

面向多层级新能源消纳的准线型需求响应

Customer directrix load-based demand response for multi-level renewable energy integration

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汇报提纲

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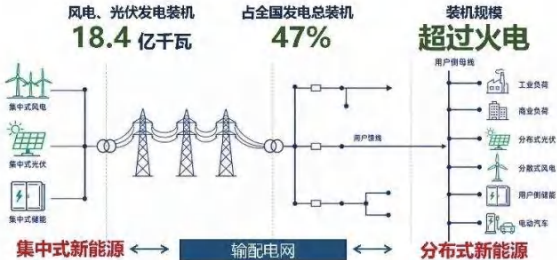
2026

第十一届紫金论电学术研讨会
The 11th Purple Mountain Forum

1 研究背景 Background

“碳达峰、碳中和”战略目标下，新能源发电规模快速增长。集中式新能源在输电网层面大规模接入，分布式新能源在配电网及用户侧广泛渗透，新能源已深入电网各个层级。

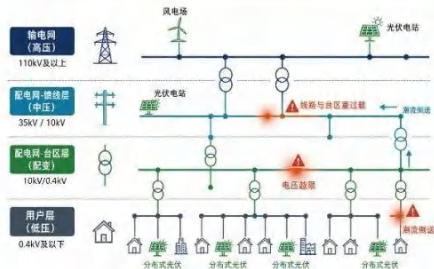
Under the strategic goals of carbon peaking and carbon neutrality, renewable power generation has expanded rapidly. Utility-scale renewable energy resources are being integrated into transmission grids on a large scale, while distributed renewable energy is increasingly penetrating distribution networks and the consumer side. Renewable energy is now deeply integrated across all levels of the power system.



1 研究背景 Background

新能源出力的大幅、持续波动，使电力系统面临时间连续的调节需求；新能源分散接入不同层级和节点，又引发线路与台区重过载、电压越限、潮流倒送等空间局部问题。**系统调节需求由“全网、偶发”转向“多层次、多节点、常态化”。**

Renewables create both continuous balancing needs due to their variability and frequent, localized balancing demands due to their integration at multiple grid levels and nodes.



南方某市分布式光伏渗透率超 100% 台区

配变潮流反送
台区占比
12%

高电压越限
台区数
121 个

配变反向重载
台区数
516 个

南方某省

重过载台区
4600 多个

重过载台区占比
2.1%

1 研究背景 Background

需求响应是挖掘用户侧灵活性的关键途径，已得到广泛应用。但现有机制主要面向系统**总体的发用平衡**和**偶发的削峰填谷**，难以应对新能源多层级高比例渗透带来的连续调节与节点差异化需求。

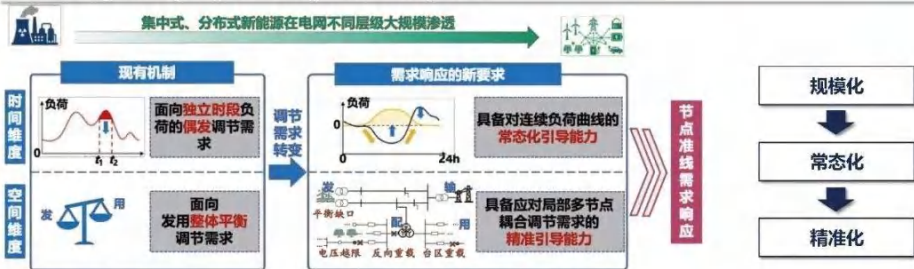
Demand response is widely studied and applied to unlock demand-side flexibility; however, existing approaches mainly support system-wide supply-demand balancing through occasional peak shaving and cannot accommodate high renewable penetration across diverse integration scenarios.



1 研究背景 Background

为适应调节需求的新特征，需求响应在规模化推广的基础上，还须实现两方面提升：时间维度上，须具备对连续负荷曲线的**常态化引导能力**；空间维度上，须具备应对局部多节点耦合调节需求的**精准引导能力**。

To meet evolving balancing needs, demand response must provide spatially precise guidance for localized, coupled multi-node balancing and temporally continuous guidance of load profiles.



1 研究背景 Background

常规的需求响应包含两类。**价格型**需求响应机制依赖不可观测的价格弹性，**基线型**需求响应机制（激励型）依赖不可证伪的反事实基线负荷，**均难以客观量化**连续负荷曲线对节点调节需求的真实贡献。

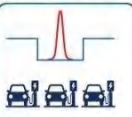
Price-based demand response relies on unobservable price elasticity, whereas baseline-based demand response relies on an unfalsifiable counterfactual baseline. Neither can objectively quantify the actual contribution of continuous load profiles to meeting nodal balancing needs.

