

Exploration of Wind Energy Storage and Its Voltage Stability

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Abstract. With the global energy transition and advancing low-carbon goals, wind power has emerged as a crucial clean renewable energy source, where large-scale grid integration has become a core trend in energy development. However, weak grid conditions significantly increase voltage stability risks during wind power integration. Insufficient reactive power support during faults may trigger protection trips, power generation restrictions, wind curtailment, cascading instability, and economic losses. To address this challenge, this paper proposed an integrated control solution for grid-connected wind farms that balances constraints and collaborative capabilities among turbines, substations, and energy storage systems. Specifically, PMSG units implement "fixed current switching" on the grid-side converter to prioritize reactive power injection for voltage recovery at the point of common coupling (PCC). The grid-side layer adopts STATCOM with dual PI controllers (DC V/Var outer loop and current inner loop), enhanced by repeated control (RC) to improve current tracking of periodic disturbances. The energy storage system employs supercapacitors for multi-level reactive power support based on voltage status, coordinating STATCOM switching through adaptive thresholds. Short-circuit and power step simulations using a high-fidelity PSCAD model demonstrate that this strategy significantly accelerates PCC voltage recovery, suppresses power oscillations, and enhances fault ride-through capability, meeting LVRT requirements while providing a viable pathway for wind power integration and operational resilience in weak grids.

Keywords: Wind Energy, Energy Storage, Voltage Stability, Reactive Power Support.

1. Introduction

With the accelerated global energy transition, wind power has emerged as a key renewable resource for low-carbon systems. As its grid share rises—especially at weak interconnection points with large equivalent impedances and limited short-circuit strength—the grid's sensitivity to reactive-power imbalance increases markedly. In practice, faults and abrupt production/load changes often materialize as voltage sags, turbine protection actions, and, in extreme cases, cascading instability [1]. Under these conditions, the Point of Common Coupling (PCC) must exhibit fast and controllable reactive-power support to sustain stability. This requirement is magnified by siting realities: many large wind bases lie at the system periphery, where the PCC voltage becomes disproportionately sensitive to the availability, speed, and stiffness of reactive support. In effect,

reactive prioritization during the millisecond–second window surrounding a fault becomes decisive for meeting LVRT obligations and avoiding post-fault oscillations.

Existing literature documents voltage and power-quality issues arising from wind integration and proposes strategies to mitigate them across analysis, modeling, and control. Benzohra et al. [2] examine system-level voltage impacts of wind integration; Islam et al. [3] study responses that preserve stability under severe or asymmetric faults; and Wang et al. [4] establish PSCAD-based pipelines that link problem identification and mechanism analysis to simulation-backed verification. Together, these studies reinforce a consistent picture: wind plants, frequently located at high-impedance margins, encounter heightened PCC sensitivity to reactive demand/supply balance, amplifying uncertainty and risk under weak-grid conditions. Building on that foundation, the present work follows the same analysis-to-validation arc while emphasizing device limits and coordination rules that are essential for dependable deployment.

At the unit layer, DFIG and full-converter PMSG machines dominate modern fleets. For PMSG, Morgan et al. [5] underscore low-voltage recovery control that prioritizes reactive current during faults to elevate PCC voltage, while Zou et al. [6] provide an equivalent electromechanical model for large-scale PMSG farms, enabling tractable plant-level studies and controller design. At the plant layer, a Static Synchronous Compensator (STATCOM)—realized as a voltage-source converter—offers high-bandwidth reactive injection suitable for deep sags on weak grids. Beyond baseline functionality, coordinated schemes with series/ancillary devices have been explored, e.g., joint operation with TCSC and coordination with UIPR, illustrating how station-level compensation can be tailored to network conditions [7-8]. In hardware/control implementation, Miremad et al. [9] present a hybrid cascaded H-bridge / three-level NPC STATCOM design and control, evidencing the maturity of high-performance reactive compensation platforms. Complementing converter and STATCOM controls, supercapacitor-based storage has attracted attention for transient voltage support thanks to millisecond response and high power density; Kuang et al. [10] propose an AC fault-ride-through strategy built on such storage, highlighting its suitability for short-duration, high-power support.

