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OPTIMIZATION BASED TUNING OF STATCOM AND BESS CONTROLLERS

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Abstract
This work investigated how to improve voltage and frequency performance in a power system by properly tuning the control settings of a STATCOM and a Battery Energy Storage System (BESS). The STATCOM is used for voltage support through reactive power control, while the BESS provides frequency support through active power injection using a PI controller. Particle Swarm Optimization (PSO) is applied to automatically search for suitable controller gains that improve dynamic response while respecting practical operating limits such as battery power rating and state-of-charge boundaries. A 10% load increase introduced at 2 seconds is used to evaluate the coordinated control strategy. The optimized controller reduces the maximum frequency deviation from 0.0351 Hz to 0.0186 Hz and improves the lowest frequency point from 49.9649 Hz to 49.9814 Hz. These improvements require increased battery contribution, with peak BESS power rising from 11.20 MW to 14.35 MW and a slightly larger reduction in state of charge. Voltage remains within acceptable limits for both baseline and optimized cases, and the STATCOM operates far below its reactive power capacity for the disturbance considered. The findings show that PSO is an effective tuning tool for coordinated STATCOM–BESS control and highlights the trade-off between improved frequency support and increased battery usage.

Keyword: STATCOM**;** Battery Energy Storage System (BESS); Particle Swarm Optimization (PSO); Frequency regulation; Voltage stability

Introduction

Background on Voltage and Frequency Stability Challenges in Modern Power Systems

Electric power systems are being reshaped by the growing integration of inverter-based resources (IBRs) such as photovoltaic (PV) plants, wind generation, battery storage, and converter-interfaced industrial loads. While these technologies improve decarbonization and operational flexibility, they also alter grid dynamics because system response increasingly depends on fast power electronic controls rather than synchronous machine behaviour. IEEE Power & Energy Society (PES) reports note that modern grids are becoming more reliant on fast-response power electronic devices and are therefore facing new stability concerns (Hatziargyriou et al., 2020).

In this evolving environment, voltage and frequency stability remain essential for secure operation. The IEEE/CIGRÉ Joint Task Force defines voltage stability as the ability of a power system to maintain acceptable bus voltages after disturbances. The same report explains that voltage instability often appears as a progressive voltage decline and may lead to voltage collapse when reactive power resources are inadequate or poorly coordinated (Kundur et al., 2004).

Frequency stability is the ability to keep system frequency within acceptable limits after severe disturbances such as generation loss or major load changes. Frequency deviations result from active power imbalance, and the depth and speed of excursions depend on inertia, damping, and primary frequency response. As IBR penetration increases, inertia is often reduced, raising RoCoF and

worsening frequency nadir during contingencies. Reliability bodies such as the North American Electric Reliability Corporation (NERC) warn that higher penetration of inverter-based technologies introduces new reliability gaps and performance risks that must be addressed to protect bulk power system security (NERC, 2025).

Voltage and frequency events are also becoming more interconnected in converter-dominated networks. Large disturbances can simultaneously reduce voltage (from reactive power stress) and frequency (from active power imbalance). Weak-grid conditions and fast converter controls can intensify these coupled effects if stability support actions are not well coordinated (Hatziargyriou et al., 2020; Kundur et al., 2004). As a result, improving stability increasingly requires technologies and control strategies that can support both voltage and frequency performance.

Problem Statement

High IBR penetration reduces inertia and strengthens voltage–frequency coupling, so STATCOM and BESS controllers must respond quickly without creating adverse interactions or instability (Hatziargyriou et al., 2020; NERC, 2025). However, these controllers are still commonly tuned using trial-and-error or fixed rules, which can become inadequate under changing grid strength, loading, and disturbance conditions, leading to excessive overshoot, slow recovery, poor damping, or conflicting actions (Kundur et al., 2004). This work therefore addresses the problem of **optimization-based tuning and coordination** of STATCOM voltage control and BESS frequency/active-power control parameters (e.g., PI gains, limits, and coordination logic) to satisfy multi-objective performance targets such as voltage deviation, RoCoF, frequency nadir, and settling time under credible contingencies

Research Aims and Objectives

The aim of this work is to develop and validate an **optimization-based tuning** framework for STATCOM and BESS controllers to enhance voltage and frequency stability during disturbances in low-inertia, converter-dominated power systems. It formulates a **multi-objective tuning problem** for coordinated STATCOM–BESS control. STATCOM **voltage PI gains** and BESS **frequency/active-power control gains** are optimized while respecting operational limits.