价格型需求响应存在的问题



调节贡献无法量化

调节需求 价格弹性
不明确 不可观测



破坏用电的连续性

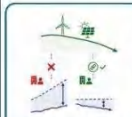
负荷 峰谷 灵活性利
反弹 倒挂 用不充分



缺乏协同优化空间

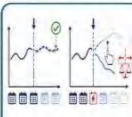
优化问题可拆分，
协同不能增效

基线型需求响应存在的问题



调节贡献量化不当

不能准确 操纵基线成为
量化贡献 主要手段



反事实推演

基线真伪 带来用户-
无从评价 电网争议



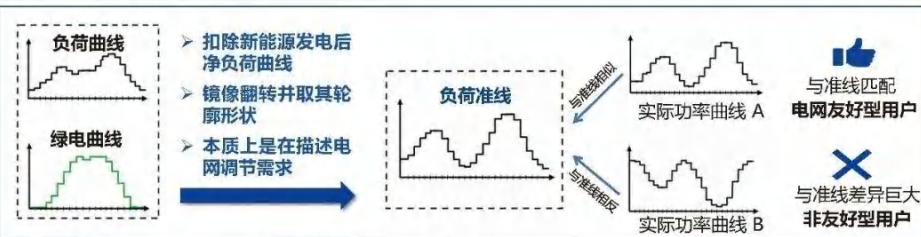
无法常态化应用

持续开展 调节能力
缺乏样本 越强越无
法计算

1 研究背景 Background

在新能源高比例多层次接入背景下，提出**负荷准线及准线型需求响应**的理念。负荷准线是连续时间调节需求的直接表征；准线型需求响应引导用户对负荷曲线进行整形，使实际负荷曲线接近负荷准线，进而满足系统调节需求，是一种以调节贡献为核心的常态化机制。

The customer directrix load (CDL) is introduced as a direct representation of continuous balancing needs, and CDL-based demand response guides customer load profiles toward the CDL to meet system balancing requirements, enabling routine demand response driven by balancing contributions.

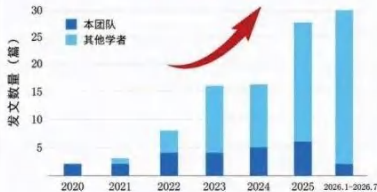


1 研究背景 Background

准线的概念得到学界认可，国内外众多学者开展了准线型需求响应的研究，建立团队标准，得到初步应用，形成特色研究方向。

The CDL concept has gained academic recognition, the development of the standard, and initial applications, thereby establishing a distinctive research direction.

以“准线”为主题的论文发文数量
逐年增加



美国国家工程院院士
Mohammad
Shahidehpour

“

基于准线的需求响应**开创**了一种负荷调节引导的**新范式**。

“Directrix-based demand response represents a **pioneering** load adjustment guidance **paradigm**”

IEEE Trans. Smart Grid, 17(3), 2026.



英国皇家工程院院士
Yonghua Song

“

负荷准线形成了自上而下组织和引导**大规模需求响应**的有效路径。

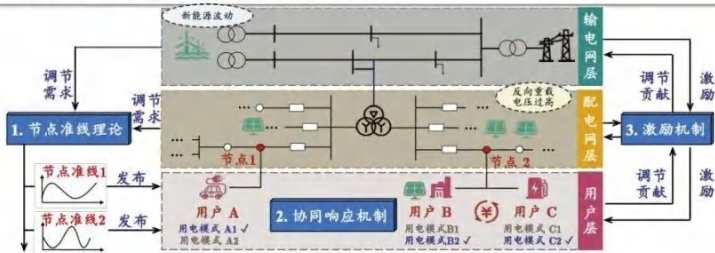
“CDL provides an up-bottom approach to DR by offering real-time, system-wide targets that **effectively** **manage large-scale DR**”

Applied Energy, 2025, 395: 126144.

1 研究背景 Background

从“调节需求表征—调节贡献形成—激励持续运行”三个方面开展了研究：① **负荷准线基础理论**，形成完整计算模型；② 面向用户侧的**准线协同响应机制**，实现用户分散决策下的调节贡献涌现；③ 面向电网侧的**准线协同激励机制**，实现多层次主体利益均衡、非迭代式的激励定价与成本溯源。

The research focuses on three areas: CDL calculation, collaborative customer response to CDLs, and multilevel incentive mechanisms across transmission, distribution, and customers.





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建立负荷准线、节点准线及多时间尺度准线的定义与计算模型，实现多层次新能源消纳调节需求的跨层级传导与各节点精准表征。

Definitions and calculation models are established for CDLs, nodal CDLs, and multi-timescale CDLs, enabling balancing needs for multilevel renewable integration to be propagated across grid levels and precisely represented at individual nodes.