Taken together, these strands suggest that no single device suffices across the full disturbance spectrum; effectiveness hinges on how turbine controls, plant-level compensation, and storage are co-designed and coordinated. Motivated by this, the present study targets PCC voltage stability of a wind plant on a weak grid and advances a three-tier, constraint-aware control concept that aligns device bandwidths and capacities with the time scales of grid events. Concretely, at the turbine layer, the PMSG grid-side converter employs constant-current switching that reassigns priority from i_d (active) to i_q (reactive) upon voltage dips—directly lifting the PCC voltage while respecting converter overcurrent limits. At the station layer, a STATCOM regulated by dual-loop PI (outer DC-voltage / vars, inner current) is augmented with a repetitive controller (RC) to reject periodic disturbances and maintain precise current tracking through faults and recovery. At the storage layer, a supercapacitor-based ESS executes multi-level, voltage-state-aware reactive dispatch: a severity index maps sag depth $\times$ duration into discrete action levels, and adaptive thresholds coordinate STATCOM–ESS participation so that ESS provides millisecond-class response while the STATCOM supplies large, rigid reactive capacity as events deepen. This sequenced complementarity is designed to address the critical milliseconds-to-seconds window that governs LVRT performance and post-fault settling.

And it's its architecture's capacity conscious. devices limits: converter current/voltage at turbine, STATCOM + PCS residual capacity, SOC limits for ESS, hard constrain shaping setpoints/participation factor. Practical tuning workflow (i) check devices limits, (ii) set PMSG

switching coefficients and i_d/i_q priority logic (iii) tune STATCOM inner/outer PI and RC internal model period / band (iv) calibrate an ESS - STATCOM threshold matrix with hysteresis to avoid chattering and over investment. This bounded envelope controls to improve troughs, shorten recovery time and damp active power oscillation while keeping all generators inside the thermal and energy window that is stated in practice and codes.

2. Wind farm modeling and fault scenarios

Two representative turbine technologies are retained as in your draft. The first is the PMSG unit, which is a full-converter machine with stator dynamics modeled in dq coordinates and a grid-side converter (GSC) tied to a DC link (≈ 0.7 kV) with DC capacitance (≈ 0.09 F). The GSC implements constant-current switching, such that upon a PCC voltage sag, current priority is reassigned from i_d (active) to i_q (reactive) subject to the converter's overcurrent envelope, and after clearance the controller returns to near-unity-power-factor operation. Filter and line inductances (on the order of 10–4–10–3 H) are modeled to reflect practical bandwidth and voltage drop. The second is the DFIG unit, which adopts a back-to-back converter topology with rotor-side and grid-side controllers implementing vector control for decoupled active/reactive regulation. For farm-level studies, a 1 MW DFIG is scaled to 100 MW ($1 \text{ MW} \times 100$), preserving per-unit dynamics and enabling clear observation of plant-level voltage support at the PCC.

At the plant level, a Static Synchronous Compensator (STATCOM) is connected at the PCC, and its control adopts dual-loop PI with an outer loop regulating DC-link voltage and reactive power/voltage, and an inner current loop augmented with a repetitive controller (RC) to reject periodic disturbances and improve current-tracking fidelity during and after faults. The STATCOM current references include anti-windup and rate limiting aligned with device ratings. In parallel, a supercapacitor-based energy storage system (ESS) is modeled with DC/DC and DC/AC stages, and the controller implements voltage-state-aware, multi-level reactive support driven by a severity index that maps sag depth $\times$ duration into four action levels (dead-band, normal, enhanced, emergency). ESS dispatch is constraint-aware because reactive output is clipped by PCS residual capacity after active-power duties and by an SOC window (e.g., 0.1–0.9) to avoid over-charge or over-discharge. A threshold matrix with hysteresis coordinates STATCOM–ESS participation so that ESS delivers millisecond-class response while STATCOM contributes large, rigid var capacity as events intensify.

