

Multi-Time-Scale Optimal Dispatch of a Drilling Microgrid with Lithium Titanate Battery Energy Storage under Impulse Loads

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Abstract

Original Research Article

To address the severe impulse loads during tripping operations, the insufficient ramp capability of diesel generators, and the poor adaptability of conventional lithium-ion batteries to frequent deep charge–discharge cycles in islanded drilling-well microgrids, a multi-time-scale optimal dispatch method using a lithium titanate (LTO) battery as the core energy storage unit is proposed. The three-component decomposition characteristics of drilling load (base, impulse, and auxiliary components) are first analyzed, and the suitability of LTO batteries for drilling impulse conditions is demonstrated in terms of high-rate charge/discharge, long cycle life, wide temperature range, and safety. A three-layer collaborative dispatch framework is then established, comprising day-ahead economic dispatch, intra-day model predictive control (MPC), and real-time PQ power control. The day-ahead layer optimizes diesel output and storage schedules to minimize daily operating cost; the intra-day layer updates PV forecast errors every 15 min; the real-time layer performs impulse power smoothing within 100 ms and recovers downward-drilling braking energy. Simulation based on a 50DB drilling rig well site in an oilfield shows that, with a 1.725 MW/0.424 MWh LTO storage system, the diesel power fluctuation rate is reduced by 79%, the diesel ramp rate is controlled within 50 kW/min, the recovered braking energy reaches approximately 300 kWh per well (2.5% of daily electricity consumption), and the daily operating cost of the three-layer dispatch is reduced by about 19% compared with the two-layer scheme. The results verify the engineering applicability of LTO storage for impulse load smoothing and energy recovery in drilling microgrids, and can provide a reference for the design of green power supply systems at well sites.

Keywords: drilling microgrid; lithium titanate battery; impulse load smoothing; multi-time-scale dispatch; braking energy recovery; model predictive control.

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0 Introduction

Driven by the "dual carbon" goals, the oil and gas industry is accelerating its transition toward green and low-carbon operation. As an energy-intensive segment of oilfield production, drilling well sites have long relied on diesel generators for stand-alone power supply, suffering from high fuel consumption,

intensive carbon emissions, and elevated electricity costs^[1-2]. In recent years, well-site microgrids integrating distributed photovoltaics (PV) with energy storage have emerged as an important technical pathway to reduce fuel consumption and improve clean energy utilization^[3].

However, the operating environment of drilling-well



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microgrids is far more complex than that of conventional industrial microgrids. On one hand, the drawworks during tripping operations generate highly periodic impulse loads with large amplitudes; power swings can reach several hundred kilowatts with periods of only 120–220 s, far exceeding the minute-level ramp response capability of diesel generators [4–5]. On the other hand, well sites are typically located in remote areas, operating in islanded mode with short relocation cycles and unmanned supervision, which imposes stringent requirements on the cycle life, temperature adaptability, and safety of energy storage systems [6]. Conventional ternary lithium batteries suffer from rapid capacity fade and high thermal safety risks under frequent deep charge–discharge conditions, and are therefore inadequate for drilling impulse-load scenarios.

For impulse-load power compensation, existing studies have mostly employed flywheel energy storage or hybrid "lithium battery plus supercapacitor" schemes. Dai et al. [7] demonstrated through field tests that flywheel storage can reduce sudden diesel generator power surges by 40%–58%, but flywheels have low energy density and short-duration compensation. Wang et al. [8] adopted frequency-divided control in which supercapacitors handle high-frequency impulses and lithium batteries handle low-frequency fluctuations, resulting in a complex and costly system. Lithium titanate (LTO) batteries use a spinel-structured lithium titanate anode, exhibiting "zero-strain" characteristics, a cycle life exceeding 20,000 cycles, support for 5C–30C rate charge/discharge, a wide operating temperature range (–30 °C to 55 °C), and high intrinsic safety due to suppressed lithium dendrite formation [9–11].

This paper takes a 50DB drilling rig well site in an oilfield as the research object and investigates the suitability and dispatch strategies of LTO storage in drilling microgrids. Based on the three-component decomposition of drilling load, the technical suitability of LTO batteries for impulse conditions is analyzed. A three-layer dispatch framework—day-ahead, intra-day, and real-time—is constructed, in which the LTO battery serves simultaneously as an

energy buffer and an impulse smoother. Simulations verify the comprehensive improvements in diesel output smoothing, braking energy recovery, and operating economy delivered by LTO storage.