Scope of the Study

This study examines short-term dynamic stability after disturbances, focusing on voltage and frequency performance. It uses STATCOM reactive power control for voltage regulation and BESS active power control for frequency support, while considering SOC and inverter power limits. An optimization-based tuning approach is applied to determine the best controller parameters, and the coordinated STATCOM–BESS strategy is evaluated through simulation to assess its overall effectiveness.

Coordinated Control Strategies for Hybrid Compensators

Coordinated control strategies aim to combine the complementary benefits of STATCOM and BESS by using STATCOM primarily for dynamic voltage/reactive support and BESS primarily for active power/frequency support. This hybrid approach is increasingly attractive because modern disturbances often cause simultaneous voltage and frequency deviations. Hybrid configurations such as STATCOM+BESS can therefore provide multi-service support, improving both voltage recovery and

frequency stabilization, while also reducing stress on any single compensator (Vilchis-Rodriguez et al., 2021).

Recent studies highlight that coordinated inverter-based support is especially important in low-inertia or inverter-dominated systems, where converter interactions can influence both voltage and frequency dynamics. For example, coordinated hybrid VAR compensation and grid-forming BESS integration has been proposed to enhance voltage and reactive power regulation while strengthening overall system resilience (Bashir et al., 2025). These studies collectively suggest that coordinated control improves dynamic performance compared with independent operation, but it also introduces challenges such as controller interaction, tuning complexity, and constraint management.

Optimization Methods Used for Controller Tuning

Controller tuning is critical in STATCOM and BESS applications because improper gains can cause oscillations, slow response, or instability, particularly in nonlinear systems with converter saturation and operational constraints. As a result, many studies use metaheuristic optimization techniques to tune PI/PID or nonlinear controller parameters.

Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) are widely applied due to their ability to handle nonlinearity and multi-objective performance measures. A well-cited example is the use of PSO and GA to optimize PI controller gains for STATCOM nonlinear control, demonstrating improved dynamic response compared to conventional tuning approaches (Farokhnia et al., 2010). Recent optimization research also demonstrates hybrid methods that combine GA with improved PSO variants to improve convergence and solution quality for FACTS-related optimization problems (Kumar et al., 2024).

Modelling Approach

Voltage Dynamics Model

Voltage behaviour is represented using a linearized relationship that captures two dominant effects: Voltage drop due to increased load demand, and Voltage restoration through reactive power support. In the implemented model, voltage is expressed as:

$V(t) = 1.0 - K_{PV}(P_{load}(t) - P_{load0}) + K_{qv}Q_{STATCOM}(t)$

where K_{pv} represents the sensitivity of voltage to load change and K_{qv} represents voltage sensitivity to reactive power injection. (Kundur et al., 2004).

Frequency Dynamics Model

Frequency dynamics are represented using a reduced swing-equation-inspired model that relates frequency deviation to active power imbalance, inertia, and damping. In classical power system dynamics, the swing equation is the fundamental basis for frequency and rotor dynamics modelling (Kundur, 1994).

In the script, the frequency state is updated using:

$$\frac{df}{dt} = \frac{-P_{imb} - D(f - f_{ref})}{2H}$$

where: H is the inertia constant, D is a damping coefficient representing load damping and frequency-sensitive effects, and P_{imb} is the active power imbalance driven by the load step and corrected by BESS active power injection. (Kundur, 1994).

STATCOM Controller Structure

The STATCOM control law in the script is a proportional voltage regulator:
$Q_{cmd}(t) = K_v(V_{ref} - V(t))$, where $K_v$is the STATCOM voltage control gain. This approach reflects the typical operational principle of STATCOM devices in which voltage error drives reactive current injection (ABB, 2017).

Reactive Power Saturation

STATCOM output is limited by converter rating, represented using saturation constraints:
$Q_{min} \leq = Q_{STATCOM}(t) \leq Q_{max}$
Reactive power limits are essential because converter-based VAR devices cannot exceed thermal and current constraints, even if voltage error persists (ABB, 2017).

