Hierarchical Coordinated Dispatch Strategy for Multiple Virtual Power Plants Based on Event-Triggered Mechanism and Energy Sharing

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***Abstract*—To address issues such as excessive communication redundancy, delayed dynamic response, and inequitable profit allocation in the coordinated dispatch of multiple Virtual Power Plants (MVPPs), a hierarchical coordinated dispatch strategy based on Event-Triggered Mechanism (ETM) and energy sharing is proposed. The proposed strategy achieves dynamic system management through a dual-layer framework of "internal dispatch–energy sharing." At the internal dispatch layer, event-triggered mechanism (ETM) is introduced, in which five types of typical events (R, I, A, O, and E) drive distributed optimization and control. This mechanism significantly reduces communication and computational burdens while maintaining system balance. At the energy sharing layer, an Energy Sharing Mechanism (ESM) based on the concept of energy level is proposed. A non-profit centralized Energy Sharing Platform (ESP) is introduced to facilitate localized energy trading and profit balancing among MVPPs through fair pricing and incentive-compatible rules. Simulation results demonstrate that the proposed strategy effectively reduces communication load, mitigates system peak-valley differences, and enhances overall economic performance.**

Keywords—virtual power plant; event-triggered mechanism; energy sharing; hierarchical dispatch

I. INTRODUCTION

With the increasing penetration of renewable energy, the volatility and uncertainty of power system have significantly intensified [1]. The traditional centralized dispatch model faces challenges such as response delays, information asymmetry, and low coordination efficiency when dealing with distributed energy resources and high-penetration renewable generation [2]. As an aggregating entity that integrates multiple types of distributed resources, Virtual Power Plant (VPP) can achieve local consumption of renewable energy and multi-energy coordinated management through information communication and optimal dispatch. However, independent optimization of a single VPP is insufficient to realize regional energy optimality. When Multiple VPPs (MVPPs) participate in dispatch simultaneously, cross-VPP coordination and fair profit allocation become new research focuses.

Existing coordination methods for MVPPs are mostly based on the Time-Triggered Mechanism (TTM), which updates information and re-optimizes at fixed time intervals. Reference [3] investigates MVPPs energy trading issues based on cooperative game theory at the hourly time scale. Reference [4] introduces a carbon trading mechanism into the MVPPs framework and develops a novel dynamic robust optimization model considering multi-source uncertainties from both generation and load sides. Although such methods ensure dispatch consistency, they result in continuous communication and computation even during stable system operation, leading to resource waste. Conversely, during sudden state changes, the fixed-period updates fail to ensure real-time responsiveness, thus affecting system economy and security. Therefore, achieving efficient, low-communication, and real-time coordinated optimization in MVPPs has become a crucial research topic in modern power systems.

Event-Triggered Mechanism (ETM) can trigger control signals based on state deviations, reducing communication costs. Therefore, it has been widely applied in multi-agent control fields. Reference [5] designs a distributed event-triggered controller for heterogeneous agents to achieve output consensus. Reference [6] introduces an adjustable variable to dynamically schedule trigger frequency for bipartite consensus control among multi-agent systems, minimizing trigger times while maintaining system performance. However, limited studies have applied ETM to VPP optimization dispatch, where both real-time performance and economic efficiency are considered.

Energy sharing mechanisms (ESM) have been extensively developed in recent years. Reference [7] proposes a multi-time-scale coordinated operation strategy for clusters of VPPs considering energy sharing, solving energy sharing problems among MVPPs and improving overall system economy. Reference [8] introduces an energy control mechanism through multi-client energy sharing. However, most of these models focus primarily on economic optimization while neglecting fairness and incentive compatibility during the sharing process.

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To address the above issues, this paper proposes a hierarchical coordinated dispatch strategy for MVPPs based on ETM and ESM. The objective is to realize economically efficient coordination among MVPPs through event-driven dynamic dispatch and energy-level-driven fair sharing. The main contributions of this paper are as follows:

1) A Single-VPP Internal Dispatch Strategy Based on the ETM: Five types of typical events (R, I, A, O, and E) are defined, and dynamic dispatch and efficient communication control are achieved through event prioritization and triggering criteria.

2) An ESM Based on Energy Levels: Inspired by the concept of physical energy levels, an Energy Sharing Platform (ESP) is established to implement energy-level partitioning and sharing algorithms. Energy flow and price coordination are driven by energy-level differences, enabling localized sharing and fair profit allocation among MVPPs.