In the fault scenarios and test protocol, the PMSG sub-case applies a non-metallic short circuit at $t = 3$ s via a grounding reactor (≈ 0.08 H) for 0.2 s, which provokes the constant-current switch into reactive-priority mode and tests voltage recovery on clearance. The DFIG + STATCOM sub-case imposes staged sags of 0.8 p.u. and 0.6 p.u. at $t = 1.5$ s, cleared at $t = 1.6$ s, through grounding reactors in the ≈ 0.11 –0.25 H range, allowing a three-way comparison among no STATCOM, dual-loop PI, and dual-loop PI + RC. To reflect operating variability, additional scenarios include load steps at the PCC, wind-power ramps, and post-fault recovery with residual oscillations. In mixed scenarios, threshold-based coordination lets ESS act first for speed, and then STATCOM engages when the severity index crosses its level-2/3/4 thresholds to provide capacity and stiffness.

Finally, in the evaluation metrics and pass/fail criteria, for each case we record (i) minimum PCC voltage (trough), (ii) recovery time to a small band around nominal, (iii) active-power oscillation amplitude and damping time for the dominant mode, and (iv) device saturation flags such as current limit hits, SOC boundary touches, and STATCOM clipping. Compliance is judged against LVRT envelopes and device-limit observance. This protocol preserves your original content while making the causal chain explicit: weak-grid sensitivity leads to controller actions (priority reactive, PI + RC,

multi-level ESS), which in turn trigger coordinated thresholds and result in measurable improvements in trough, recovery, and oscillation without violating converter or storage constraints.

3. Analysis of multi-layer voltage support

The proposed scheme assembles a three-tier reactive-power stack—unit-level priority reactive current, plant-level high-bandwidth compensation, and storage-level multi-level support—to construct a millisecond-to-second voltage-support chain for weak grids. Each tier is aligned to a distinct time constant and capacity envelope, and the tiers are coordinated by threshold logic so that fast actions arrive first and large, rigid vars arrive when severity escalates. This section analyzes the mechanism, coordination, constraint handling, and observed effects across the tiers, staying within the modelling and scenarios defined earlier.

At the unit layer, when a sag is detected at the PCC, the PMSG grid-side converter switches its current priority from i_d (active) to i_q (reactive) subject to the converter's over-current envelope, thereby lifting the PCC voltage along the shortest control path; after clearance, the controller returns to near-unity-power-factor operation. In the non-metallic short-circuit test (grounding inductance ≈ 0.08 H for 0.2 s at $t = 3$ s), the “priority reactive” mode produces a rapid i_q rise with a corresponding i_d reduction and a visibly higher voltage trough, confirming the intended behavior under weak-grid conditions. Filter and line inductances (order 10–4–10–3 H) make the effect observable within realistic bandwidths. The switching and return operations are completed under current limiting, so voltage support does not violate device envelopes.

At the plant layer, the Static Synchronous Compensator (STATCOM) supplies high-bandwidth reactive injection governed by dual-loop PI—outer DC-voltage/vars and inner current—and is augmented with a repetitive controller (RC). The RC acts as an internal model for periodic disturbances, suppressing residual ripple that dual PI alone tends to leave, and thereby improving current-tracking fidelity through the fault and recovery phases. In the scaled 100 MW DFIG farm, staged sags of 0.8 p.u. and 0.6 p.u. (applied via grounding reactors ≈ 0.11 – 0.25 H) demonstrate that STATCOM raises the PCC voltage during the dip and reduces DFIG active-power oscillations, while adding RC further damps periodic components and shortens settling. Rate limits and anti-windup are included to enforce device limits.

At the storage layer, the supercapacitor-based ESS is modelled with DC/DC and DC/AC stages and controlled by a voltage-state index that maps sag depth $\times$ duration into four discrete action levels: dead-band $\rightarrow$ normal $\rightarrow$ enhanced $\rightarrow$ emergency. Two hard constraints shape dispatch: PCS residual capacity (after active-power duties) and an SOC window (e.g., 0.1–0.9) to prevent over-charge or over-discharge. Under load surges, wind ramps, and fault-clearance conditions, the multi-level strategy accelerates voltage recovery and increases dynamic var availability without over-using the storage. These behaviors are observed consistently across the EMT scenarios.

The three tiers are coordinated by an adaptive threshold matrix with hysteresis so the system avoids chattering and “over-investment.” In mixed scenarios, the ESS acts first for speed through small, early, short-duration injections, and then the STATCOM engages as the severity index crosses higher levels, contributing large, rigid var capacity; upon recovery, hysteresis ensures smooth withdrawal. This sequencing aligns device bandwidths and capacities with the evolving disturbance, yielding smoother voltage profiles and markedly shorter recovery times in deep-sag cases.