2 负荷准线基础理论 (1)负荷准线 CDL

负荷准线 (CDL) 由区域内常规负荷、新能源等不可调节资源形成的净波动生成, 表征系统层面的连续调节需求, 为需求响应用户提供共同的负荷曲线整形目标。用户实际负荷与准线的接近程度, 可进一步用于量化其调节贡献。

A CDL calculation model is developed from the balancing needs of regional inflexible resources to provide a unified response target, together with a CDL-similarity-based method for quantifying customer contributions.

计算模型

➤ “可调” 平衡 “不可调”

$$\sum_{g \in G} E_g^G M_t^G - \sum_{d \in D} E_d^D M_t^D = \sum_{j \in C} P_{j,t}^C - \sum_{r \in R} P_{r,t}^{R, \max}$$

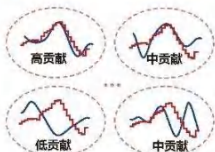
➤ “可调” 资源发/用属性, 趋势相反

$$M_t^G + M_t^D = \frac{2}{T} \quad t \in T$$

➤ 统一准线

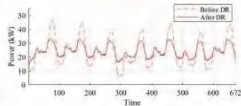
$$M_t^D = \frac{2 \sum_{g \in G} E_g^{G^2} + T \left(\sum_{r \in R} P_{r,t}^{R, \max} - \sum_{j \in C} P_{j,t}^C \right)}{T \left(\sum_{g \in G} E_g^{G^2} + \sum_{d \in D} E_d^{D^2} \right)} \quad t \in T$$

贡献评价

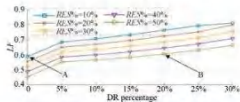


基于曲线相似度评价用户
需求响应贡献

算例分析



连续多日
开展需求
响应



提升需求
响应规模

2 负荷准线基础理论 (2)节点准线 Locational CDL

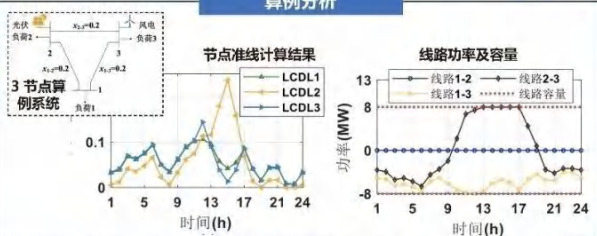
在统一的负荷准线基础上，考虑网络拓扑、资源接入位置及运行约束，建立节点准线计算模型。节点准线表征特定节点的连续调节需求轮廓，并作为该节点用户负荷曲线整形与调节贡献评价的目标。

Based on a unified CDL, a Locational CDL (LCDL) model is established considering network topology, resource locations, and operational constraints.

计算模型

$$\begin{aligned} \min \quad & \sum_{g \in \mathcal{G}} \sum_{l \in \mathcal{L}} (M_{gl}^{G,\Delta})^2 + \sum_{d \in \mathcal{D}} \sum_{l \in \mathcal{L}} (M_{dl}^{D,\Delta})^2 \\ & \text{以相较统一准线偏差最小为目标} \\ \text{s.t.} \quad & \sum_{l \in \mathcal{L}} M_{gl}^{G,\Delta} = 0, \sum_{l \in \mathcal{L}} M_{dl}^{D,\Delta} = 0 \\ & M_g^G + M_g^{G,\Delta} \geq 0, M_d^D + M_d^{D,\Delta} \geq 0 \\ & \sum_{g \in \mathcal{G}} E_g^G M_{gl}^{G,\Delta} - \sum_{d \in \mathcal{D}} E_d^D M_{dl}^{D,\Delta} = 0 \\ & P_l^{\text{line,max}} \leq \sum_{g \in \mathcal{G}} H_{l-g} E_g^G (M_g^G + M_{gl}^{G,\Delta}) + \sum_{d \in \mathcal{D}} H_{l-d} P_{dl}^{\text{line,max}} \\ & - \sum_{g \in \mathcal{G}} H_{l-g} E_g^D (M_g^D + M_{gl}^{D,\Delta}) - \sum_{d \in \mathcal{D}} H_{l-d} P_{dl}^{\text{line,max}} \leq P_l^{\text{line,max}} \\ & d \in \mathcal{D}, g \in \mathcal{G}, l \in \mathcal{L}, t \in \mathcal{T} \\ & \text{嵌入网络约束} \end{aligned}$$