BESS PI Frequency Controller, Power Limits, and SoC Dynamics

BESS provides fast active power injection/absorption through inverter control and is widely applied for frequency stabilization and fast frequency response (FFR) services in low-inertia systems (Huang & Vyakaranam, 2022).

BESS Frequency Controller

The implemented BESS controller is a PI regulator based on frequency error:
$P_{bess}(t) = K_p(f_{ref} - f(t) + K_i \int (f_{ref} - f(t))dt$ where K_p and Ki are proportional and integral gains. This PI structure is commonly used in power system frequency control due to its simplicity and effectiveness in reducing steady-state frequency error (Kundur, 1994).

State-of-Charge (SoC) Dynamics

The SoC is updated based on energy exchanged by the battery. With battery power in MW and time step in seconds, the energy change is:
$\Delta E_{Mwh} = \frac{P_{bess}(t)\Delta t}{3600\cap}$
and the SoC update is:
$SOC(t) = SOC(t - \Delta t) - \left(\frac{\Delta E_{Mwh}}{E_{max}}\right) X\ 100$(Huang & Vyakaranam, 2022).

Constraints and Anti-Windup

SoC bounds are enforced:
$SOC_{min} \leq SOC(t) \leq SOC_{max}$
When SoC reaches a limit, the script blocks further charging/discharging in the constrained direction and applies a basic anti-windup correction by rolling back the integrator update. Constraint-aware control is essential because frequency response services must respect energy limitations and sustain performance across multiple events (Huang & Vyakaranam, 2022).

Coordination Logic and Implementation Details

Coordinated STATCOM–BESS Architecture

The coordination strategy is structured as complementary control actions operating in parallel:

- STATCOM regulates voltage through reactive power injection/absorption,
- BESS regulates frequency through active power injection/absorption.

This coordination is justified because voltage instability is strongly linked to reactive power deficiency, while frequency instability is primarily driven by active power imbalance (Kundur et al., 2004).

Implementation Flow in the Script

At each simulation time step, the control system executes:

1. STATCOM loop: compute voltage error → generate (Qcmd → apply saturation → update voltage.
2. BESS loop: compute frequency error → update PI integrator → generate Pcmd → apply power limits.
3. SoC checks: enforce SoC bounds and apply anti-windup if required.
4. System dynamics update: update frequency using the swing-equation-inspired model and update SoC using energy balance.

Controller Tuning Using PSO

Particle Swarm Optimization (PSO) is used to tune [K_V, K_P, Ki] because it can handle nonlinear dynamics, saturation, and multi-objective cost functions without requiring gradient information. PSO is widely used for controller tuning in power systems and FACTS applications due to its robustness and simplicity (Kennedy & Eberhart, 1995).

Optimization Methodology

This section presents the optimization framework used to tune the coordinated STATCOM–BESS controller gains. The tuning process is implemented using Particle Swarm Optimization (PSO) because it is simple to implement, does not require gradient information, and performs well for nonlinear objective functions with saturation and penalty constraints (Kennedy & Eberhart, 1995).

Definition of Decision Variables[K_V, K_P, K_i]

The coordinated controller is parameterized using three decision variables:

$$\boldsymbol{X = [K_V, K_P, K_i]}$$

where: $K_v$is the STATCOM proportional voltage gain, K_P is the proportional gain of the BESS frequency PI controller, and K_i is the integral gain of the BESS frequency PI controller.

These gains directly influence the control effort and dynamic response of the two compensators (Farokhnia et al., 2010).

Constraint Handling Using Penalties

The optimization problem includes practical constraints due to converter ratings and battery energy limits. Since classical PSO does not directly enforce constraints, violations are handled using penalty functions, a common approach in metaheuristic optimization (Kennedy & Eberhart, 1995).

Constraints Considered

The following constraints are enforced in the simulation model:

1. STATCOM reactive power limits:

$Q_{min} \leq Q_{STATCOM}(t) \leq Q_{max}$

2. BESS power limits:
   $-P_{max} \leq P_{bess}(t) \leq P_{max}$
3. Battery state-of-charge limits:
   $SOC_{min} \leq SOC(t) \leq SOC_{max}$

Penalty Term

The penalty term accumulates violations across all time steps:

$$J_{pen} = \sum violation(t)$$

and the overall cost includes:

$W_{pen}J_{pen}$

where W_{pen} is chosen very large to ensure infeasible solutions are strongly discouraged. This ensures the PSO converges toward solutions that respect physical and operational limits (Huang & Vyakaranam, 2022).

