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Transmission-Targeted Demand-Side Response for Congestion Relief: A Systematic Review

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Abstract

Variable renewable energy sources and cross-zonal trades stress transmission grids, pushing them toward thermal limits. This systematic review, reported in accordance with PRISMA 2020, examines how demand-side response (DSR) can provide relief at the transmission scale. We screened peer-reviewed literature and operator documentation, from 2010 to 2025, indexed in Web of Science, Scopus, and IEEE Xplore; organized remedial actions across supply, network, and demand/storage levers; and categorized operational attributes (time to effect, spatial targeting, activation lead times, telemetry, and measurement and verification). Few reviewed sources explicitly link DSR to transmission congestion relief, highlighting the gap between its mature use in frequency and adequacy services and its still-limited, location-specific application on the grid. We identify feasibility conditions, including assets downstream of the binding interface, minute-scale activation, and feeder-grade baselines with rebound accounting. This implies the following design requirements: TSO–DSO eligibility registries and conflict resolution, portfolio mapping to power-flow sensitivities, and co-optimization with redispatch, HVDC, topology control, and storage within a security-constrained optimal-power-flow framework. No full-text risk-of-bias assessment or meta-analysis was undertaken; the review used English-only title/abstract screening. Registration: none. Funding: none.

Keywords: transmission congestion; demand-side response; N-1 security; PTDF/LODF; redispatch and countertrading; PST/FACTS/HVDC; dynamic line rating; remedial action schemes; TSO–DSO coordination; measurement & verification

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1. Introduction

Congestion in transmission networks occurs when scheduled or actual power transfers exceed the secure limits of lines or transformers under N-1 operating criteria [1]. Although often perceived as a thermal constraint, in high-voltage systems ($\geq$400 kV) the binding limits are frequently defined by voltage- and angle-stability margins [2]. Managing congestion, therefore, requires both preventive and curative actions that maintain the reliability and economic efficiency of interconnected grids.

In European market coupling, congestion control combines preventive capacity calculation with curative redispatch and counter-trading in day-ahead and intraday markets. Details of these mechanisms are discussed later in Section 3, while this Introduction focuses on their relation to transmission-side flexibility.

Demand-side response (DSR) denotes measurable and intentional adjustments of electricity use in reaction to price signals or operator instructions [3]. DSR is established for

balancing and adequacy purposes, yet its direct application to relieve transmission congestion remains rare [4–6]. The main limitations include limited spatial granularity of aggregation, uncertain activation reliability, and insufficient verification procedures during short-notice events.

Alongside conventional AC operation, hybrid AC/DC grids and HVDC systems (LCC/VSC) increasingly influence congestion patterns by providing controllable transfers and fast corrective set-point adjustments [7,8]. These developments form the technological backdrop for the present review, which focuses on transmission-targeted DSR as an emerging remedial tool.

This paper reviews the state of research on DSR for transmission-network congestion relief, identifies key methodological trends and knowledge gaps, and outlines implications for TSOs, DSOs, and policy makers. Section 2 describes the review methodology and PRISMA workflow; Section 3 summarizes the operational context of congestion management; Section 4 compares remedial actions on the supply, network, and demand sides; Section 5 synthesizes DSR approaches and their applicability; Section 6 discusses implications and future research; and Section 7 provides the conclusion.

2. Materials and Methods

2.1. Review Design and Reporting

This review adheres to the PRISMA 2020 guidelines [9] (study selection summarized in Figure 1). A completed PRISMA 2020 Checklist is provided in the Supplementary Materials (File S1). No protocol was prospectively registered.

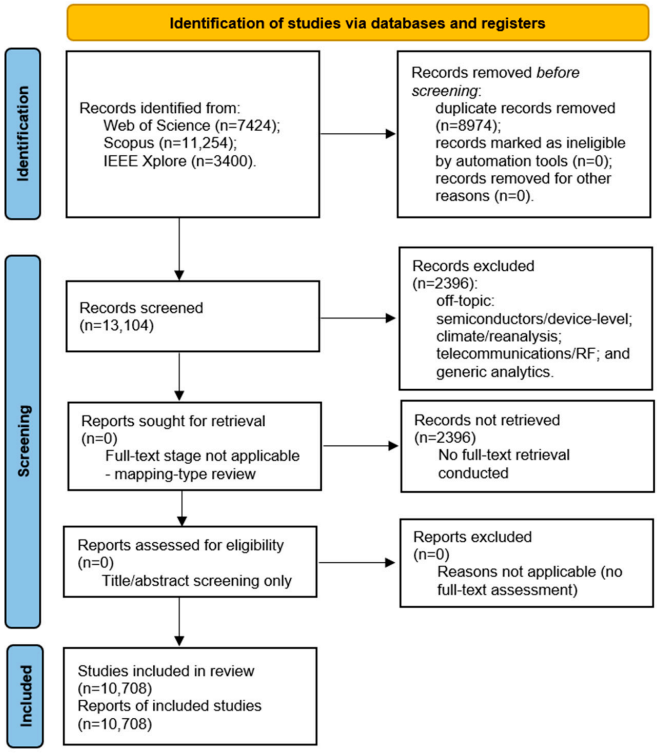


Figure 1. PRISMA 2020 flow diagram (databases & registers only). Searches were conducted on 10 September 2025 in Web of Science, Scopus, and IEEE Xplore with filters for English, years 2010–2025, and Article/Review. Records identified: 22,078 (WoS: 7424; Scopus: 11,254; IEEE: 3400). Duplicates removed: 8974. Records screened: 13,104. Records excluded: 2396. Studies included in the review: 10,708. Exclusion reasons at screening: semiconductors/device-level materials; climate/reanalysis; telecommunications/RF; and generic analytics unrelated to power-system operation. No separate full-text eligibility stage was undertaken (reports sought/assessed = 0).

2.2. Information Sources and Eligibility Criteria

Three bibliographic databases were searched, as follows: Web of Science Core Collection (WoS), Scopus, and IEEE Xplore. In addition, institutional sources (TSO and market-operator reports, national/regional regulators, ENTSO-E, and EU documents) were consulted to clarify terminology and program designs. These sources were used qualitatively and are not counted in the PRISMA flow.

The eligibility criteria were defined as follows: publication years 2010–2025 (inclusive; search freeze: 10 September 2025), English language, and the following document types: Article or Review. The topical focus required an explicit link to demand-side response/flexibility (DSR) and transmission-level congestion/constraints (identified via the title/abstract/keywords). Non-scholarly items (e.g., standards and editorials) and off-topic studies that did not address demand-side response/flexibility in the context of transmission-level congestion/constraints were excluded at screening.