3) A Hierarchical Coordinated Dispatch Model for MVPPs: Through a dual-layer architecture consisting of an "internal dispatch layer–energy sharing layer," local information exchange enables the transition from single VPP optimization to MVPPs coordinated dispatch.

II. Hierarchical Coordinated Dispatch Framework for MVPPs

The hierarchical coordinated dispatch framework for MVPPs based on the ETM and ESM is illustrated in Fig. 1. At the internal dispatch layer, each VPP serves as an independent operating entity. The ETM is employed to realize on demand optimization and local power balance, reducing unnecessary communication while maintaining operational efficiency. At the energy sharing layer, the ESP acts as the coordination center. Based on energy-level partitioning and fair pricing, the ESP enables cross-VPP energy exchange and profit equilibrium among MVPPs.

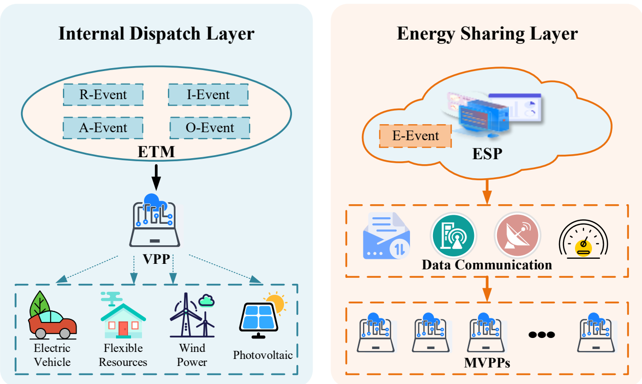

Fig. 1. Framework of hierarchical coordinated dispatch for MVPPs.

III. Dispatch Strategy for MVPPs Based on ETM

To enhance the dispatch flexibility, communication efficiency, and system stability of the MVPPs system under a multi-source heterogeneous environment, this paper develops a dynamic dispatch framework based on ETM. The core concept is that the existing dispatch strategy remains active while the system operates within a stable region. Redispatch is triggered only when key state variables deviate from their predefined thresholds or when external disturbances occur. Compared with traditional TTM, this mechanism significantly reduces data exchange and redundant computation through on-demand triggering, thereby achieving low communication overhead and fast-response distributed coordinated control.

A. Classification and Definition of ETM

1) Request Event (R-Event)

This event is triggered when an end user connects to VPP or submits a dispatch request. The triggering condition is given by

$$u_i(t) = 1 \Rightarrow \text{Trigger } R_i \tag{1}$$

where $u_i(t)$ denotes the connection status of user *i* at time *t* (1 indicates connection, 0 indicates disconnection).

Once triggered, the ETS client generates the user's optimal dispatch plan based on the real-time internal electricity price, enabling a rapid response to newly connected loads or access requests.

2) Imbalance Event (I-Event)

This event is triggered when the deviation between the predicted net load and the actual load of VPP exceeds a tolerance threshold, serving to correct power imbalances caused by renewable generation fluctuations. The triggering condition is expressed as

$$\left|P_{n,t}^{\text{act}} - P_{n,t}^{\text{pre}}\right| > \delta_n P_{n,t}^{\text{pre}} \tag{2}$$

where $P_{n,t}^{\text{act}}$ and $P_{n,t}^{\text{pre}}$ denote the actual and predicted load of VPP *n* at time *t*, and δ_n is the tolerance coefficient.

Once triggered, the system restores dynamic balance by adjusting flexible loads and energy storage power:

$$P_{n,t}^{\text{bal}} = \beta_f P_{n,t}^{\text{flx}} + \alpha_{\text{PV}} P_{n,t}^{\text{PV}} + \alpha_{\text{WT}} P_{n,t}^{\text{WT}} \tag{3}$$

where β_f is the flexible load adjustment coefficient, and α_{PV}, α_{WT} are the dynamic response coefficients of photovoltaic (PV) and wind turbine (WT) generation.

3) Abrogation Event (A-Event)

This event is triggered when a user disconnects prematurely or fails to execute the scheduled power consumption task as planned. Let the set of users who exit early be Ω_d; the system reselects an alternative user set Ω_r based on the dispatchable potential of candidate users:

$$P_t^{\text{loss}} = \sum_{i\in\Omega_d} P_{i,t} \Rightarrow \text{Re-schedule } \left\{ j\in\Omega_r \mid \phi_j = \max(\phi) \right\} \tag{4}$$

where ϕ_j is the response potential of candidate user *j*.

