symmetry

Editorial

Special Issue: New Power System and Symmetry

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Global challenges such as fossil energy depletion, environmental pollution, and climate warming are driving the rapid development of renewable energy sources (RESs), including wind power and photovoltaics [1–3]. However, the increasing integration of these RESs has significantly altered the structure and operational characteristics of power systems. The variable and uncertain nature of RES outputs exacerbates disturbances that compromise power symmetry and balance [4,5]. Although power-electronic-interfaced sources offer flexible and fast regulation capabilities, their limited immunity to grid disturbances may further amplify the degree of power asymmetry and imbalance [6–8]. Consequently, maintaining power symmetry and balance poses a substantial challenge in the evolving new power system. To address this pressing issue, this Special Issue, titled "New Power System and Symmetry", presents advanced perception, cognition, and decision-making technologies aimed at restoring and preserving system symmetry.

The contributions assembled in this Special Issue present novel approaches for strengthening power system symmetry and balance from multiple angles. The mechanisms and characteristics underlying power asymmetry and imbalance are thoroughly analyzed. Furthermore, flexible resources within the new power system, particularly energy storage systems, are leveraged to bolster power symmetry and balance. Scenario generation methods are proposed to handle the inherent uncertainty of RESs, thereby enabling the extraction and characterization of disturbances affecting system symmetry. Additionally, data-driven artificial intelligence techniques are employed for precise assessment and robust control. Taken together, these studies deliver profound insights into the origins, assessment, and mitigation of symmetry-related issues in modern power systems.

A total of 14 manuscripts were submitted to this Special Issue. After a thorough and rigorous peer-review process, eight papers were finally accepted for publication. The following paragraphs provide a concise overview of the primary goals and principal results of these selected contributions.

Contribution 1 presents a probabilistic evaluation framework for determining the renewable energy hosting capacity of power grids, explicitly accounting for the stochastic nature of load and wind generation while upholding supply–demand symmetry. A tenth-order Gaussian mixture model is adopted to accurately characterize the probability distributions of load and wind power, achieving a favorable balance between modeling fidelity and computational cost. The Metropolis–Hastings algorithm, grounded in Markov chain Monte Carlo theory, is subsequently applied to generate representative sample spaces, which are then fed into power flow studies to derive the maximum allowable renewable

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penetration under static security limits. Validation against Monte Carlo simulations and Gibbs sampling on modified IEEE 39-bus and 102-node AC–DC hybrid testbeds confirm the method's high accuracy and efficiency, yielding maximum hosting capacities of 1054.87 MW and 1250.91 MW, respectively. Additional short-circuit ratio evaluations and N-1 contingency simulations corroborate the system's voltage stability and robustness at elevated renewable penetration levels.

Contribution 2 introduces a data-driven dynamic security assessment (DSA) methodology that leverages a grid partitioning strategy to construct accurate and incrementally updateable DSA models with streamlined architectures. The power network is autonomously segmented into localized zones via the mean shift algorithm, wherein node positions are encoded by a symmetric electrical distance matrix and the Chebyshev distance metric is employed to enhance partitioning quality by approximately 50%. Operating-condition features are subsequently extracted using a stacked denoising autoencoder, while the symmetric electrical distance matrix is tailored to encode fault locations within each subregion, thereby mitigating feature redundancy. Multiple radial basis function neural network (RBFNN)-based DSA models are then established for fault positions per region, complemented by an online incremental update mechanism that prevents catastrophic forgetting. Evaluations on both a 112-bus simplified provincial network and a 2624-bus large-scale practical system in China, conducted with PSS/E, reveal that the partition-based RBFNN model attains 98.96% accuracy, surpassing unified models with more complex architectures. The incremental update strategy preserves over 98% accuracy while curtailing update time to 30 s, underscoring its suitability for online preventive and restorative control applications.