2.3. Search Strategies and Limits

Database-specific field tags and limits were applied, as follows:

- Web of Science (Advanced Search): queries restricted to the categories ENGINEERING, ELECTRICAL & ELECTRONIC; ENERGY & FUELS; and COMPUTER SCIENCE, INFORMATION SYSTEMS, with PY = 2010–2025, LA = English, and DT = (Article OR Review).
- Scopus (Advanced Search): embedded limits PUBYEAR 2010–2025, LANGUAGE = English, DOCTYPE = ar/re, and Subject Areas SUBJAREA $\in$ {ENER, ENGI, COMP} (OR-combined).
- IEEE Xplore (Keyword/Command): text queries executed as written; facets on the results page constrained by Publication Year (2010–2025), Content Type (Journals + Early Access), and Language (English).

For full reproducibility, the exact as-run search strings are listed verbatim in Supplementary Table S1 (File S2).

2.4. Record Identification, Management, and Deduplication

Across databases, we identified 22,078 records (WoS: 7424; Scopus: 11,254; and IEEE: 3400). Deduplication proceeded in the following two steps:

- Step 1 (within-database): Duplicates removed within each source using a deterministic key (DOI, else normalized Title + Year) amounted to 5292 (24.0%) overall, as follows: WoS: 821 (11.1%); Scopus: 3880 (34.5%); and IEEE: 591 (17.4%). After this step, 16,786 unique records remained (WoS: 6603; Scopus: 7374; and IEEE: 2809);
- Step 2 (cross-database): merging the three deduplicated sets, we removed a further 3682 (16.7%) cross-source duplicates (same key), yielding 13,104 unique records for screening.

Totaling both steps, 8974 of the initially identified records (40.7%) were removed before screening.

2.5. Selection Process (Screening)

After cross-database deduplication, 13,104 unique records were screened at the title/abstract level using the rule-based criteria described in Supplementary File S3. Screening proceeded in two steps. First, we looked for positive anchors that indicate power-system relevance, transmission-level congestion/constraints, or demand-side response/flexibility (DSR). If any positive anchors were present, the record was kept. Second, if no positive anchor was found, we checked for strong off-topic signals (materials/semiconductors and lab analytics; climate/reanalysis; telecommunications/RF and net-

working; and related journal-scope hints). Records with strong off-topic signals and no positive anchors were excluded. Exact term lists and precedence rules are specified in Supplementary Tables S2 and S3 (File S3). Screening excluded 2396 (18.3%) records as off-topic, most commonly in the categories listed above, whereas 10,708 (81.7%) were retained for analysis and descriptive mapping. Screening and inclusion decisions were made at the title/abstract level by a single reviewer (P.S.). An automation-assisted, rule-based approach based on keyword/regex lists was used to flag off-topic records (see Supplementary File S3). No separate full-text eligibility stage was undertaken (reports sought/assessed = 0). This review performs descriptive mapping. A brief qualitative appraisal of the methodological quality and potential sources of bias is provided in Section 6. The full flow is presented in Figure 1, which annotates the number of records removed at each step together with the primary reasons for exclusion.

2.6. Topic Tagging and Descriptive Trends

Using the deduplicated dataset, we computed three indicators for 2010–2025. The first covers DSR-related records. The second covers congestion and overload-management records, including N-1 and contingencies. The third is their intersection. Over 2010–2025, DSR appears in 5444 records (50.84% of 10,708), congestion/overload in 3055 (28.53%), and the intersection in 401 (3.74%). Figure 2 shows the annual trajectories (DSR, congestion, and intersection). DSR is shown as bars on the left axis. Congestion is shown as bars on the right axis. The intersection appears as a line and indicates a small but persistent overlap that grows toward 2022 and then eases in the most recent years.

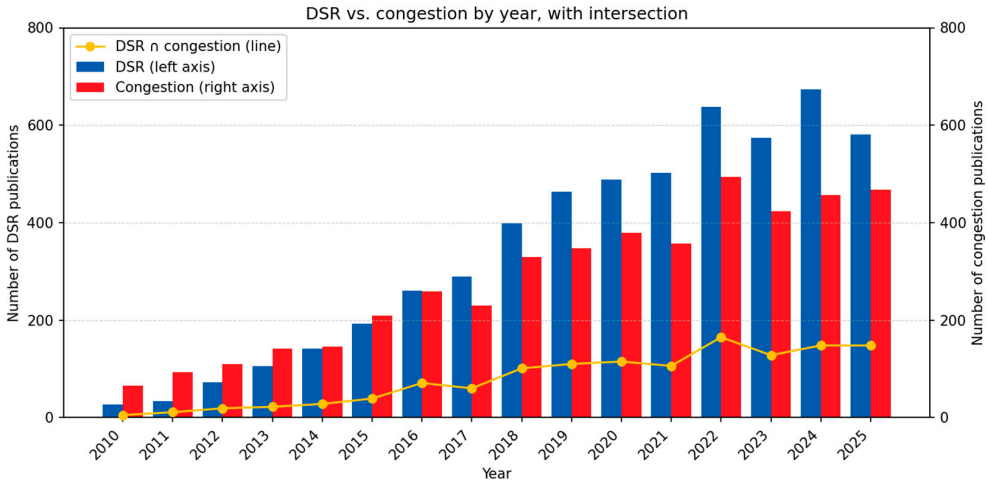


Figure 2. Annual counts of DSR, congestion, and DSR ∩ congestion, 2010–2025.

The trends indicate that research on demand-side flexibility has expanded markedly since 2015, primarily around balancing, aggregation, and market integration, whereas papers that explicitly connect DSR to transmission-level congestion form a comparatively modest subset. In the analyzed corpus of 10,708 records, the DSR-tagged group is much larger than the congestion-tagged group, and their intersection remains limited (≈15% of the total). After 2020, a substantial share of the intersection papers self-identify as pilots or case studies, and about half explicitly mention a TSO-level context. Taken together, these observations reveal clear research gaps: methods that couple DSR activation with locational congestion metrics, auditable measurement and verification under short-notice events, and reliability indicators at the transmission-system scale.

Generative AI was used only to assist the literature search and screening (query refinement and prioritization).