This event is primarily designed to address power deficits caused by user behavior uncertainty, ensuring local power balance and system continuity.

4) Overload Event (O-Event)

This event is triggered when the total output power of VPP exceeds the capacity limit of the external tie-line $P_{\text{line}}^{\max}$. Upon triggering, the system sequentially curtails the scheduled power of participating users according to their load response potential, from lowest to highest priority:

$$\sum_i P_{i,t} > P_{\text{line}}^{\max} \tag{5}$$

$$\text{Cancel } P_i \text{ s.t.} \sum_i P_i \le P_{\text{line}}^{\max} \tag{6}$$

This process effectively prevents network overload and local node congestion, enhancing the system security margin.

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5) Energy-Sharing Event (E-Event)

This event is triggered when, during a specific time period, there simultaneously exist seller VPPs with surplus energy and buyer VPPs with power deficits, initiating cross-VPP energy sharing:

$$E_{s,b}(t) = \min(P_s^{\text{sur}}(t), P_b^{\text{req}}(t)) \quad (7)$$

where $P_s^{\text{sur}}(t)$ is the available redundant power of the *s*-th seller VPP; $P_b^{\text{req}}(t)$ is power demand of the *b*-th buyer VPP.

The ESP coordinates the execution of energy-sharing transactions, following fair incentive principles and tie-line capacity constraints to ensure the stability and feasibility of the trading process.

B. Dispatch Process of MVPPs

All event types are categorized into three priority levels according to their impact on system stability and real-time performance. Level I is instantaneous trigger events (R-Event). These events require immediate response to ensure real-time user access and system connectivity. Level II is dynamic adjustment events (I-Event, A-Event, O-Event). Their priority order is I>A>O, primarily addressing power deviation, contract abrogation, and overload issues. Level III is system coordination events (E-Event). These are executed at a higher hierarchical level to coordinate energy sharing among MVPPs. The event-triggered dispatch process for multiple VPPs is illustrated in Fig. 2, which depicts how different event types are sequentially identified, prioritized, and executed within the hierarchical dispatch framework.

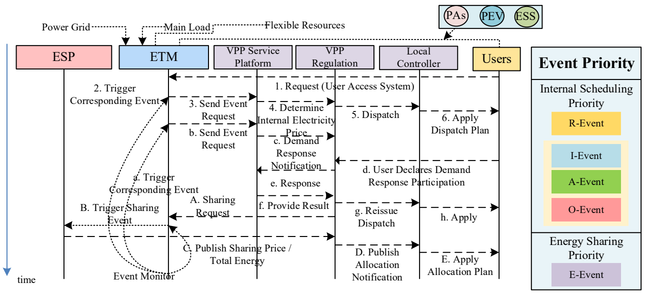

Fig. 2. Dispatch process of MVPPs based on EMT.

IV. ESM Based on Energy Levels

To achieve fair and efficient coordination among MVPPs, this paper proposes ESM based on the concept of energy levels. Inspired by the physical concept of energy levels, the proposed mechanism quantifies the energy state of each VPP into discrete hierarchical "energy levels." Through hierarchical energy transfer, MVPPs energy optimization can be realized with low computational complexity.

A. Principles of Energy Sharing

The hierarchical partitioning enables the energy-sharing process to be coordinated among multiple participants using local information and low computational effort, thereby improving both fairness and stability of the overall system. The energy-sharing process follows the following fundamental principles: 1) Prior to energy sharing, the ESP classifies all VPPs into *D* hierarchical energy levels according to their respective energy states, denoted as *d=1,2,…,D*; 2) Energy transfer proceeds from lower levels to higher levels, and reverse flow is strictly prohibited; 3) Each sharing transaction is only permitted between adjacent energy levels, preventing multi-level redundant transmission. 4) When a VPP reaches demand-compensation equilibrium (free state), it exits the energy-sharing process.

B. Novel ESM Based on Energy Levels

To achieve efficient matching and transfer during the energy-sharing process, this paper further proposes an energy allocation strategy based on energy levels.