Overshoot Penalty

To enforce acceptable performance bands, overshoot penalties are added when voltage or frequency exceed predefined thresholds, e.g.:$V_{max} > 1.02, f_{max} > 50.05$
This encourages smoother responses and reduces risk of control-induced oscillations (Kundur, 1994).

PSO Algorithm Steps, Parameter Selection, and Implementation Procedure

PSO Concept

PSO is a population-based algorithm in which each candidate solution is a "particle." Particles move through the search space based on their own best-known position and the best-known position among the swarm (Kennedy & Eberhart, 1995).

Update Equations

Particle velocity and position updates follow:

$$v_i^{k+1} = wv_i^k + c_1 r_1 (pbest_i - x_i^k) + c_2 r_2 (gbest - x_i^k)$$
$$x_i^{k+1} = x_i^k + v_i^{k+1}$$

where:

- w is inertia weight,
- c_1 is cognitive coefficient,
- c_2 is social coefficient,
- r_2, $r_2$are random numbers in [0,1].

These update rules are consistent with the original PSO formulation (Kennedy & Eberhart, 1995).

Parameter Selection

The PSO parameter selection in the script includes:

- population size: nPop = 30
- maximum iterations: MaxIt = 40

- inertia weight: w = 0.72
- acceleration coefficients: (c_1 = 1.49, c_2 = 1.49)
  Such settings are commonly used to achieve a balance between exploration and convergence in PSO-based control tuning (Kennedy & Eberhart, 1995).

Results and Discussion

Result

The optimization and performance assessment results are presented using both tabulated metrics and time-domain plots. Table 1 provides the PSO convergence summary, and Table 2 reports the performance indices for voltage and frequency regulation.

Table 1 PSO convergence summary

Best Gains:	
Kv	50.000000
Kp	100.000000
Ki	200.000000
Best Cost	24.6654

Table 2: performance indices for voltage and frequency

Metric	Baseline	Optimized
Max |V-Vref	0.002000pu	0.002000 pu
Vmin/Vmax	0.998000 / 1.000000	0.998000 / 1.000000
Max |f-fref|	0.035084Hz	0.018644Hz
fnadir/peak	49.964916 / 50.000000 Hz	49.981356 / 50.007363 Hz
Peak |Pbess	11.198107 MW	14.346652 MW
Peak |Qstat|	0.010000 MVAr	0.100000 MVAr
SOC change	-0.011359 %	-0.021946 %

The corresponding dynamic responses are shown in Figure 1, which compares bus voltage, system frequency, BESS active power, and BESS SoC across the studied scenarios.

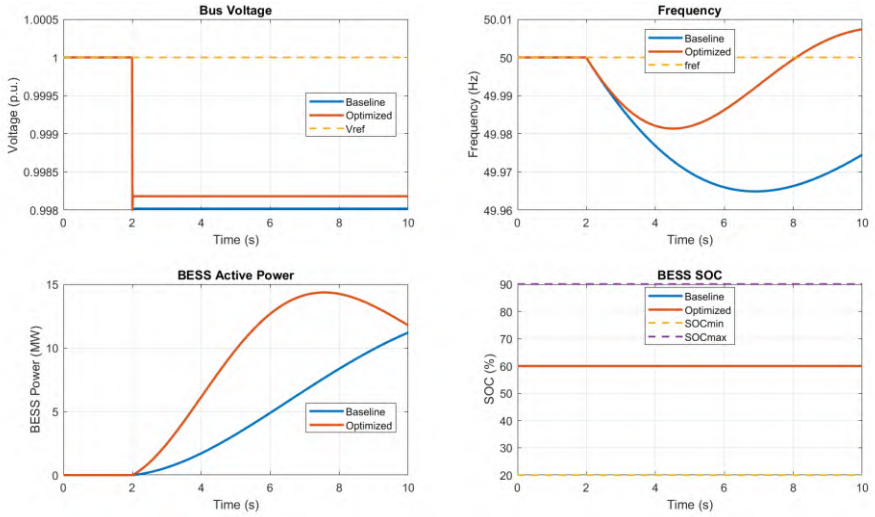


Figure 1: Bus Voltage, Frequency, BESS Active Power and BESS SOC in the Various Scenario Against Time

Figure 2 depicts the STATCOM reactive power response, and Figure 3 shows the PSO convergence characteristic in terms of best cost value versus iteration count.

