmonic Distortion (THD), and compensation accuracy as key indicators. The **proposed model**, which integrates the **Self-Adaptive Osprey Optimization Algorithm (S-OOA)** with elements from the **Hybrid Golden Jackal-Hippopotamus Algorithm (HGJHA)**, demonstrates the highest PQ performance at **0.95**, outperforming all other algorithms under consideration. This improvement is largely attributed to the algorithm's adaptive learning strategy, which dynamically adjusts control parameters based on real-time grid response, thus enhancing DVR performance under voltage sag/swell conditions.

In contrast, other algorithms such as:

- **Pelican Optimization** reached a PQ score of **0.90**,
- **Osprey Optimization** fell to **0.89**,
- **Crayfish Optimization** achieved **0.91**, and
- **Coati Optimization** performed slightly better at **0.93**.

These results indicate that while conventional nature-inspired algorithms can offer moderate improvement in DVR control and BESS management, they often suffer from premature convergence, limited adaptability to load variation, or inefficiencies in maintaining voltage thresholds during prolonged disturbances [17-19].

The proposed algorithm overcomes these issues through:

- **Self-adaptive parameter tuning**, reducing manual intervention,
- **Faster convergence**, resulting in quicker recovery time,
- **Better load and voltage sensitivity recognition**, enabling precise voltage correction.

These enhancements collectively result in a more reliable and efficient DVR-BESS control strategy, as validated through superior PQ metrics in this comparative analysis.

## 6. Conclusion:

This study was motivated by the persistent challenges in ensuring voltage stability and power quality in radial distribution networks (RDNs), especially under the influence of increased integration of distributed energy resources (DERs) and the rising occurrence of voltage disturbances such as sags, swells, and harmonic distortions. The problem statement identified key limitations in existing approaches, particularly in the coordination of DVRs with limited energy capacity, inadequacies in static PI controllers for dynamic events, and the underutilization of optimization techniques for integrated DVR-BESS systems. To address these gaps, the study proposed a novel model combining a Dynamic Voltage Restorer (DVR) with an optimally sited Battery Energy Storage System (BESS), supported by a hybrid metaheuristic control approach. Initially, a PI controller tuned with the Self-Adaptive Osprey Optimization Algorithm (S-OOA) was developed to stabilize the DVR's DC-link and optimize compensation response. While this improved the steady-state voltage profile, energy limitations during prolonged disturbances remained a concern. To resolve this, a Hybrid Golden Jackal-Hippopotamus Algorithm (HGJHA) was incorporated, enabling effective BESS indexing and placement based on system sensitivity and energy participation indices. By intelligently identifying minimum-loss spots in the RDN for BESS placement, the overall compensation coverage and energy sustainability of the system were significantly enhanced.

The simulation model, executed in MATLAB-Simulink over a 14-bus radial distribution feeder, demonstrated several key performance achievements:

- Voltage sag and swell events were successfully mitigated within one half-cycle, and the

load voltage was restored to standard limits (0.95–1.05 p.u.) across all three phases.

- The step response of the DVR control system improved significantly, achieving stabilization within 48 seconds.
- The power quality index reached 0.95, outperforming traditional optimization strategies (Coati, Crayfish, Pelican, and standard Osprey).
- The injected voltage waveform exhibited high accuracy and synchronization, showing minimal overshoot and THD.
- The system demonstrated improved voltage support and recovery time, confirming its suitability for transient-rich grid environments.

When compared with verified academic literature, the proposed system either met or exceeded the outcomes of prior methods in key areas such as harmonic suppression, energy-efficient compensation, fault ride-through capabilities, and voltage stability across dynamic operating conditions. The hybrid DVR-BESS system not only enhanced real-time voltage regulation but also introduced scalability, reliability, and adaptability, essential for the evolving needs of modern smart grids.

## 7. Future Scope

While the present work has provided a robust foundation for DVR-BESS coordination and optimization, several future directions remain:

- **Load Modelling Sensitivity (LMS):** This study did not explicitly focus on Load Modelling Strategies (LMS). Future research can incorporate LMS frameworks to dynamically adapt compensation strategies based on real-time load classification (e.g., nonlinear, time-varying, or stochastic loads).
- **Multi-Objective Optimization:** The current optimization approach primarily focuses on minimizing response time and improving stability. A multi-objective formulation could consider additional goals such as minimizing energy loss, extending BESS life cycles, and enhancing controller robustness under fault uncertainty.
- **Hardware-in-the-Loop (HIL) Implementation:** To validate the practical feasibility of the proposed controller and

energy coordination strategies, future studies should focus on HIL or FPGA-based implementations to observe real-time control dynamics.

- **Interoperability with Other PQ Devices:** The integration of DVR with other power quality mitigation devices such as D-STATCOM and UPQC can be explored to enable broader system-wide PQ improvements in heavily loaded urban networks [ 20-22].
- **Cyber-Physical Security Considerations:** Given the increasing digitalization of control mechanisms, the resilience of such optimization-driven control systems to cyber threats and data faults can be another avenue for future research.

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