1. Drilling Load Characteristics and LTO Storage Suitability

1.1 Drilling Process and Three-Component Load Decomposition

Drilling operations are classified into typical modes such as drilling, tripping out, tripping in, making connections, and standby, with markedly different equipment compositions across modes [12]. Taking a 50DB rig as an example, the main electrical loads include the drawworks, rotary table, mud pumps, and auxiliary systems (ventilation, lighting, control systems, etc.). Based on statistical analysis of on-site power time-series data, the total drilling load can be decomposed into three components:

$$P_L(t) = P_{base}(t) + P_{pulse}(t) + P_{aux}(t) \quad (1-1)$$

(1) Base component: Composed of mud pumps, circulation systems, and auxiliary equipment; the power is stable with daily fluctuations generally within $\pm 10\%$, forming the baseline of the well-site load.

(2) Impulse component: Generated by drawworks during tripping, exhibiting quasi-periodic pulsations. The power reaches 300–600 kW when pulling the drillstring up and drops to 150–300 kW when lowering, with a period of 120–220 s and an instantaneous peak up to 800 kW.

(3) Auxiliary component: Intermittent operational loads such as making connections and pipe racking, with short duration and strong randomness.

The engineering significance of the three-component model lies in the clear division of responsibility across time scales: the base component is supplied by the diesel generator, the impulse component must be compensated rapidly by the energy storage converter, and the auxiliary component is reserved with a probability margin in day-ahead dispatch. This division directly determines the design principles for subsequent equipment configuration

and control strategies.

1.2 Technical Requirements for Energy Storage under Impulse Loads

Drilling impulse loads exhibit three salient features. First, the rate of change is fast, with power ramps often exceeding 200 kW/min, which the diesel generator cannot track due to mechanical inertia. Second, cycling frequency is high: over a single well, tripping operations may exceed 50 cycles, subjecting the battery to numerous charge–discharge loops every day. Third, the operating environment is harsh: container temperatures can exceed 40 °C in summer, and the site is unmanned, imposing extreme requirements on battery rate capability, cycle life, temperature adaptability, and thermal safety.

1.3 LTO Battery Characteristics and Suitability

The LTO battery anode adopts spinel-structured $\text{Li}_4\text{Ti}_5\text{O}_{12}$, with a lattice volume change of less than 1% during lithium insertion/extraction, hence termed a "zero-strain" material. Compared with conventional ternary lithium (NCM) batteries, LTO batteries offer the following advantages in drilling scenarios:

(1) Long cycle life. Cyclic experiments by Zhong et al. show that LTO batteries cycled within the 20%–90% SOC range exhibit slow capacity fade, with a cycle life exceeding 20,000 cycles—roughly 5 to 10 times that of NCM batteries. This accommodates the high-frequency, deep charge–discharge patterns at drilling sites and significantly reduces whole-life replacement costs.

(2) High-rate capability. LTO batteries support 5C–30C rate charge/discharge with millisecond-level response, enabling them to independently handle second-level drilling impulse components without additional supercapacitor frequency-divided compensation required for NCM systems.

(3) Excellent safety. The high anode potential of LTO (about 1.55 V vs. Li/Li^+) suppresses lithium dendrite plating and reduces internal short-circuit risk; the battery also maintains favorable thermal

safety even under mild over-discharge, making it suitable for unmanned well-site operation.

(4) Wide temperature range. LTO batteries operate reliably from $-30\text{ }^{\circ}\text{C}$ to $55\text{ }^{\circ}\text{C}$, adapting well to both summer heat and winter cold at remote well sites.

1.4 SOC Operating Range Optimization Based on Aging Mechanisms

Battery cycle life is closely related to the operating SOC window. Zhong et al. showed that reducing the SOC upper limit from 100% to 80%, or raising the SOC lower limit from 0% to 20%, significantly improves capacity retention; within the 0%–20% low-SOC range, active lithium loss and cathode material degradation occur simultaneously, resulting in more complex fading mechanisms. Wang et al.^[13] further pointed out that calendar aging at high temperatures is positively correlated with storage SOC, and long-term high-SOC storage accelerates cathode side reactions.

Based on these aging mechanisms, the SOC operating range of the LTO storage is set to 0.1–0.9, avoiding both the 0%–20% high-degradation low-SOC region and prolonged full charge to 100%. In addition, to ensure emergency power supply, at least 30% of rated capacity must be reserved at any time to meet 10-minute full-load emergency requirements for critical drilling loads. This operating range provides a physical basis for the SOC constraints in the subsequent dispatch model.

2. Well-Site Microgrid Architecture and Multi-Time-Scale Dispatch Model

2.1 System Architecture

The well-site microgrid consists of a PV unit, an LTO storage unit, a diesel generator, and drilling loads, configured with a DC bus and operating in islanded mode. The PV array connects to the DC bus through a DC/DC converter operating in MPPT mode, with full consumption under normal conditions. The LTO storage connects to the bus through a bidirectional DC/DC converter in PQ control mode. The diesel generator connects through

a rectifier, serving as the main source for base-load supply and power balance. The system topology and

energy flow are shown in Fig. 1.