1) Definition and Calculation of Energy Level

The energy level of VPP *n*, denoted as E_n, is determined by its required compensation power and priority factor:

$$E_n = \alpha_n P_n^{\text{rep}} + \beta_n \Delta P_n^{\text{bal}} \quad (8)$$

where P_n^{rep} is the required power compensation, ΔP_n^{bal} is the power imbalance caused by renewable generation and load fluctuations, and α_n, β_n are the weight coefficients.

A larger energy level value indicates that the VPP is more energy-deficient, and thus possesses higher priority in the energy-sharing process.

2) Energy Transfer and Update Rules

The power transfer between adjacent energy levels $P_{d\to d+1}^{\text{trans}}$ is defined as:

$$P_{d\to d+1}^{\text{trans}}(t) = \xi_d \left[E_{d+1}(t) - E_d(t) \right] \quad (9)$$

where ξ_d is the energy-level transfer coefficient.

After sharing is completed, the available power P_d^{ava} of each VPP layer is updated as:

$$P_d^{\text{ava}}(t+1) = P_d^{\text{ava}}(t) - P_{d\to d+1}^{\text{trans}}(t) \quad (10)$$

3) Matching Principles for Energy Sharing

All seller and buyer VPPs are ranked according to their energy levels and priority factors. Buyer VPPs with higher priority obtain shared energy first, following the matching sequence:

$$S_i \to B_j \quad (11)$$

$$s.t.\ \ E_{S_i} < E_{B_j}, P_{S_i} < P_{B_j} \quad (12)$$

After matching is completed, ESP dynamically calculates and updates the transaction price and energy flow direction in real time. The overall process is illustrated in Fig. 3.

Through the proposed strategy, efficient energy allocation can be achieved under limited communication and local information, ensuring fair profit distribution among VPPs while enhancing the overall system economy.

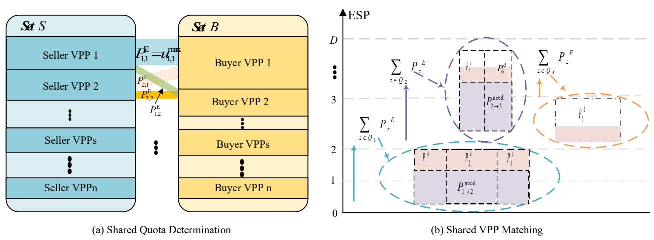

Fig. 3. Framework of ESM.

V. MVPPs Hierarchical Coordinated Dispatch Model

A. Internal Dispatch Layer

To maximize the profit of each individual VPP, a dispatch strategy based on ETM is applied in the internal dispatch layer. The objective is to minimize the total intra-day operating cost,

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subject to power balance constraints and event-triggering conditions.

$$\min J_n = \sum_t (C_{n,t}^{\text{grid}} + C_{n,t}^{\text{user}}) \tag{13}$$

$$C_{n,t}^{\text{grid}} = \rho_t^{\text{buy}} P_{n,t}^{\text{buy}} - \rho_t^{\text{sell}} P_{n,t}^{\text{sell}} \tag{14}$$

$$C_{n,t}^{\text{user}} = \gamma_n (P_{n,t}^{\text{use}} - P_{n,t}^{\text{ref}})^2 \tag{15}$$

where $C_{n,t}^{\text{grid}}$ is the energy exchange cost between VPP n and the main grid; $C_{n,t}^{\text{user}}$ is the consumer cost considering users' psychological response; ρ_n^{buy} and ρ_n^{sell} are the buying and selling prices; γ_n is the psychological sensitivity coefficient, reflecting users' tolerance toward price fluctuations; $P_{n,t}^{\text{use}}$ is the actual power consumption; and $P_{n,t}^{\text{ref}}$ is the baseline power.

B. Energy-Sharing Layer

To address the lack of unified coordination among independently operated VPPs, ESP is introduced as a nonprofit intermediary institution. ESP is responsible for calculating trading prices, determining energy flow directions, and ensuring economic fairness among all participants in the sharing process.

At time t, suppose there are N VPPs participating in energy sharing. The optimization objective of the energy-sharing system is defined as:

$$\max = \sum_n U_{n,t} \tag{16}$$

where $U_{n,t}$ is the profit function of the n-th VPP at time t.