3. Transmission Overloads—Definitions and Impacts

3.1. Mechanisms of Overloads in Meshed Transmission Networks

In high-voltage transmission grids, the binding transfer limit is often set by the small-signal, transient, or voltage stability before the thermal ratings are reached, particularly at 400 kV and above [1,10]. When thermal constraints do bind, resistive heating raises the conductor temperature, increases sag through the thermal expansion, and can erode statutory clearances. At sustained elevated temperatures of around 90 °C and above, aluminum strands are prone to creep and clamp forces in fittings may not prevent permanent elongation, which accelerates irreversible sag and can degrade hardware integrity [11]. Operators distinguish continuous ratings for normal operation and emergency ratings that allow for short exposures. Many TSOs apply a dynamic line rating (DLR), which sets the ampacity based on weather and wind, when safe data assurance is available [12–15].

Power flows in meshed networks follow impedance rather than contractual paths. Parallel-path sharing produces loop and long-distance transit flows that can relocate thermal stress across regions. Even small topological changes or cross-zonal trades may shift bottlenecks far from the initiating transaction. Evidence and measurement frameworks for loop and unscheduled flows are documented in [16–19].

For screening and remedial-action design, operators use linear sensitivity factors. Power transfer distribution factors (PTDFs) map incremental transfers to line-flow changes, while line outage distribution factors (LODFs) quantify redistribution after an element trips. These factors support contingency selection, real-time overload monitoring, and the placement of corrective controls [20,21].

3.2. The N-1 Security Criterion and Operational Standards

The N-1 security criterion requires the system to remain within thermal, voltage, and stability limits after the loss of any single credible element, such as a line, transformer, generator, or HVDC pole. Some policies extend this logic to N-1-1, which considers two sequential credible events within the corrective window. In Europe, these obligations are codified in Commission Regulation (EU) 2017/1485 (SOGL) and implemented through ENTSO-E operational-security guidance [1,2].

Preventive operation keeps pre-contingency flows sufficiently below ratings so that credible events do not violate limits. Corrective operation allows for brief exceedances that must be relieved within emergency exposure times using pre-qualified actions. The corrective toolkit includes redispatch and countertrading between areas, topology switching, and controllable devices, such as phase-shifting transformers, FACTS controllers, and HVDC setpoint adjustments [22–27].

Security-constrained optimal power flow (SCOPF) formalizes these preventive and corrective requirements for planning and real-time decision support. Implementations co-optimize the base case and a selected set of post-contingency states, with PTDF/LODF screening to control the computational burden [28].

3.3. Technical, Economic, and Market Impacts of Overloads

Sustained operation near thermal limits accelerates aging and increases resistive losses. Excessive sag reduces clearances and narrows safety margins during emergency exposure windows. When the corrective headroom is exhausted, thermal constraints interact with voltage control and transient stability, shrinking the feasible operating set and increasing sensitivity to further disturbances [12,13,29].

Short-run economic impacts are driven by the cost of remedial actions required to relieve binding constraints. Redispatch and countertrading change the generation pattern and reallocate flows. Costs often concentrate temporally and locationally during stressed

conditions. Long-run impacts include reduced cross-border transfer capability, weaker price convergence, and distorted investment signals if constraints persist [22,23].

Market representations of congestion differ across designs and lead to distinct observable indicators. In European zonal markets with flow-based market coupling (FBMC), binding constraints reduce cross-zonal capacity, produce persistent price spreads between bidding zones, and generate congestion rents on constrained interfaces [30,31]. The Single Day-Ahead Coupling (SDAC) algorithmic documentation and recent updates on Advanced Hybrid Coupling describe how the Euphemia algorithm uses network constraints provided by TSOs [6,32]. In nodal markets with locational marginal pricing (LMP), congestion is represented directly in nodal prices. The congestion component reflects the shadow values on transmission constraints and is combined with system energy and marginal-loss components to form the total LMP [33–35].

System operators and regulators track indicators, such as redispatch or countertrading cost, price spreads, congestion rents, hours with binding constraints, and curtailed transfers. Representative measurement frameworks are discussed in [30].

4. Methods for Transmission Congestion Elimination—Comprehensive Review

This section reviews actionable methods for eliminating overloads on meshed transmission networks, with emphasis on how they are engineered, controlled, and used in operations. We organize the discussion by system lever, as follows: supply-side measures (redispatch and countertrading), network-side measures (phase-shifting transformers, FACTS, HVDC/MTDC coordination, topology programs, and dynamic line rating), and demand/energy-side measures (transmission-targeted DSR and storage), with a comparative overview provided in Table 1. For each, we outline the control mechanism, time-to-effect, locational targeting, validation and telemetry requirements, operational risks, and typical TSO use cases. The review also covers automated corrective schemes (RAS/SPS), probabilistic risk-based operation, and predictive tools (including ML/GNN) that support early warning and coordinated activation of remedial actions.

4.1. Redispatch and Countertrading (Supply-Side)

Redispatch changes the output of committed generators to unload the limiting element while preserving system balance. Candidate up/down pairs are screened by their sensitivity to the constrained branch and then verified in security-constrained formulations that respect activation times, ramp limits, and unit constraints [20,28,29,36]. When the bottleneck is cross-border or at a bidding-zone boundary, coordinated countertrading achieves the equivalent physical effect through paired energy trades that restore feasible flows without directly altering unit commitment [22,37,38]. European practice specifies responsibilities, data exchange, and settlement in public methodologies and monitoring documents, which makes redispatch and countertrading the default curative tools for zonal markets [2–5,39]. Costs are typically concentrated in stressed periods and rise non-linearly with required relief, which explains the strong interest in complementary network-side measures [22,37,38].

4.2. Phase-Shifting Transformers (PST)

PSTs impose a controllable phase shift across a corridor, altering active-power sharing among parallels and constraining loop flows that would otherwise load the limiting path. They are most effective when placed electrically close to the bottleneck or on high-impact tie-lines, and they remain valuable both as structural assets for chronic constraints and as operational levers for seasonal patterns. In practice, operators compute tap sched-

ules for representative scenarios and adjust them in operations under limits that protect voltage, thermal headroom, and on-load tap-changer duty. Protection and design need attention paid to differential elements, current-transformer placement, and inrush behavior, and cross-border coordination is essential to avoid conflicting actions across control areas [40–47]. PST setpoints can be computed with PTDF-guided programs and validated on AC models to ensure that local relief does not trigger voltage or stability issues elsewhere.

4.3. FACTS Controllers (Series, Shunt, and Unified)

FACTS provide fast, reversible modulation of impedance and voltage that can steer flows away from the limiting element and stabilize the system during corrective actions. TCSC increases the effective series reactance of the stressed path and pushes transfers to alternative paths. Operational experience and performance data are consolidated in CIGRE's review of field devices [48–50]. SVC and STATCOM enhance voltage control and reactive margin, which indirectly frees thermal headroom under reactive stress and improves dynamic stability. Comparative studies show STATCOMs deliver faster support during low-voltage excursions [26,51–53]. UPFC combines series and shunt control to regulate branch power more directly, which is attractive for corridors with limited alternatives but requires careful coordination with protection and neighboring controls [53–58].