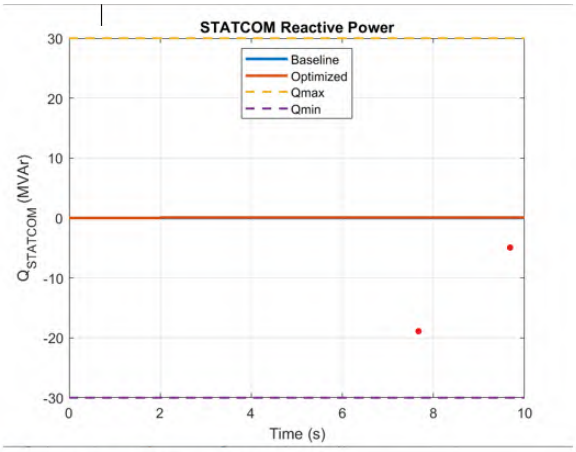


Figure 2 STATCOM Reactive Power

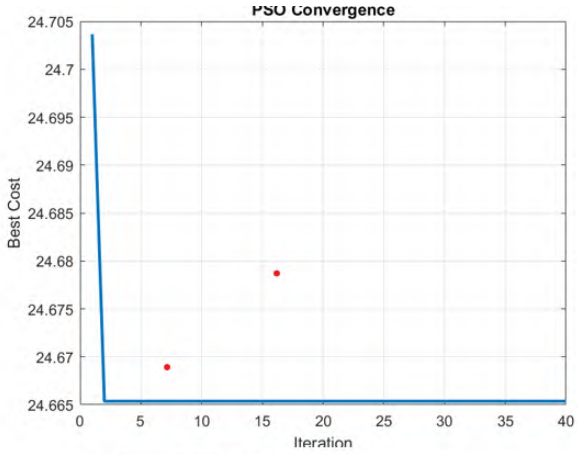


Figure 3 PSO Convergency

Discussion

PSO Convergence Behavior

Particle Swarm Optimization (PSO) was used to tune the coordinated STATCOM–BESS controller gains [K_V Kp, Ki] with the objective of improving voltage and frequency regulation under a 10% load step disturbance applied at t = 2s. The convergence plot shows that the best cost drops sharply within the first two iterations and then remains constant up to iteration 40.

However, the optimized gains were repeatedly driven to the upper bounds of the search region: K_V= 50, K_P= 100, Ki = 200

Voltage Regulation Performance

Table results show that both baseline and optimized control maintain voltage stability with identical maximum voltage deviation: Baseline: max |V - V_{ref}| = 0.0020p.u, Optimized: max |V - V_{ref}| = 0.0020 p.u.

The minimum and maximum voltages are also the same in both cases:V_{min} = 0.998p.u., Vmax = 1.000, p.u. This indicates that the STATCOM's voltage support contribution is minimal in this study. This is consistent with the reactive power plot, where the STATCOM injection remains close to zero for both baseline and optimized cases. Specifically, the peak STATCOM reactive power is extremely low: Baseline:Q_{peak} = 0.01MVAr, Optimized: Q_{peak}= 0.10MVAr

Even in the optimized case, the STATCOM operates far below its rating pm 30 MVAr, meaning the voltage disturbance created by the load change is small and can be handled without significant reactive support. As a result, the optimization has little room to improve voltage behavior because it is already within an acceptable range.

Frequency Regulation Performance

In contrast to voltage, the optimization produced noticeable improvements in frequency response: Baseline maximum deviation: $\max|f - f_{ref}|$ = 0.0351 Hz and Optimized maximum deviation: $\max|f - f_{ref}|$= 0.0186) Hz

This corresponds to roughly a 47% reduction in peak frequency deviation. Similarly, the frequency nadir improves significantly: Baseline nadir: f_{nadir}= 49.9649Hz and Optimized nadir: f_{nadir}= 49.9814 Hz

Thus, the optimized BESS control strategy reduces the depth of the frequency dip following the disturbance. The improvement can be clearly observed in the frequency plot, where the optimized curve exhibits faster recovery and a smaller deviation from 50 Hz.