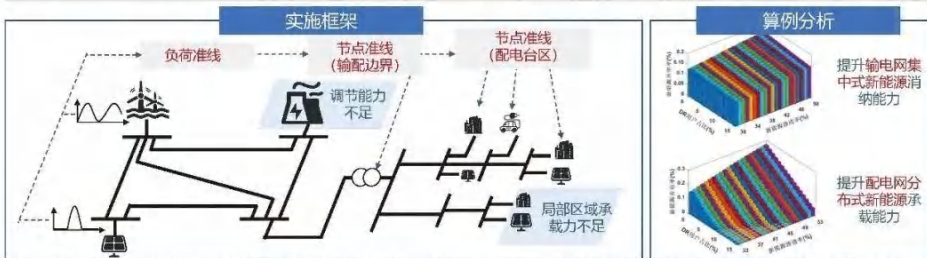
算例分析



2 负荷准线基础理论 (2)节点准线 Locational CDL

集中式新能源与分布式新能源分别接入输、配电网，网络约束使统一调节需求在空间上传导并分化。为此，分别构建输电网层级节点准线（T-LCDL）与配电网层级节点准线（D-LCDL），既支撑集中式新能源消纳，又缓解分布式新能源引发的局部承载力问题。

To address spatial variations in balancing needs caused by grid constraints, LCDLs are established at transmission-distribution and distribution-customer PCCs to facilitate the coordinated integration of large scale and distributed renewables.

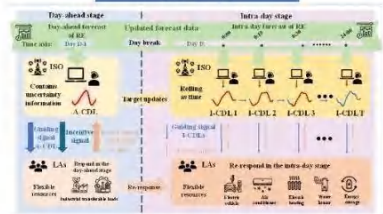


2 负荷准线基础理论 (3) 多时间尺度准线 Multi-time scale CDL

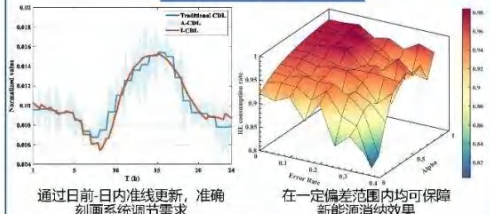
针对新能源预测误差与用户响应偏差，利用日前、日内滚动更新的预测和响应信息，动态修正准线；同时，建立聚合商响应偏差范围自主上报机制，刻画用户产生的调节需求，使准线持续、准确地表征系统真实的调节需求。

To account for renewable forecast uncertainty and response deviations, a rolling day-ahead/intraday CDL calculation model is developed with aggregator-reported deviation bounds, ensuring that the CDL accurately reflects system balancing needs.

实施框架



算例分析





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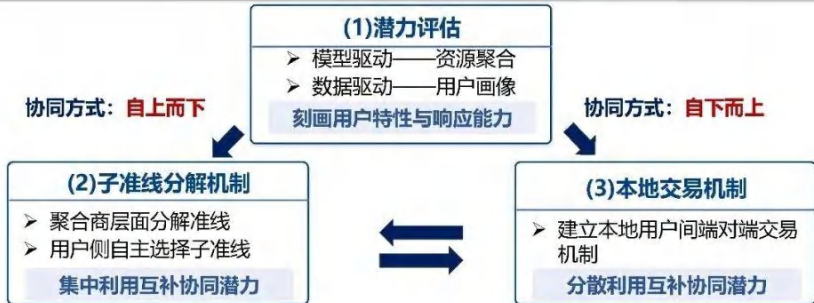
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3 准线协同响应机制 Collaborative Response Mechanism to CDL



在准线机制引导下，面向海量异质用户，建立潜力评估、子准线分解与本地交易机制，实现分散决策下的调节贡献涌现。

Flexibility assessment, sub-CDL decomposition, and local trading mechanisms are developed for large populations of heterogeneous customers, enabling balancing contributions to emerge from decentralized decisions.



3 准线协同响应机制 (1)潜力评估——资源聚合

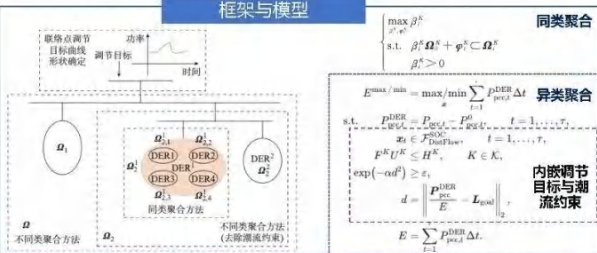
Flexibility Assessment — Resource Aggregation



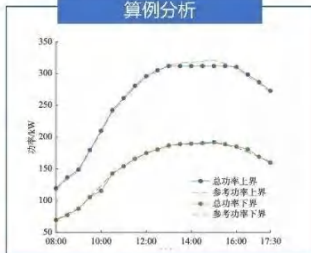
针对海量异构灵活性资源，建立内嵌准线目标与潮流约束的分层分类聚合方法，同类资源采用相似多面体内逼近，异类资源沿目标曲线方向聚合，在保留时间耦合特性的同时形成可执行的聚合可行域，为用户群体潜力评估与协同响应奠定基础。

For large-scale heterogeneous flexible resources, an aggregation method incorporating CDL targets and power-flow constraints is developed to construct a dispatchable aggregate feasible region while preserving temporal coupling.