4.4. HVDC and Multi-Terminal DC Coordination

VSC-HVDC links deliver controllable transfers with rapid set-point changes and reactive support at terminals, while emerging MTDC systems extend these advantages to multiple ports. In hybrid AC/DC grids, coordinated HVDC orders can bypass congested AC corridors with high temporal precision and reversible effect, provided converter contingencies and terminal–voltage interactions are handled explicitly in procedures and tools and in line with the Network Code on HVDC [59–62]. This controllable DC capability complements PST and FACTS by acting as a flexible "bypass" that can be scheduled curatively without physically altering the AC topology. Beyond operational coordination of existing links, interconnection planning across AC and DC grids adds a programmatic dimension with different siting and controllability trade-offs, as illustrated by recent work on bi-directional converter-based planning in hybrid AC/DC clusters [63].

4.5. Programmatic Topology Changes (Optimal Transmission Switching)

Beyond ad hoc switching, operators can adopt topology programs that plan preventive or corrective reconfigurations over a horizon. Foundational work and recent surveys show that optimal transmission switching can reduce congestion and curtailment materially, yet tractability and AC feasibility remain key challenges. AC-informed DC relaxations and mixed-integer formulations mitigate infeasibility risk while retaining scalability on large systems, and practical deployments include screening rules, limits on the frequency of operations, and explicit penalties on switching activity [24,64–70].

4.6. Dynamic Line Rating (DLR)

DLR recalculates admissible current using ambient conditions and wind cooling, which can unlock significant headroom in temperate and windy regimes. Field deployments demonstrate material gains relative to static ratings, but safe operation depends on conservative data assurance, robust fallback to static values, and explicit treatment of forecast error in procedures and tools [14,71–73]. DLR interacts naturally with risk-aware operation because stochastic ratings can be embedded in decision models rather than treated as fixed limits.

4.7. Remedial Action Schemes (RAS/SPS/SIPS)

RAS implement pre-engineered automatic actions, such as tripping, PST moves, switching, or HVDC orders, once monitored variables cross arming thresholds. Compared with manual redispatch, RAS offer deterministic response times and formal governance for arming logic, performance verification, and failure management. Standards and guidance describe roles, change control, testing, and documentation, which are essential when schemes touch multiple assets or areas [74–76]. Modern schemes are increasingly integrated with HVDC controls and topology programs to create layered defense against overloads.

4.8. Risk-Aware Operation and Probabilistic Security

Operators are shifting from purely deterministic criteria to risk-based decision frameworks that propagate uncertainty in injections, topology, and ratings to actionable indicators used in coordination. European progress reports and decisions describe how probabilistic security assessment and risk metrics are embedded in day-to-day processes and how they interact with remedial actions [4,77,78]. At the modeling level, chance-constrained and risk-aware OPF formulations cap the probability of violating thermal limits while internalizing stochastic ratings such as DLR and variable renewables [79,80].

4.9. Predictive Operations with Machine Learning and Graph Neural Networks

Data-driven early-warning systems identify hours, corridors, and topologies with elevated congestion risk so that operators can pre-arm remedial actions and narrow the candidate set for exact solvers. Recent work uses graph neural networks to forecast flows at the nodal or transformer level and to approximate AC relationships at speed, while other studies build probabilistic risk forecasts and cascade-prediction tools that support situational awareness under extreme events [81–85]. These tools complement, rather than replace, SCOPF and rule-based screening.

4.10. Storage as Fast Corrective Energy

Utility-scale storage injects or absorbs power with fast ramps and bridges the system until slower measures take effect or until the market rebalances. Effectiveness depends on state-of-charge planning, co-scheduling with redispatch, and siting where the PTDF leverage to the constrained element is high. Storage also hedges uncertainty in DSR availability by covering shortfalls against contracted volumes [86,87]. Grid-code requirements at the connection point and energy capacity limit the sustained duration of relief, which is why storage is best used as a corrective buffer rather than a stand-alone substitute for structural constraints.

4.11. Transmission-Targeted DSR

DSR can reduce or shift consumption at locations that are electrically downstream of the constrained element, but the eligible subset is narrow because transmission-level products must satisfy strict locational targeting, short activation lead times, and robust verification at feeder or substation granularity. Open specifications and program guides (e.g., OpenADR 2.0b) codify baseline methods, telemetry, and reporting in ways that TSOs and DSOs can reuse for procurement and measurement and verification [88–92]. In practice, DSR works best as a complement to network-side tools and storage, not as a replacement.

Table 1. Comparative attributes and references of transmission-scale congestion-relief methods.

Method	Mechanism	Time to Effect	Spatial Targeting	Typical Scale	Duration/ Reversibility	Activation Lead Time	Key Operational Caveats	Key References
Redispatch/ countertrading	Change injections	min–h	High with good locations	100–1000+ MW	Sustained within commitments	Market cycle → real-time	Cost concentration, cross-border settlement	[2–5,20,22,23,28,29,36–39,93–97]
PST	Phase shift on corridor	s–min	Very high on targeted ties	50–1000+ MW	Continuous within tap/thermal limits	Scheduling → real-time	OLTC duty, protection specifics, cross-border coordination	[40–47,98–103]
FACTS—TCSC	Series reactance control	<1 s–s	High on equipped branch	10–300+ MW shift	Fully reversible	Real-time	SSR risk, protection tuning	[48–50]
FACTS—SVC/ STATCOM	Shunt reactive control	cycles–100 ms	Indirect via V/Q margin	frees thermal headroom	Reversible, continuous	Real-time	Interaction with AVR/OLTC	[26,51–53,104]
FACTS—UPFC	Unified series + shunt	cycles–s	High on target branch	direct branch-power control	Reversible	Real-time	Control complexity, protection coordination	[53–58]
HVDC/MTDC	Controllable DC transfer	s–min	High at terminals	100–1000+ MW	Reversible, sustained	Real-time	Converter contingencies, voltage interactions	[59–62,105–109]
Topology programs (OTS)	Reconfiguration program	min–real-time	High if AC-informed	corridor-dependent	Reversible by switching back	Dispatch → real-time	Frequency limits, AC feasibility	[24,64–70,110–113]
DLR	Weather-based rating	min–h	Corridor-specific	margin increase	Reversible via fallback	Scheduling	Data assurance, uncertainty	[12,14,71–73,114–117]