The optimization is subject to the energy balance constraint, line capacity constraint, and fairness constraint, which jointly ensure power conservation between trading parties, prevention of line overload, and a shared price bounded within the grid's buying and selling prices:

$$P_{n,t}^{\text{buy}} - P_{m,t}^{\text{sell}} = \sum_{m \neq n} P_{n,m,t} \tag{17}$$

$$P_{n,m,t} \leq \eta_{n,m} P_{n,m}^{\max} \tag{18}$$

$$\rho_t^{\text{buy}} \geq \rho_{n,m,t}^{\text{share}} \geq \rho_t^{\text{sell}} \tag{19}$$

where $P_{n,m,t}$ is the power transferred from the n-th VPP to the m-th VPP; $\eta_{n,m}$ is the line capacity coefficient; and $\rho_{n,m,t}^{\text{share}}$ is the shared electricity price.

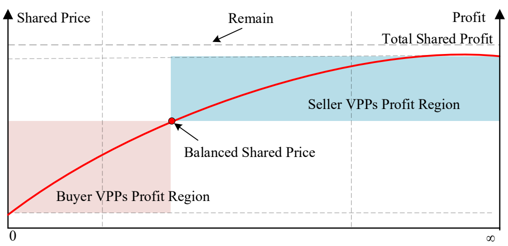

Fig. 4. Schematic diagram of the shared pricing mechanism.

To further enhance fairness, a shared pricing mechanism is defined, as illustrated in Fig. 4. This pricing approach ensures that the profits of both seller and buyer VPPs fluctuate within acceptable bounds, ensuring price fairness and incentive compatibility:

$$\rho_{n,m,t}^{\text{share}} = \omega_n \rho_t^{\text{sell}} + (1 - \omega_n) \rho_t^{\text{buy}} \tag{20}$$

Where ω_n is the participation weight of VPP n, reflecting its contribution and priority level in the sharing process.

VI. Case Study

To verify the effectiveness of the proposed MVPPs hierarchical coordinated dispatch method based on ETM and ESM, a MVPPs system comprising three representative VPPs is constructed. The parameter configuration of the MVPPs is as specified in Table I. The dispatch horizon is set to 24 hours.

TABLE I. Parameter Configuration of the MVPPs

VPP	Capacity			Maximum Output (KW)	Number of Users
	PV(KW)	*WT(KW)*	*ES(KWh)*		
1	68	72	40	100	8
2	60	90	50	90	9
3	87	90	60	120	11

To demonstrate the performance advantages of the proposed strategy, three comparative cases are designed:

Case 1: Each VPP operates independently, without communication or energy sharing.

Case 2: A periodic centralized optimization is performed, with updates executed only at fixed time intervals.

Case 3: The proposed hierarchical coordinated dispatch strategy integrating ETM and energy-level-based energy sharing.

The representative dispatching results of the three cases are illustrated in Fig. 5.

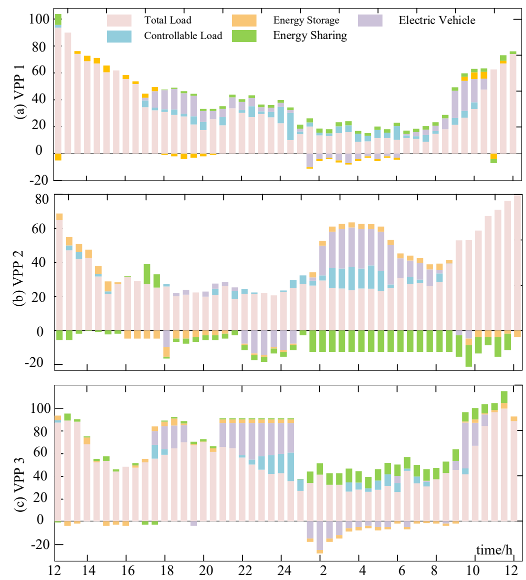

Fig. 5. Dispatch results of VPP 1-3.

A. Performance Analysis of the ETM

To validate the dynamic responsiveness and communication efficiency of ETM, the temporal distribution characteristics and communication performance of various events are analyzed. The triggering frequency and temporal distribution of each event type are illustrated in Fig. 6.

R-Events primarily occur during midday peak hours and evening charging periods; I-Events are distributed throughout the entire day; whereas A-Events and O-Events exhibit low triggering frequencies, only occurring under extreme operating conditions. This feature significantly reduces redundant dispatch actions and communication load.