Contribution 3 formulates an optimal dispatching model for multiple pumped hydro storage (PHS) stations to supply operational flexibility across distinct regions of East China's state grid, responding to the escalating randomness and flexibility requirements imposed by high renewable penetration. The credible predictable power of renewables is first derived from forecast data, and system flexibility demand is defined as the net-load variation per unit time, giving rise to a multi-timescale flexibility quantification model. A refined PHS station operation model is subsequently devised, encompassing power limits, mode-transition constraints, start–stop restrictions, minimum run times, and reservoir capacity limits with differentiated hydro-conversion efficiencies. In light of regional allocation constraints, a decentralized multi-PHS model is established, and flexibility provisions to each region are quantified via allocation ratios. The overarching objective is to minimize the mismatch between flexibility supply and demand across all regions. A case study on an East China regional grid comprising 10 PHS stations with a combined capacity of 13,700 MW verifies that the proposed approach effectively aligns flexibility supply with regional demand while respecting actual PHS operating characteristics. Comparative economic analysis further demonstrates that the optimal dispatching strategy substantially lowers flexibility supply costs relative to thermal-only or manual dispatch benchmarks, confirming its effectiveness and superiority.

Contribution 4 puts forward a novel multi-agent deep reinforcement learning (MADRL) framework for automatic generation control (AGC) in interconnected power systems, tackling the dual challenges of active-power symmetry preservation and frequency stability maintenance under high RES penetration and system expansion. The core innovation is a Learning to Coordinate and Teach Reinforcement (LECTR) mechanism, through which expert agents from the original system offer demonstration actions to guide novice agents in newly incorporated regions, expediting strategy-network convergence by 58.73% to 75.01% while enhancing control precision. A double-target critic network with delayed updates is introduced to curb overestimation biases in the target critic, improving learning stability and yielding higher-quality experience data. The cooperative reward function integrates area control error, frequency deviation, and tie-line power into steer agent training. Simulations on expanding IEEE test systems subject to step-load variations and stochastic renewable disturbances reveal that the proposed method reduces mean absolute area control error (ACE) by 54.93% to 84.80% relative to alternative algorithms, achieves superior reward performance, and sustains robust convergence and control efficacy without necessitating retraining of all regional agents, attesting to its viability for real-time frequency regulation in flexibly extensible power grids.

Contribution 5 presents a scenario construction methodology that preserves spatiotemporal correlations among multiple renewable generation outputs, overcoming the limitations of conventional approaches that neglect such interdependencies and thus inadequately represent the distributional attributes of original data. The framework first defines a symmetric spatial correlation matrix and a temporal autocorrelation matrix to quantitatively encode spatiotemporal relationships. Distributional discrepancies between typical and original scenarios are subsequently characterized across mean, variance, spatial correlation, and temporal autocorrelation dimensions, and a scenario-reduction optimization problem is formulated to minimize these disparities. An enhanced genetic algorithm, featuring adaptive parameter tuning and an elitist preservation strategy, is developed to efficiently derive high-quality representative scenarios. Case studies on five wind farms and fourteen photovoltaic installations in Belgium demonstrate that the improved genetic algorithm achieves accelerated convergence and superior solution quality, producing four representative scenarios within three minutes. The mean absolute percentage error between spatial correlation matrices of original and reduced sets is 2.5% for wind farms and 0.78% for PV plants, while the corresponding errors for first-order temporal autocorrelation coefficients are 2.75% and 2.45%, respectively, confirming that the constructed scenarios faithfully preserve both spatial and temporal dependencies inherent in the original data.

Contribution 6 devises a self-adaptive virtual synchronous generator (VSG) control strategy for PV hybrid energy storage systems (PV-HESS), leveraging a radial basis function (RBF) neural network to dynamically optimize inertia and damping parameters in response to the erosion of dynamic symmetry induced by high renewable penetration. The DC-side storage architecture incorporates a passive filter to decouple high- and low-frequency power components, with supercapacitors mitigating fast fluctuations and batteries smoothing slow variations. A small-signal model of the VSG active-power loop is established to delineate permissible ranges for rotational inertia and damping coefficient, considering cutoff frequency, grid-code requirements, stability margins, and frequency-response time. The RBF network takes angular frequency deviation and its derivative as inputs to adaptively adjust these parameters within optimal bounds, with a sigmoid activation function enforcing physically realizable inertia values and a damping ratio of 0.75 set as the design target. The simulations under power-supply–demand imbalance and grid-frequency disturbance scenarios reveal that the RBF-based strategy substantially outperforms both fixed-parameter and linear adaptive alternatives, achieving respective improvements in power overshoot, settling time, and fluctuation range of 52.7%, 50.1%, and 59.4% under power imbalance, and corresponding frequency-domain enhancements of 68.18%, 41.02%, and 70.37% under frequency disturbances, thereby confirming superior transient response, oscillation damping, and overall system robustness.