The multi-layer stack is tuned under explicit device limits so that internal limits are respected before external performance is pursued. First, current/voltage limits of the PMSG converter and STATCOM, together with ESS PCS and SOC bounds, are verified to define the feasible operating region. Second, the PMSG switching coefficients and i_d/i_q priority logic are set so reactive priority

is achieved without crossing over-current boundaries. Third, STATCOM inner/outer PI gains and RC internal-model period/band are tuned to balance disturbance rejection with stability margins under the weak-grid impedance. Fourth, the threshold matrix with hysteresis for ESS–STATCOM coordination is calibrated to reflect the site’s disturbance statistics, minimizing unnecessary cycling. Where applicable, SOC-sensing droop/distribution logic can allocate var duties away from the ESS when SOC nears its limits, letting the STATCOM provide the rigid component. Robust PLL, dual-SRF (positive/negative-sequence) control, and selective multi-resonant compensators can be included for unbalance or harmonics without altering the core sequencing.

Across the PMSG short-circuit case and the DFIG + STATCOM staged-sag tests, the multi-layer coordination yields higher voltage troughs at the PCC when the sag hits, shorter recovery times to a tight band around nominal, reduced active-power oscillation amplitudes with faster damping, and fewer saturation events such as converter current clipping, SOC boundary hits, and STATCOM clipping, because duties are shared according to device strengths and limits. The ESS’s early action trims the initial voltage plunge, the STATCOM’s follow-up supplies sustained var stiffness, and the PMSG’s priority-reactive mode ensures unit-level participation is immediate and bounded.

The performance is sensitive to thresholds and gains: overly tight thresholds can over-trigger storage or STATCOM, while overly loose thresholds delay support. While the RC excels at periodic disturbances, broadband or random perturbations may require pairing with adaptive filtering or alternative supervisory logic. Finally, the validation scope remains EMT-simulation-centric; incorporating measurement and communication delays, thermal limits, and asymmetric faults in HIL or field pilots is recommended for completeness, without changing the core coordination logic analyzed here.

The three tiers act as a sequenced, constraint-aware ensemble in which the unit layer provides immediate, bounded reactive priority, the plant layer supplies high-bandwidth, large-capacity support with RC-based ripple suppression, and the storage layer offers graded, SOC-aware injections to bridge the fastest part of the transient. Their coordination via adaptive thresholds and hysteresis explains the observed improvements in trough, recovery, and oscillation metrics across the modeled weak-grid scenarios.

4. Implementation and optimization strategies

The control stack is deployed in three coordinated tiers—turbine (PMSG), station (STATCOM), and storage (supercapacitor ESS)—with a common PCC voltage and current measurement backbone and per-tier local controllers. Device limits are pre-modeled as hard constraints, including converter current and voltage bounds for the PMSG and STATCOM, and PCS residual capacity plus SOC window (e.g., 0.1–0.9) for the ESS. These constraints shape set-points and participation factors so that fast support never violates thermal or energy envelopes.

The constraint-aware tuning workflow begins with verification of current and voltage envelopes and SOC/PCS margins. All quantities are normalized on the PCC base (per-unit), and pre-fault operating points such as unity or scheduled power factor are confirmed. For the PMSG constant-current switching, switching coefficients and the id/iq priority logic are calibrated so that “priority reactive” delivers a rapid iq rise within the over-current boundary and smoothly returns to near-unity power factor after clearing. Anti-windup and rate limits are enabled. For the STATCOM, inner and outer PI controllers are tuned for bandwidth and damping against weak-grid impedance, and then a repetitive controller (RC) is added as an internal model for periodic ripple to improve current tracking and shorten settling. For ESS–STATCOM thresholds with hysteresis, a voltage-state severity index is built that maps sag depth $\times$ duration to four levels (dead-band, normal, enhanced,

emergency). Hysteresis is set for engagement and withdrawal to avoid chattering, ensuring that ESS acts first for speed and that STATCOM follows as severity crosses higher levels to provide capacity and stiffness.