Table 1. *Cont.*

Method	Mechanism	Time to Effect	Spatial Targeting	Typical Scale	Duration/ Reversibility	Activation Lead Time	Key Operational Caveats	Key References
Storage	Fast corrective energy	s–min	Locational, PTDF-dependent	10–200+ MW (short)	Limited by energy	Real-time	SoC management, grid code	[86,87,104,118–122]
DSR (transmission-targeted)	Load reduction/shift	min–tens of min	High only for well-located portfolios	5–50+ MW per program	Event-limited	Intraday → real-time	Baselines, telemetry, persistence	[88–92,123–126]
RAS/SPS	Automatic corrective schemes	cycles–s	By design of arming	portfolio-dependent	Deterministic when armed	Real-time	Governance, failure modes	[48,74–76,109]
Risk-aware ops	Probabilistic security/chance constraints	planning → real-time	System-wide	—	—	—	Uncertainty modeling	[4,28,30,77–80,127]
Predictive ops	ML/GNN early warning	h–day-ahead	Corridor-/topology-aware	—	—	—	Data drift, explainability	[23,81–85,128]

5. Demand-Side Response in the Transmission Context

5.1. Definitions and Approaches

Demand-side response (DSR) in the transmission context denotes intentional, measurable changes in electricity consumption, both downward or upward, within defined time frames, triggered either by prices (implicit DSR) or by dispatch/market instructions (explicit DSR), to provide transmission system operator (TSO)-level services, such as frequency containment and restoration, adequacy support, and, where assets are mapped to constrained interfaces, congestion relief. The definition is operational: delivery must be attributable to the instruction, verified by telemetry, and settled against a robust baseline so credited reductions reflect real system value rather than normal variability [129–134]. In Europe, the legal and market frame comes from the System Operation Guideline and the Electricity Balancing Guideline, implemented via the pan-EU platforms FCR Cooperation, PICASSO (aFRR), and MARI (mFRR), which harmonize product definitions, activation times, performance measurement, and cross-border exchange [1,135–138]

Implicit DSR shifts energy across hours through time-of-use (ToU), dynamic/real-time pricing (RTP), and event-based mechanisms such as critical-peak pricing (CPP) or peak-time rebate (PTR). These instruments become transmission-useful when event windows and price formation align with TSO procurement and settlement timelines so observed reductions coincide with periods of system stress rather than creating baseline artefacts [134,139–141]. Explicit DSR participates in FCR/FFR for fast stability and aFRR/mFRR for restoration and balancing, with pre-qualification on dynamic capability, telemetry quality, and performance metrics tuned to product granularity. A smaller set of arrangements admits locational redispatch where portfolios are telemetered at the feeder/substation level and mapped to PTDF/LODF-relevant nodes [135–137,142–144].

A consolidated overview of the identified DSR methods is presented in Table 2. Each category is described together with its operational focus, activation timescale, and representative studies. The table distinguishes between consumer-oriented mechanisms (price- and incentive-based), direct load control, and reserve-type DSR that participate in balancing or capacity markets.

Table 2. DSR service types and representative references.

DSR Type	Short Description	Advantages	Limitations/ Transmission Applicability	Key References
Peak shaving	Targeted reduction in critical peak hours to limit balancing costs and interface stress	Simple deployment, high user acceptance, direct reduction in peak load	Effect is non-locational, congestion relief only if peaks coincide with constrained interfaces	[129,145–162]
Load shifting (ToU/RTP)	Move energy to unconstrained hours and into DA/ID procurement windows	Scalable and market-compatible, smooths demand curve, supports DA/ID alignment	Limited spatial accuracy under zonal pricing, possible rebound effects	[130,143,144,163–184]

Table 2. *Cont.*

DSR Type	Short Description	Advantages	Limitations/ Transmission Applicability	Key References
CPP/PTR (event-based)	High incentives during declared stress windows, settlement vs. baseline	High responsiveness in tight system hours, measurable through event-based baselines	Requires verified baselines and telemetry, locational effect uncertain	[185–204]
Direct load control/interruptible	Deterministic curtailment via control signals or contractually interruptible load	Fast, deterministic, and verifiable; complements redispatch	Requires controllable downstream portfolios, high coordination cost	[205–225]
FCR/FFR/aFRR/mFRR	Frequency-related reserves from aggregated demand	Provides system-wide stability and reliability	Locationally neutral, acts globally, not suitable for targeted congestion management	[205,226–299]
Market-integrated DR (DA/ID)	DR bids co-optimized with energy markets (e.g., NEBEF)	Compatible with market design, aligns with SDAC/IDAs, scalable	Congestion relief indirect, depends on market granularity	[300–320]
RA-countable DR (US)	DR that counts toward resource adequacy (e.g., CAISO PDR/RDRR)	Enhances system adequacy and reliability	Market-specific, focused on capacity adequacy, not network relief	[321–337]

The synthesis shows that most DSR frameworks prioritize economic optimization or balancing services, while only a few are explicitly designed for transmission congestion management. Approaches that incorporate network sensitivity (e.g., PTDF- or LODF-based selection of nodes, feeder or substation mapping) demonstrate the highest potential for TSO integration but require granular telemetry, robust measurement and verification, and activation windows aligned with intraday or real-time constraints. Consequently, DSR can complement network-side actions most effectively when applied to downstream portfolios that exert a measurable impact on the targeted transmission elements. In Europe, market-integrated DSR schemes focus on cross-zonal cost-efficiency and alignment with energy markets, whereas in the United States, resource-adequacy programs emphasize reliability and capacity assurance. Both frameworks remain predominantly market-centric, with limited direct coupling to transmission-congestion indicators.

5.2. TSO vs. DSO—Objectives, Coordination, and Deliverability

Transmission and distribution operators use DSR for different objectives, which drives product design and data requirements. TSOs prioritize system security, including frequency arrest and restoration, N-1 compliance, and thermal limits on internal lines and interconnectors, while distribution system operators (DSOs) focus on voltage quality and local thermal constraints in medium-voltage/low-voltage (MV/LV) networks. Because most flexible assets connect to distribution, the deliverability of a TSO activation depends on structured TSO–DSO coordination, as follows: eligibility registries, conflict checks against DSO operating envelopes, and event tagging that prevents double counting and confirms that a curtailment downstream of a binding interface truly reduces flow

on that interface rather than relocating stress [338,339]. The EU balancing implementation through FCR Cooperation [135], PICASSO [136], and MARI [137] standardizes telemetry minima, gate closures, and performance scoring for aggregators while keeping security constraints—activation times, saturation handling, and fallback behavior—central to market design. Where locational congestion is at issue, operators either require explicit nodal/feeder mapping for portfolios or rely on hybrid setups, such as the Dutch GOPACS platform, that couple DSR to redispatch and network levers so that activation windows match the constraint, not just system-wide scarcity [142–144,340,341].