框架与模型



算例分析



3 准线协同响应机制 (1)潜力评估——用户画像

Flexibility Assessment — Customer Profiling

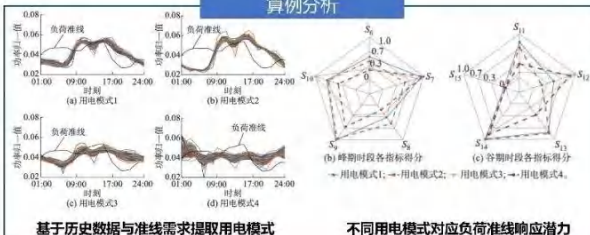


从用户历史负荷中提取与节点准线响应相关的时序特征，识别典型用电模式；综合实施成本与模式切换能力评价响应潜力，进一步构建准线响应成本函数与可行域，实现对用户“何时可调、向何方向调、以多大代价调”的量化刻画。

Temporal features relevant to LCDL response are extracted from historical user loads to identify typical consumption patterns. Response potential is then evaluated by integrating implementation costs with pattern-switching capabilities, based on which the CDL response cost function and feasible region are constructed.

指标	定义	物理含义
正负坡度	$\alpha_1 = (P_{max} - P_1) / \Delta t$	正向爬坡斜率
负负坡度	$\alpha_2 = (P_{min} - P_1) / \Delta t$	负向爬坡斜率
最大负荷率	$\alpha_3 = P_{max} / P_{rated}$	用户峰值负荷最大水平
最小负荷率	$\alpha_4 = P_{min} / P_{rated}$	用户峰值负荷最小水平
峰谷差率	$\alpha_5 = (P_{max} - P_{min}) / P_{rated}$	用户负荷波动程度
耗电量	$\alpha_6 = P_{max} / P_{rated}$	用户全峰用电量水平
可调度	$\alpha_7 = T_{max} - T_{min}$	用户与CDL峰值时刻偏移程度
最大负荷率	$\alpha_8 = P_{max} / P_{rated}$	用户谷期负荷最大水平
最小负荷率	$\alpha_9 = P_{min} / P_{rated}$	用户谷期负荷最小水平
峰谷差率	$\alpha_{10} = (P_{max} - P_{min}) / P_{rated}$	用户谷期负荷波动程度
耗电量	$\alpha_{11} = P_{max} / P_{rated}$	用户谷期用电量水平
可调度	$\alpha_{12} = T_{max} - T_{min}$	用户与CDL的谷期时刻偏移程度

算例分析



基于历史数据与准线需求提取用电模式

不同用电模式对应负荷准线响应潜力

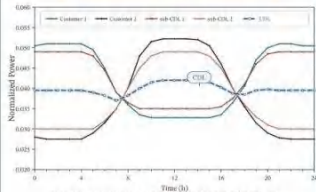
3 准线协同响应机制 (2)子准线分解机制

Sub-CDL Decomposition Mechanism

聚合商基于所代理用户的历史用电模式、响应潜力与选择概率，将负荷准线分解为多条个性化的子准线。用户选择与自身用电特性更匹配的子准线自主响应，充分利用用户差异化响应能力，降低需求响应实施成本，提升用户群体对准线的总体跟踪效果。

Aggregators decompose the CDL into personalized sub-CDLs, allowing customers to select and independently respond to the sub-CDL best aligned with their consumption patterns, thereby improving aggregate CDL tracking.

分解原理



分解可以降低用户需求响应实施成本

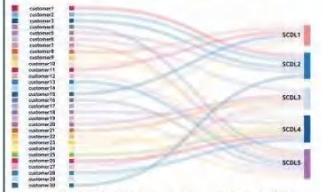
计算模型

基于历史数据的分解

$$\begin{aligned} \min_{\{P_{i,t}^{D*}\}} \quad & \sum_{i \in \mathcal{N}} \sum_{t \in \mathcal{T}} \mathbb{E} \left[\sum_{a \in \mathcal{M}} \alpha_{ai} W_a (P_{i,t}^{D*} - L_{i,t}^*)^2 \right] \\ \text{s.t.} \quad & P_D^*(t) = \sum_{i \in \mathcal{N}} \mathbb{E} \left(\sum_{a \in \mathcal{M}} \alpha_{ai} W_a \right) P_{i,t}^{D*}, \\ & 0 \leq P_{i,t}^{D*} \leq 1, \quad i \in \mathcal{N}, t \in \mathcal{T}, \\ & \sum_{t \in \mathcal{T}} P_{i,t}^{D*} = 1, \quad i \in \mathcal{N}. \end{aligned}$$