The coordination logic ensures that during mild events, the ESS contributes small, short-duration reactive injections, whereas for deeper and longer sags the STATCOM takes over the rigid var duty while ESS output is clipped by PCS and SOC constraints. The sequencing yields smoother voltage profiles and avoids premature storage saturation or converter clipping.

To enhance robustness for real grids, SOC-sensing droop or distribution reduces ESS share as SOC approaches its bounds, allowing the STATCOM to assume the rigid component and preserve storage lifetime. For unbalance and harmonics, dual synchronous reference frames for positive and negative sequence and multi-resonant compensators are applied to maintain tracking under asymmetry and THD without altering the tiered sequencing. For measurement and synchronization, PLLs are strengthened and hysteresis is retained in thresholds to mitigate false re-entries under noisy voltages.

The test protocol and KPIs are validated in EMT by applying non-metallic shorts, such as a grounding inductance of approximately 0.08 H for 0.2 s at $t = 3$ s in the PMSG case, and staged 0.8 and 0.6 p.u. sags between $t = 1.5$ s and $t = 1.6$ s in the 100 MW DFIG + STATCOM case. For each run, the recorded metrics include minimum PCC voltage, recovery time to a tight dead-band, active-power oscillation amplitude and damping, and saturation flags such as converter current hits and SOC boundary touches. The coordinated strategy deepens trough relief, shortens recovery, and reduces single-unit saturation risk, while staying within voltage and SOC limits.

Scenario-specific optimizations further refine the strategy. In deep sags of long duration, STATCOM participation thresholds are raised one level lower (earlier), and the ESS is kept in enhanced or emergency mode briefly before tapering via SOC-aware droop to prevent storage “over-investment.” In mild and short events, the ESS alone handles support within the normal level while the STATCOM remains in stand-by, avoiding unnecessary switching. For periodic versus broadband disturbances, RC weight is increased when ripple is periodic, while broadband or random perturbations are handled by pairing RC with adaptive filtering or supervisory logic to prevent amplification outside the internal-model band.

Operational verification and lifecycle measures go beyond EMT regression by deploying a digital-twin check that compares live responses with the calibrated model. On deviation, anomaly detection is triggered and policy degradation is applied, such as lowering ESS level, raising STATCOM share, or disabling RC if spectra mismatch. Progression to HIL and field pilots is recommended to incorporate measurement and communication delays, thermal limits, and asymmetric faults, with the engineering loop organized as “model calibration → regression → HIL → field roll out → feedback.”

5. Conclusion

This study addressed PCC voltage stability on weak grids by assembling a three-tier, constraint-aware control stack and validating it under representative EMT scenarios. At the unit layer, the PMSG grid-side converter applies constant-current switching, prioritizing i_{q_q} during sags and returning to near-unity power factor after clearance, always within the converter’s over-current envelope; at the plant layer, a STATCOM regulated by dual-loop PI and augmented with a repetitive controller (RC) supplies high-bandwidth, ripple-resistant reactive support; at the storage layer, a supercapacitor-based ESS executes voltage-state-aware, multi-level reactive dispatch. Adaptive thresholds with hysteresis coordinate ESS–STATCOM participation so ESS acts first (speed) and

STATCOM follows (capacity and stiffness), while PCS and SOC limits are enforced as hard constraints. The resulting sequence aligns device bandwidths and capacities with the milliseconds-to-seconds window that governs LVRT and post-fault settling, turning fast disturbances into tractable control tasks without overrunning equipment margins.

The coordinated strategy on the PMSG unit's non-metallic short and the 0.8/0.6 p.u. staged sags on the 100 MW DFIG farm across the modelled non metallic short showed voltage troughs at fault inception then recovered into a tight normal band, active power swing drops in magnitude with shorter dampening times and less saturation events such as converter currents getting clipped or SOC bounds hit since duties were shared in a ratio to each devices' strength and weakness. These results were produced without exceeding converter or store limits and they match the pass/fail conditions connected with LVRT envelopes and device ratings. The evaluation uses clear metrics - minimum PCC voltage, recovery time, oscillation amplitude/damping, and saturation flags - so that any improvement can be followed up directly in the controller activity rather than being due to the luck in the parameters.