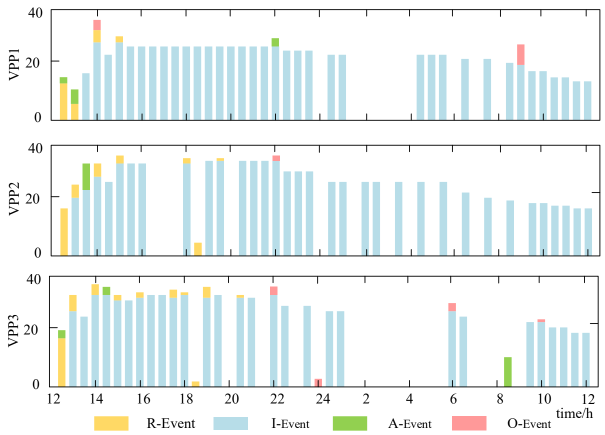

Fig. 6. Temporal distribution of event triggering.

Table II presents a comparison of communication volume and computation time across VPP systems of different scales. Since Case 1 does not consider coordinated optimization, its communication and computation burdens are minimal. Compared with Case 2, the proposed Case 3 achieves an average computation time reduction of 52.27%, and average communication data volume is approximately 46.12% of that in Case 2. These results demonstrate that the proposed ETM-based strategy effectively alleviates communication burden and reduces computational stress, while maintaining stable system performance.

TABLE II. COMPARISON OF COMMUNICATION PERFORMANCE AND COMPUTATION TIME

Case	Data Transmission Requirement (KB/N[a])		Computation Time (s)
	Input	*Output*	
1	0.605	0.358	2.50
2	12.372	8.511	24.68
3	6.049	3.583	11.78

a. N is the total number of users in the VPP.

B. *Analysis of Energy-Sharing Performance*

ESP coordinates energy exchanges among MVPPs based on energy-level partitioning results. As illustrated in Fig. 7, bidirectional energy compensation is achieved among MVPPs. When VPP 1 and VPP 3 have surplus renewable generation, they sell excess power to VPP 2, thereby realizing local energy balance and maximizing overall profit.

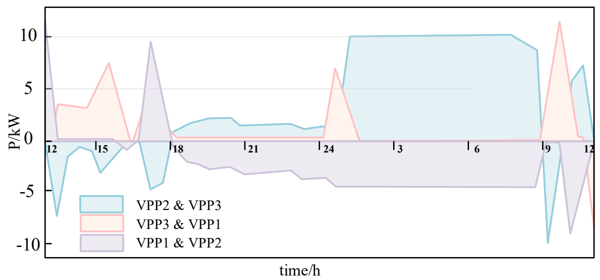

Fig. 7. Energy-sharing results among MVPPs.

Table III summarizes the grid transaction costs and sharing profits of each VPP under the three scenarios. Under the proposed ETM-based strategy, the total system cost is minimized. The energy-sharing behavior significantly enhances resource utilization efficiency and improves economic fairness among all participating VPPs.

TABLE III. COMPARISON OF ECONOMIC COSTS IN MVPPS

Case	Transaction with Grid ($)		Transaction with Other VPPs ($)		Total Cost ($)
	Cost	*Profit*	*Cost*	*Profit*	
1	49.133	25.002	0	0	24.131
2	19.304	17.633	0	0	1.671
3	3.234	3.675	12.094	11.574	0.079

C. *Comparative Analysis of Different Dispatch Strategies*

As shown in Table IV, the net-load peak-to-valley difference in Case 3 is reduced by 87.69% and 45.83% compared with Case 1 and Case 2, respectively. This indicates that the proposed strategy effectively enhances the stability of power system and promotes renewable energy consumption.

TABLE IV. REGULATION PERFORMANCE OF MVPPS UNDER THREE CASES

Case	Net-Load Fluctuation (kW^2)	Peak-to-Valley Load Difference (kW)	Relative Peak Variation (%)	Flexible Renewable Energy Utilization (%)
1	38.25	166.45	\	82.22
2	6.42	36.88	82.65	93.43
3	4.25	20.65	91.76	98.86

VII. CONCLUSION

This paper proposes a hierarchical coordinated dispatch strategy for MVPPs systems, integrating ETM with an energy-sharing framework, to address the issues of high communication redundancy, delayed response, and uneven profit distribution in coordinated dispatch processes.

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