Contribution 7 proposes a hybrid model- and data-driven optimization framework for emergency load shedding (ELS) in receiving-end power systems following HVDC blocking incidents, addressing frequency security concerns while honoring transient frequency, rotor-angle, and voltage stability constraints. An ELS decision model is first constructed, incorporating both conventional loads and pumped-storage units, with continuous load-shedding variables and discrete pumping-cut decisions, and seeks to minimize control costs under dynamic security constraints. The particle swarm optimization (PSO) algorithm is augmented with symmetric opposite learning to boost initial-population diversity and Tent chaotic mapping to broaden the exploration space, thereby elevating solution quality. A hybrid neural-network-based multi-task DSA model is established to rapidly screen candidate ELS schemes during optimization iterations, with time-domain simulations serving as a validation anchor for initial and final solutions to guarantee feasibility. Testing on a provincial receiving-end grid featuring 132 buses, 29 generators, and three HVDC lines totaling 20 GW infeed capacity shows that the enhanced PSO outperforms traditional PSO, adaptive PSO (APSO), hierarchical PSO (HPSO), mutated PSO (MPSO), differential evolution (DE), and genetic algorithm (GA) in solution quality. The hybrid neural network attains a 98.67% assessment accuracy, markedly surpassing artificial neural network (ANN) (93.56%), support vector machine (SVM) (89.00%), and decision tree (DT) (86.77%). The proposed approach yields a viable, least-cost ELS scheme within 0.63 s, representing an approximately 541-fold improvement in optimization efficiency relative to TDS-dependent PSO, while retaining robust generalization to unseen operating conditions with over 92% accuracy at a 1:1 generalization ratio.

Contribution 8 presents a disturbance location-aware coordination framework for frequency support in low-inertia power systems populated by heterogeneous converter types, directly confronting the symmetry-breaking phenomenon whereby post-fault nodal frequency responses are contingent upon disturbance location, network topology, and the coexistence of synchronous generators, grid-forming (GFM) converters, and grid-following (GFL) converters with phase-locked loops (PLLs). The core element is a heterogeneous nodal frequency response (HNFR) state-space model that consolidates SG/GFM electromechanical frequency channels and GFL PLL-estimated frequencies into a unified output matrix, eliminating algebraic network variables via reduced-order representation while explicitly retaining disturbance location as an input dimension for scalable analysis. A reproducible signal-processing protocol is established to compute nodal rate of change of frequency (RoCoF), nadir, and frequency-split indices, facilitating large-scale location sweeps through atlas-ready matrices amenable to high-performance computing. A robust min–max allocation formulation determines GFM virtual-inertia and droop settings across disturbance locations subject to device limits and a fixed aggregate budget. This is complemented by an atlas-based gain-scheduling workflow that obviates online disturbance localization. The atlas functions as a pre-validated repository of frequency-support gain configurations keyed to operating conditions and can be retrieved online without re-optimization. Simulations on a modified IEEE 39-bus system with three wind farms and four tunable GFM buses under a six-location disturbance sweep confirm that the HNFR-based allocation bolsters worst-node security and curtails frequency split while preserving comparable center of inertia (COI) behavior. Under budget-matched conditions, the proposed allocation diminishes worst-node RoCoF by 32.2% and maximum nodal frequency split by 17.8% relative to the COI-oriented benchmark, with a more modest 0.0036 Hz nadir improvement, evidencing that the HNFR formulation effectively resolves localized stress patterns and affords enhanced protection to stressed nodes over aggregated-frequency methods, although RoCoF gains exhibit greater scenario dependence than nadir and split improvements.

Collectively, the eight papers featured in this Special Issue have made notable contributions to the study of power system symmetry. It is our hope that this collection will provide a valuable reference and inspire further inquiry in the field. Future research avenues may include the application of large language models (LLMs) to the assessment and enhancement of system symmetry, as well as a more detailed consideration of the dynamic effects of power electronic converters, particularly GFM and GFL types.

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