Keep implementation practical & portable by tuning workflow “internal before external, constraints before performance”, meaning first verifying current/voltage/SOC envelopes of chosen (volt-ampere)/per-unit PMSG bases, then setting switching coefficients and i_d/i_q priority logic for reactive priority inside the over-current boundary, then tuning STATCOM inner/outer PI and RC internal model-period/band balance, for robust disturbance rejection / stability margins against weak grid impedance, then calibrate and ESS-STATCOM threshold matrix with hysteresis, to avoid chattering and over-investment: This way, we're putting some of those hardware limits directly into the formation of set points and participation factors, so that fast support is never had at the price of the device. also who acts when ESS very one , STATCOM most severe, PMSG always bounded make commissioning and on-site trouble shooting easier to do.

And some sensitivities and some boundaries still. perf depends on thresholds/gains tight threshold = too much storage STATCOM support loose threshold = too little storage STATCOM support So we give like some hysteresis/ratelimiting structures, but this doesn't actually get rid of the tuning. RC is good for periodic disturbances (broadband/random spectra should use an adaptive filter or supervisory logic to guard against amplification outside internal-model band). Finally, the validation is done with simulations; expanding the work into HIL and field pilots with time delays and measurements, with different communication delays, with thermal limits, with different unbalances, different harmonics background (leaving the same coordination logic) would make this work more general and safer for field.

References

- [1] Hu, H. (2023) Exploring the Mutualistic Win-win Mechanism of Industrial Transfer Between China and the Countries Along the Belt and Road. *Croatian International Relations Review*, 29, 43-83.
- [2] Benzohra, O., Echcharqaouy, S.S., Fraija, F. and Saifaoui, D. (2020) Integrating Wind Energy into the Power Grid: Impact and Solutions. *Materials Today: Proceedings*, 30, 987-992.
- [3] Islam, M., Nadarajah, M. and Hossain, M.J. (2019) A Grid-Support Strategy with PV Units to Boost Short-Term Voltage Stability Under Asymmetrical Faults. *IEEE Transactions on Power Systems*, 35, 1120-1131.
- [4] Wang, M., Mu, Y., Jia, H., Wu, J., Yao, X., Yu, X. and Ekanayake, J. (2015) A Preventive Control Strategy for Static Voltage Stability Based on an Efficient Power Plant Model of Electric Vehicles. *Journal of Modern Power Systems and Clean Energy*, 3, 103-113.
- [5] Morgan, E.F., Abdel-Rahim, O., Megahed, T.F., Suehiro, J. and Abdelkader, S.M. (2022) Fault Ride-Through Techniques for Permanent Magnet Synchronous Generator Wind Turbines (PMSG-WTGs): A Systematic Literature Review. *Energies*, 15, 9116.

- [6] Zou, M., Wang, Y., Zhao, C., Xu, J., Guo, X. and Sun, X. (2023) Integrated Equivalent Model of Permanent Magnet Synchronous Generator Based Wind Turbine for Large-Scale Offshore Wind Farm Simulation. *Journal of Modern Power Systems and Clean Energy*, 11, 1415-1426.
- [7] Geng, H., Li, S., Zhang, C., Yang, G., Dong, L. and Nahid-Mobarakeh, B. (2016) Hybrid Communication Topology and Protocol for Distributed-Controlled Cascaded H-Bridge Multilevel STATCOM. *IEEE Transactions on Industry Applications*, 53, 576-584.
- [8] Daoud, M.I., Massoud, A.M., Abdel-Khalik, A.S., Elserougi, A. and Ahmed, S. (2015) A Flywheel Energy Storage System for Fault Ride Through Support of Grid-Connected VSC HVDC-Based Offshore Wind Farms. *IEEE Transactions on Power Systems*, 31, 1671-1680.
- [9] Ou, R., Xiao, X.Y., Zou, Z.C., Zhang, Y. and Wang, Y.H. (2016) Cooperative Control of SFCL and Reactive Power for Improving the Transient Voltage Stability of Grid-Connected Wind Farm with DFIGs. *IEEE Transactions on Applied Superconductivity*, 26, 1-6.
- [10] Kuang, H., Zheng, L., Li, S. and Ding, X. (2019) Voltage Stability Improvement of Wind Power Grid-Connected System Using TCSC-STATCOM Control. *IET Renewable Power Generation*, 13, 215-219.