5.3. Requirements for Transmission-Level Participation

Pre-qualification demonstrates dynamic capability at the product time scale, as follows: sub-second to seconds for FCR/FFR, accurate ramp tracking under automatic generation control (AGC) for aFRR, and sustained delivery over minutes for mFRR. Operators verify minimum bid sizes, sampling frequency, accuracy bands, and fail-safe behaviors, and they re-test portfolios periodically to ensure performance persistence [339,342]. Integration with supervisory control and data acquisition/energy management system (SCADA/EMS) brings telemetry discipline, including secure, high-resolution measurements, event IDs and auditable logs, and, increasingly, phasor measurement unit (PMU) and state-estimator inputs for validation of fast products. These costs are non-trivial but essential for credible settlement [339,342]. Baseline design matters as much as measurement: models must reflect what load would have done absent the instruction and must handle rebound/cold-load pickup to avoid mis-crediting in the event hour and under-crediting in recovery hours. Practical guides and program specifications offer workable baseline recipes and audit trails that TSOs/DSOs can adapt for transmission-grade products [90–92]. From a portfolio perspective, aggregators diversify availability risk by mixing heterogeneous assets, yet they must account for correlated behavior (weather-driven loads and common occupancy patterns) and ensure that contracted capacity is actually downstream of the target interface. Otherwise, activation can net out internally or even create counter-flows [142–144,339].

5.4. Programs Operated by TSOs/ISOs/RTOs

Market-integrated DSR such as France's NEBEF pays for verified energy reductions in day-ahead (DA) and intraday (ID) time frames and treats them as fungible with generation, which improves adequacy and price formation but generally lacks explicit locational mapping to a binding transmission interface [343,344]. Mass-market stress-event programs like Great Britain's Demand Flexibility Service mobilize hundreds of megawatts across a few dozen events per winter and deliver GWh-scale energy relief, yet by design they are system-oriented and not aimed at a specific corridor [345,346]. In the balancing domain, tech-neutral FCR/aFRR/mFRR products in Belgium, the Nordics, and many ENTSO-E members admit DSR alongside storage and generation once measurement and control meet standardized thresholds [131–133]. US markets offer RA-countable DSR (e.g., CAISO PDR/RDRR) and capacity/reserve DR (e.g., PJM), where large C&I portfolios provide dependable megawatts for adequacy and operating reserve even though the products are not explicitly locational at the transmission-constraint level [347–349]. These arrangements create scale and reliability, which is why DSR is now a regular contributor to frequency and adequacy services, but they rarely coincide with the topology-specific timing required for curative congestion management. A program-level summary is provided in Table 3.

Table 3. TSO/ISO/RTO DSR programs.

Region/TSO	Product (Type)	Primary Objective	Typical Assets	MW (Latest)	Key References
Poland-PSE	IRP/IZP	Adequacy & short-notice relief	Large C&I via aggregators	~950 (2022)	[350–352]
France-RTE	NEBEF (market-integrated)	DA/ID demand reductions	≥100 kW industrial/commercial	~1100 (indicative)	[343,344]
Belgium-Elia	FCR/aFRR/mFRR	Frequency & restoration	Mixed portfolios	—	[353,354]
Netherlands-TenneT NL	aFRR aggregation (pilot), GOPACS	Demonstrate deliverability, local CM	Heat pumps, EVs, CHP	multi-MW	[340,341]
GB-NESO	DFS (energy-based)	Peak shaving in stress events	Mass-market via suppliers	3.7 GWh, >400 MW peak (2023/24)	[345,346]
Nordics (SvK, Fingrid, Statnett, Energinet)	FCR-N/FCR-D /aFRR/mFRR/FFR	Low-inertia stability	Mixed flexible loads	e.g., SE ~147 MW (22/23)	[355–359]
USA-PJM	DR in RPM & reserves	Adequacy & operating reserve	C&I portfolios	8065 MW UCAP (DY24/25)	[360,361]
USA-MISO	Demand-side Response types	Ancillary	C&I via aggregators	~12,700 (2023)	[362]
USA-ERCOT	LR/CLR	Ancillary & scarcity	Large industrial	events >3500 MW	[363–365]
USA-CAISO	PDR/RDRR (RA-countable)	Adequacy & event DSR	Aggregated C&I/res	~1400 MW RA (2024)	[347–349]
USA-ISO-NE	Price-responsive demand	Market-integrated DSR	Large C&I portfolios	~436 MW (2023)	[366]
Canada-AESO	FFR (ex-LSSi)	FFR (ex-LSSi)	FFR (ex-LSSi)	-	[367–369]
Australia-AEMO	WDRM, RERT	Wholesale DSR, emergency	DRSP portfolios	~74 MW WDR (2025)	[370–372]

5.5. Comparative Analysis: Dominant Objectives and the Narrow Role in Congestion Relief

The weight of evidence shows that DSR's dominant contributions in transmission operations are frequency services and adequacy support, which are largely system-wide by construction and, therefore, insensitive to the exact network location of participating loads [131–133,373]. Program evaluations and market monitoring in Europe and North America report sizeable delivered energy and dependable capacity, especially during stressed conditions, which supports the case for continued expansion of explicit DSR in balancing and adequacy products [230,374–376]. Yet where the objective is to eliminate a thermal overload on a specific corridor, DSR faces much tighter constraints: assets must be demonstrably downstream of the binding interface, activation windows must match the constraint's time profile, and baselines must be granular enough to isolate the causal effect of the instruction. Peer-reviewed studies confirm that DSR can participate in congestion management when these conditions hold—often as part of co-optimized schemes with redispatch, network reconfiguration, and storage—but the eligible subset of portfolios is narrow compared with balancing markets [123,125,126]. Re-

cent system-level analyses also show that the cost drivers of congestion and redispatch are highly locational and non-linear, which helps explain why TSOs continue to rely primarily on PST/FACTS/HVDC/topology programs for curative relief and treat DSR as a complement that fills specific gaps where industrial loads with strong PTDF leverage are present [23,377,378].

6. Discussion

Figure 3 provides a visual overview of the review framework and the thematic relationships that structure the discussion.