考虑用户选择不同子准线的概率

算例分析



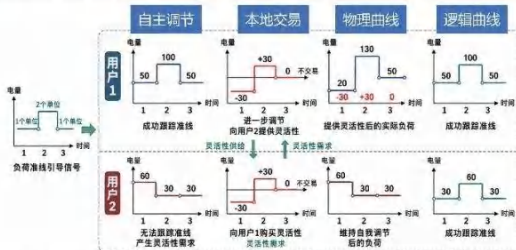
用户选择契合自身需求的子准线进行响应

3 准线协同响应机制 (3)本地交易机制

Local Trading Mechanism

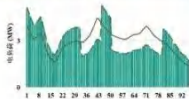
在用户自主调节基础上，将可释放或所需的协同调节量作为本地交易标的，由用户竞价、统一出清，实现灵活性在用户间互补流动。个体仅基于本地信息决策，即可在群体层面形成“整体大于部分之和”的调节贡献涌现。

Available or required balancing flexibility is traded locally through user bidding and centralized clearing, enabling peer-to-peer flexibility trading. Individual decisions based solely on local information can produce emergent balancing contributions.

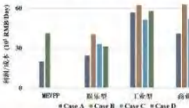


算例分析

端对端交易下需求响应整体效果提升



端对端交易降低综合用电成本





上海交通大学

SHANGHAI JIAO TONG UNIVERSITY

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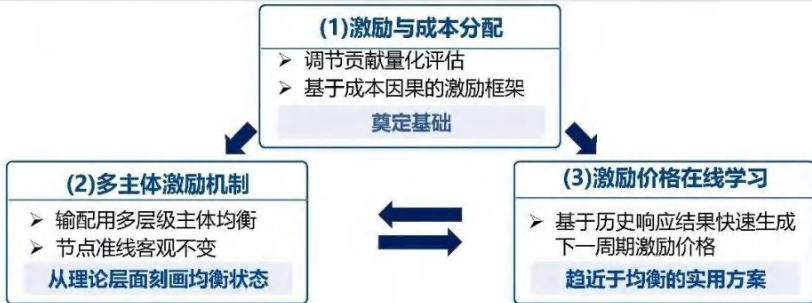
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4 准线协同激励机制 CDL-based Incentive Mechanism

以调节贡献和成本因果为依据，构建输配用多主体均衡与在线定价机制，实现非迭代、可持续激励。

Based on balancing contributions and cost causation, multistakeholder equilibrium and online pricing mechanisms are developed across transmission, distribution, and customers to enable non-iterative, sustainable incentives.



4 准线协同激励机制 (1)激励分配与成本疏导

Payment and Incentive Allocation



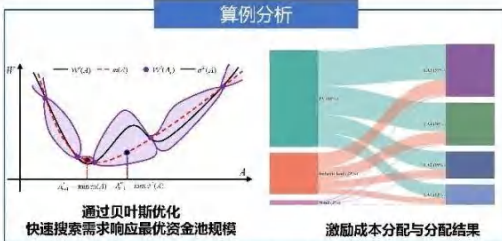
遵循成本因果原则，建立准线型需求响应的激励分配与成本疏导框架。调节成本按需求归因分摊，激励收益按贡献分配；通过优化确定激励资金池规模，并从新能源消纳增量收益中疏导激励费用，保障机制可持续运行。

Following the cost-causation principle, an incentive allocation and cost-recovery framework is developed for CDL-based demand response, with balancing costs allocated by the sources of balancing needs, rewards distributed by contribution, and the incentive pool sized through optimization.

实施框架



算例分析



4 准线协同激励机制 (1) 激励分配与成本疏导

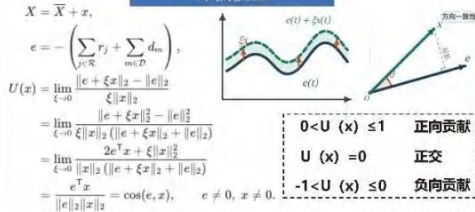
Payment and Incentive Allocation



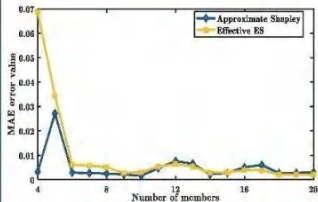
基于加托方向导数理论，将用户负荷曲线对调节需求的边际消弭作用化简为其与节点准线的余弦相似度，形成可事前、显式计算的贡献评价函数，具备明确的物理可解释性和调节引导效果。

Using Gateaux directional derivatives, a customer's marginal contribution to mitigating balancing needs is expressed as the cosine similarity between its load profile and the CDL, providing clear physical interpretability and effective response guidance.