However, the optimized case shows a slightly higher frequency overshoot above nominal as 0ptimized peak: f_{peak} = 50.0074 Hz and baseline peak: 50.0000Hz

Battery Power and Energy Utilization (BESS Stress)

The improved frequency performance comes at the cost of higher battery power usage. The optimized controller injects more active power into the system: Baseline:P_{peak} = 11.20MW,

Optimized: P_{peak}= 14.35) MW

This is a 28% increase in peak battery power. The BESS active power plot shows higher and earlier power injection for the optimized case, consistent with higher K_P and Ki.

The impact on energy is reflected in SoC change: Baseline SoC change: (-0.0114%), Optimized SoC change: (-0.0219%)

While this SoC decrease is still small in absolute terms due to the short simulation window (10 seconds), it demonstrates that better frequency support requires greater energy expenditure.

STATCOM–BESS Coordination and Interaction Effects

The results indicate that the BESS plays the dominant role in improving system performance under the studied disturbance. STATCOM contribution is negligible because reactive power injection remains near zero. Consequently, the optimization mainly tuned the BESS controller gains while $K_V$reached its maximum without affecting voltage output significantly.

This suggests:

1. The modeled disturbance primarily affects frequency (active power imbalance) rather than voltage (reactive power imbalance).
2. The system voltage is relatively strong, requiring minimal reactive support.

3. True coordinated interaction between STATCOM and BESS would become more pronounced under:
   I. weaker voltage sensitivity conditions,
   II. larger reactive load components,
   III. fault recovery cases,
   IV. or voltage-dependent load models.

Core Findings

From the optimization study, the following conclusions can be drawn:

1. PSO achieved fast convergence, reaching the best solution within two iterations.
2. Frequency regulation improved significantly, with almost 47% reduction in maximum deviation and improved frequency nadir.
3. Voltage regulation remained unchanged, showing STATCOM contribution is minimal under the chosen parameters.
4. Improved frequency support increased battery stress, with peak power rising by about 28% and SoC depletion nearly doubling.
5. The optimized gains saturating at the upper bounds indicates that the objective function should include additional real-world penalties to avoid unrealistically aggressive tuning.

Suggested Improvements for Further Work

To enhance realism and increase the research contribution, the following extensions are recommended:

- Introduce a weaker grid condition increase Kpv, reduce inertia H, or add reactive power sensitive loads.
- Include battery degradation cost or cycling penalty to capture long-term impact.
- Add overshoot and settling-time penalties explicitly to prevent frequency overshoot.
- Extend the disturbance scenarios (20% load step, stochastic load variation, and fault recovery) to test robustness.
- Adopt multi-objective PSO (Pareto analysis) to explicitly show trade-offs between stability improvement and battery usage.

Conclusion

This study applied Particle Swarm Optimization to tune a coordinated STATCOM–BESS control scheme for voltage and frequency regulation under a step load disturbance. The STATCOM provided voltage support through reactive power control, while the BESS supported frequency through active power injection using a PI controller with power and state-of-charge constraints. The optimization procedure successfully selected controller gains that improved system response without violating the defined operating limits.

The most significant improvement was achieved in frequency performance. The optimized controller reduced the maximum frequency deviation by nearly half and raised the minimum frequency level after the disturbance, demonstrating that the BESS controller settings are critical for fast frequency response. This improvement came with increased battery output, shown by a higher peak BESS power and slightly greater state-of-charge reduction. Voltage performance remained almost unchanged for both baseline and optimized cases, while the STATCOM reactive power output remained close to zero,

indicating that the disturbance did not create a strong voltage challenge in the model and therefore did not demand substantial reactive support.

Overall, the results confirm that optimization-based tuning can enhance coordinated STATCOM–BESS operation, particularly for frequency stability, while revealing the practical trade-off between improved frequency regulation and increased battery usage. Future work should test the approach under more severe disturbances, weaker grid conditions, and different load profiles to better capture STATCOM contribution, and should include additional performance measures such as overshoot penalties, control effort limits, and battery degradation indicators.

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