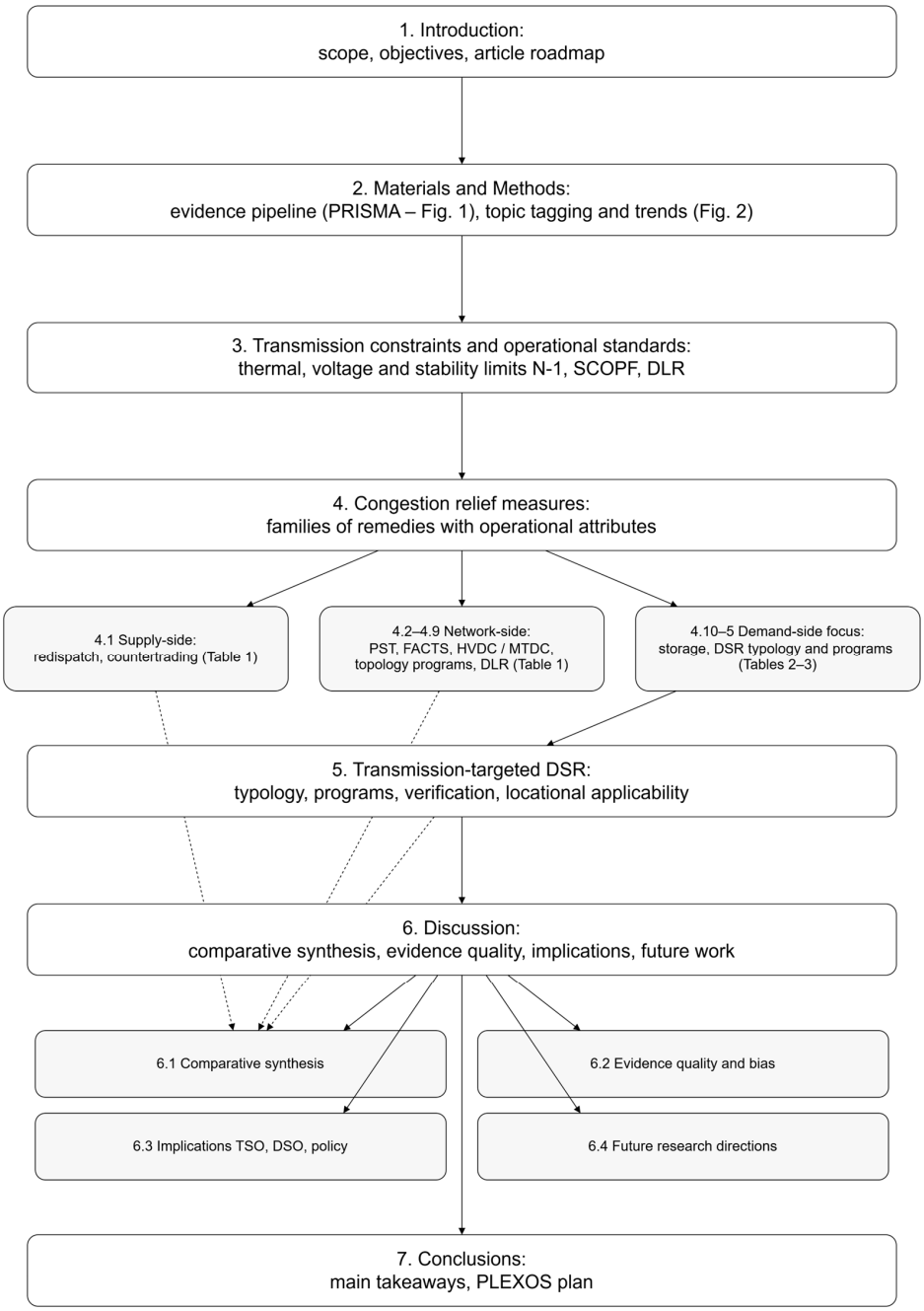


Figure 3. Article structure and thematic flow. Sections 2–7 form a single path from methods and context to remedies, DSR, discussion, and conclusions. Solid arrows show the main narrative. Dashed arrows show how the families in Section 4 and the DSR track in Section 5 feed the comparative synthesis in Section 6.1.

The review is constrained by the heterogeneity of publicly available reporting and by the mixed nature of the evidence base. The corpus combines simulation studies, operator notes, pilot evaluations, and market documentation. This mix is valuable for operational insight, yet it complicates comparisons across contexts and limits strong claims about effect sizes. The discussion integrates the main findings and explains what they imply for practice, policy, and research.

6.1. Comparative Perspective Across Supply, Network, and Demand Measures

This subsection contrasts supply-, network-, and demand-side remedies by what they control, how fast they act, and how precisely they target a constraint.

Supply-side and network-side instruments continue to dominate practical congestion relief. Redispatch and countertrading provide predictable impact within short time frames and can be aligned with security constraints. Topology optimization, phase-shifting transformers, FACTS, dynamic line rating, and HVDC coordination increase the controllability of flows or transfer capability, which explains their prevalence in transmission operators' toolkits. These measures act directly on injections, impedances or controllable set-points and therefore address network constraints with high locational specificity.

Demand-side response is mature for balancing and adequacy, yet its explicit and locational use for transmission congestion remains uncommon. Price-based and event-based schemes scale well and are cost-effective; however, their influence on location is indirect under zonal market arrangements. Direct load control and interruptible contracts can deliver fast and verifiable reductions, but their usefulness for congestion depends on whether contracted portfolios are electrically downstream of the constrained elements and whether activation windows match the temporal profile of the constraint. Reserve-type DSR contributes to frequency performance at the system level and is not designed to target specific corridors, which limits its direct value for transmission overloads. In practice, DSR is most credible when it complements network measures, shapes net injections near binding interfaces, and reduces curative actions where verification is auditable and timing is aligned with operational processes. At 400 kV and above, stability limits can bind before thermal ratings. Shifting energy out of sensitive periods preserves margins only when activation coincides with those stability constraints.

6.2. Evidence Quality and Bias Considerations

Study quality varies across the corpus and reflects the contexts in which evidence is produced. Selection often favors portfolios with existing telemetry and controllability, which narrows generalizability to diffuse or small loads. Intervention fidelity depends on auditable baselines and on short-notice activation that is visible in event data. Outcome reporting is uneven because many sources do not disclose delivered versus requested megawatts, success rates, or event timestamps with sufficient resolution. Reporting can be incomplete when null or negative activations are omitted. External validity is narrow where results come from a single transmission operator, a specific market product, or a national code that does not transfer to other jurisdictions. Simulation studies offer design insight but require security-constrained network models to capture locational effects. Field evaluations bring operational relevance, although measurement and selection risks remain where metering and documentation are limited. These constraints do not invalidate the evidence; they motivate conclusions that focus on feasibility conditions, verification needs, and integration with operator workflows.