评估模型



算例分析



用户数量增加，基于准线相似度的评价结果与Shapley值评价结果趋近

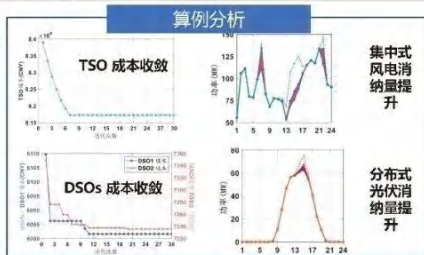
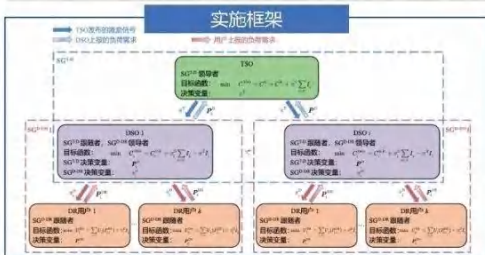
4 准线协同激励机制 (2) 输配用多主体激励机制

Multistakeholder Incentive Mechanism



面向输电网运营商、配电网运营商和用户三层主体，构建双环主从博弈模型，围绕客观不变的节点准线交互激励与响应信息，形成解兼顾集中式、分布式新能源消纳及各层级主体收益的均衡激励方案。

A Stackelberg game among TSO, DSO, and customers yields an equilibrium incentive scheme that balances utility-scale and distributed renewable integration with stakeholder benefits across all levels.



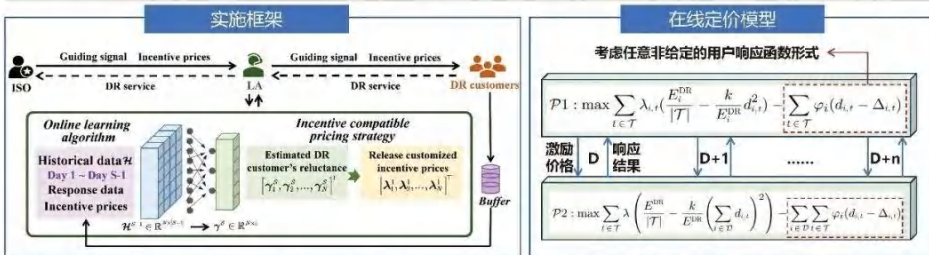
4 准线协同激励机制 (3) 激励价格在线学习

Online Pricing



针对运营商无法观测用户协同响应特性、反复迭代易产生决策疲劳的问题，将“激励价格—群体响应”映射关系转化为可在线学习的参数化模型。运营商依据历史价格—响应数据估计用户特性，直接制定下一周期 (D+1) 的激励价格。

The incentive price-aggregate response mapping is formulated as an online-learnable parametric model, enabling operators to estimate customer characteristics from historical price-response data and directly set the next-period (D+1) incentive price.



4 准线协同激励机制 (3) 激励价格在线学习

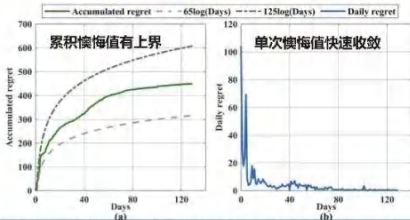
Online Pricing



所提出的在线学习机制具有 $O(\log(Days))$ 的累积懊悔上界，激励价格可随响应周期推进渐近逼近理论均衡值。该机制无需在当期进行多轮交互，即可持续降低系统调节需求，并适应用户行为随季节、分布式新能源装机等外部环境变化产生的漂移。

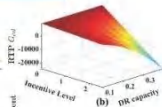
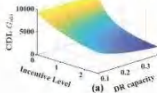
The proposed online learning mechanism achieves an $O(\log(Days))$ cumulative regret bound, with incentive prices asymptotically converging to the theoretical equilibrium over successive response periods.