6.3. Implications for Practice and Policy

For TSOs, the most reliable use of DSR arises when flexible portfolios can be mapped to the electrical areas that drive a constraint and when activation is timed within intra-

day and real-time processes. Simple location evidence that links portfolios to feeders or substations reduces the risk of netting-out effects and supports settlement. Event-level records that include timestamps and requested and delivered megawatts make outcomes auditable and allow operators to learn across repeated activations. In operational planning, DSR should be treated as a complement to redispatch, topology actions, and controllable transfers. Co-optimization across these levers reduces total curative cost and preserves headroom where constraints are recurrent.

Distribution operators enable transmission-targeted DSR by maintaining registration of flexible resources with feeder or substation attachment and by validating baselines with telemetry that operators can audit. Even lightweight data that confirm the timing and magnitude of the response increase trust in delivered relief and support cross-boundary coordination without exposing sensitive customer information.

Policy and market design can make targeted DSR usable by defining simple contractual products for congestion relief alongside market-integrated schemes. Clear measurement and verification rules reduce dispute risk and lower entry barriers for aggregators. Standardized disclosure of anonymized event summaries improves transparency and creates a shared evidence base for benchmarking. Consumer protection and data governance remain essential. Location evidence and telemetry can be handled through tiered access and aggregation, which balances operational needs with privacy.

6.4. Future Research Directions

Future work should link activation decisions to congestion indicators in ways that are simple to audit. Publishing event-level datasets with timestamps, requested and delivered megawatts, baseline method and validation, and minimal location evidence relative to constrained elements would raise the standard of empirical evaluation. Co-optimization models that integrate DSR with redispatch, topology actions, and controllable transfers are needed, with timelines that mirror real activation processes and with explicit treatment of delivery uncertainty. The interaction between timing, rebound, and stability or voltage margins on extra-high-voltage backbones remains under-documented and merits targeted study within intraday horizons. Scalable verification methods that rely on lightweight telemetry and transparent baselines would widen the usable resource pool while keeping auditability. Finally, institutional interfaces deserve comparative analysis. Clear procedures for TSO–DSO coordination, layered data access, and product definitions can turn isolated pilots into repeatable services, and cross-jurisdiction studies can separate design features from local context.

7. Conclusions

Building on the discussion, this section summarizes the main conclusions and the operational implications that follow from the evidence.

This review mapped how demand-side response (DSR) is used for transmission congestion relief and organized the findings in an operational perspective. The literature shows that targeted flexibility can relieve network constraints in specific settings, yet documented use remains limited and strongly context-dependent. Credible use depends on three recurring conditions. Resources need to be electrically downstream of the constrained element, with simple location evidence that relates portfolios to PTDF or LODF impacts. Activation must be verifiable at the event level, with clear timestamps, requested and delivered megawatts, and a transparent baseline method. Timing needs to overlap hours in which constraints bind within intraday and real-time processes.

In this setting, DSR is a complement rather than a substitute for network and supply measures. The most robust value appears when DSR is co-optimized in a security-

constrained optimal power flow (SCOPF) together with redispatch, topology actions, phase-shifting transformers, FACTS, HVDC coordination, and dynamic line rating. When portfolios are mapped to the electrical areas that drive a constraint and results are auditable, DSR can lower curative costs and preserve operational headroom. Reserve-type products improve frequency performance at the system level but rarely deliver corridor-specific relief. Price-based and event-based schemes contribute when location, verification, and timing conditions are met. Direct load control and interruptible contracts provide fast and measurable reductions when controllability and telemetry are in place.

Interpretation is bounded by heterogeneous reporting and by the descriptive scope of this review. Study designs and metrics vary, which limits cross-study comparability. The conclusions, therefore, emphasize feasibility conditions, measurement and verification, and integration with operator workflows rather than effect sizes.

Future work will use a PLEXOS tool [379] to test whether transmission-targeted DSR can reduce redispatch costs and operate in coordination with redispatch under realistic operating conditions.

Transmission-targeted DSR does not replace network measures. It adds flexibility where portfolios can be credibly located and verified and where activation overlaps the hours when constraints bind.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en18215705/s1, File S1 (DOCX): PRISMA 2020 Checklist [380]; File S2 (DOCX): As-run database search log (Web of Science, Scopus, and IEEE Xplore; search date: 10 September 2025); File S3 (DOCX): Rule-based off-topic screening specification (tabular; positive anchors and strict-keep terms; consolidated negative cues; and decision precedence).

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Abbreviations

The following abbreviations are used in this manuscript:

AGC	Automatic Generation Control
AHC	Advanced Hybrid Coupling (SDAC)
aFRR	Automatic Frequency Restoration Reserve
AVR	Automatic Voltage Regulator
CACM	Capacity Allocation and Congestion Management
DLR	Dynamic Line Rating
DSO	Distribution System Operator
DSR	Demand-Side Response
EA	Emergency/Corrective Action (contextual)
ENTSO-E	European Network of Transmission System Operators for Electricity
Euphemia	SDAC Market-Coupling Algorithm
FBMC	Flow-Based Market Coupling
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
GNN	Graph Neural Network

GOPACS	Grid Operators Platform for Congestion Solutions
HVDC	High-Voltage Direct Current
ISO/RTO	Independent System Operator/Regional Transmission Organization
LMP	Locational Marginal Pricing
LODF	Line Outage Distribution Factor
MTDC	Multi-Terminal Direct Current
mFRR	Manual Frequency Restoration Reserve
NEBEF	Notification d'Échanges de Blocs d'Énergie (FR demand response)
N-1	Security Criterion: Withstand Loss of One Element
OLTC	On-Load Tap Changer
OPF/SCOPF	(Security-Constrained) Optimal Power Flow
OTS	Optimal Transmission Switching
PMU	Phasor Measurement Unit
PST	Phase-Shifting Transformer
PTDF	Power Transfer Distribution Factor
RA	Resource Adequacy
RAS/SPS/SIPS	Remedial Action/Special Protection/System Integrity Protection Scheme
RERT	Reliability and Emergency Reserve Trader (AEMO)
RTP/ToU/ CPP/PTR	Real-Time Pricing/Time-of-Use/Critical-Peak Pricing/Peak-Time Rebate
SDAC	Single Day-Ahead Coupling
SOGL	System Operation Guideline (EU 2017/1485)
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
TSO	Transmission System Operator
TCSC	Thyristor-Controlled Series Capacitor
UPFC	Unified Power Flow Controller
VPP	Virtual Power Plant
VSC	Voltage-Source Converter

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