在线学习效果

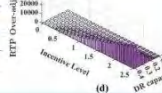
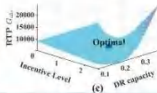


算例分析

准线型需求响应效果提升



价格型机制存在过调节





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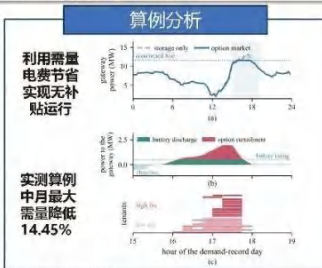
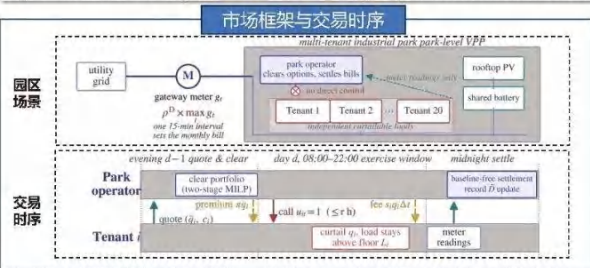
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5 应用场景 (1)园区多用户需求交易

Maximum Demand Trading Mechanism

面向转供电园区场景，基于准线对调节时段与方向的引导，将用户可提供的需量削减承诺定义为“需量权”，建立日滚动期权市场，进而通过两阶段随机出清衔接月度需量目标与逐日交易，实现用户个体和园区整体的需量降低。

For industrial/commercial parks with electricity, customers' demand-reduction commitments are defined as "demand rights" and traded locally to reduce max demand (MD) for both individual customers and the park as a whole.



5 应用场景 (2)台区储能与需求响应协同调节

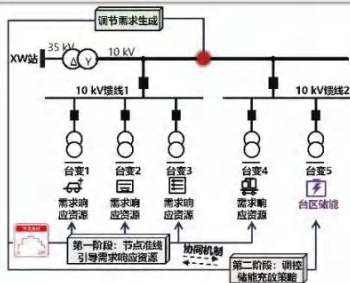
Coordinated Energy Storage and Demand Response



面向分布式新能源高渗透台区，节点准线首先引导海量需求响应资源形成前置、低成本的柔性调节；当响应偏差或网络安全约束仍未满足时，再由台区储能提供精准的调节，并通过多档激励价格提升进行需求响应资源-台储资源的协同。

For distribution areas with high distributed renewable penetration, LCDLs enable two-stage coordinated balancing of energy storage and demand response.

	台区储能	需求响应资源
优势	可直接调控 控制精确度高	容量大 建设成本低
不足	容量有限 建设成本高	不能直接控制 响应精确度不高
利用方式	作为满足目标或约束的精准调节资源	作为前置引导的灵活调节资源



5 应用场景 (3)主配微协同调控

Coordinated Transmission-Distribution-Microgrid Control



面向主配微多层级电网场景，建立节点准线引导的协同调控体系，园区用户自主协同响应，实现主网统筹、配网协调、微网执行的分层闭环控制，提升承载力、促进新能源消纳。

For multilevel transmission-distribution-microgrid systems, a LCDL-guided coordinated control framework is developed to enhance grid hosting capacity and renewable integration.

虚拟电厂运营平台（省级）

既有功能模块

节点准线计算模块

负荷准线
节点准线

主动虚拟电厂聚合平台（可由配电网运营）

节点准线1

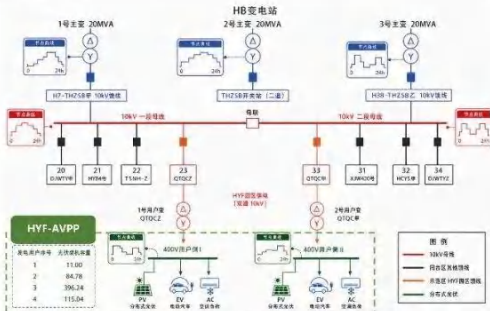
节点准线2

节点准线N

主动虚拟电厂
园区1

主动虚拟电厂
园区2

主动虚拟电厂
园区N





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6 总结与展望 Summary and Outlook



负荷准线直接表征连续时间调节需求，推动需求响应由偶发削峰填谷走向以调节贡献为导向的常态化机制。CDL directly represents continuous-time balancing needs, enabling demand response to evolve from occasional peak shaving into a routine, contribution-oriented mechanism.



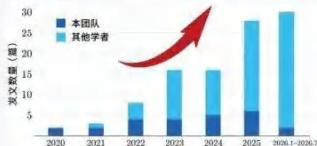
节点准线进一步融入网络约束，实现多层次、多节点调节需求的精准传导及用户调节贡献的客观量化。LCDL incorporates network constraints to precisely convey multilevel, locational balancing needs and objectively quantify customer contributions.



围绕准线形成用户协同**响应**与输配用**激励**机制，并在园区需量交易、台区储能、主配微协同等典型场景应用。CDL-based collaborative response and incentive mechanisms have been developed and extended to park-level maximum-demand trading, energy storage, and dispatching.



负荷准线研究正受到国内外学者关注，相关发文量逐年上升。期待各位专家贡献智慧与力量，共同完善理论、建立标准、推动应用。 CDL research is attracting increasing attention worldwide, with publications rising steadily. We welcome your insights and collaboration in advancing its theory, mechanisms, and applications.



汇报结束 敬请指正

Thank You



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