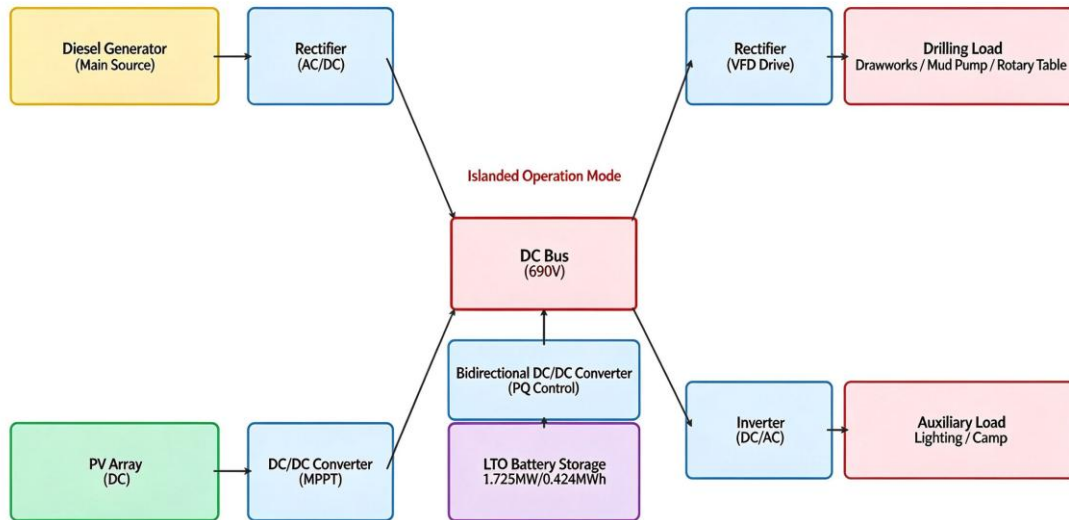


Fig. 1 Schematic diagram of the well-site microgrid topology

According to demonstration project parameters, the PV capacity is sized based on available well-site area, with a performance ratio (PR) of 0.80. The standard LTO storage unit is rated at 1.725 MW/0.424 MWh, integrated into a 30-foot container and paired with a PCS-1725/0.69 converter, providing 0.8 MW full-load emergency backup for at least 10 min. A single diesel generator is rated to cover the 800 kW maximum load with margin, with a full-load fuel consumption of approximately 198 g/kWh.

2.2 Three-Layer Multi-Time-Scale Dispatch Framework

Drilling impulse loads and PV forecast deviations occur across different time scales; a single-time-scale dispatch cannot simultaneously balance economy and fast response. This paper establishes a three-layer collaborative framework: day-ahead economic dispatch, intra-day MPC rolling optimization, and real-time PQ impulse smoothing. The time scales and responsibilities of each layer are listed in Table 1.

Table 1 Time scales and tasks of the three-layer dispatch framework

Dispatch layer	Time scale	Core task	Solution method
Day-ahead	24 h / 15-min step	Unit commitment, daily storage schedule	MILP optimization
Intra-day	4-h horizon / 15-min rolling	Correct PV and load forecast deviations	MPC rolling optimization
Real-time	100-ms response	Impulse smoothing, braking energy recovery	PQ control rules

The three layers form a closed loop through "reference dispatch–actual feedback": the day-ahead layer generates 96-interval diesel output and SOC trajectories; the intra-day layer revises the plan every 15 min based on the latest PV forecast and measured SOC; the real-time layer controls the converter according to the intra-day references and feeds back actual SOC to the intra-day layer.

2.3 Day-Ahead Economic Dispatch Model

The day-ahead layer minimizes total daily operating cost, including diesel fuel cost, unit startup/shutdown cost, and storage cycling loss cost:

$$\min F = \sum_t [C_f \cdot P_{DG}(t) + C_{su} \cdot u(t) + C_{ess} \cdot (|P_{ch}(t)| + |P_{dis}(t)|)] \quad (2-1)$$

where C_f is the diesel fuel cost coefficient; $P_{DG}(t)$ is diesel output at interval t ; C_{su} is the startup/shutdown cost; $u(t)$ is the unit commitment state; C_{ess} is the per-unit charge/discharge loss cost of storage; $P_{ch}(t)$ and $P_{dis}(t)$ are storage charging and discharging power, respectively.

The constraints include:

① Power balance: $P_{PV}(t) + P_{DG}(t) + P_{dis}(t) = P_L(t) + P_{ch}(t)$;

② Storage SOC dynamics: $SOC(t+1) = SOC(t) + (\eta_{ch} \cdot P_{ch}(t) - P_{dis}(t) / \eta_{dis}) \cdot \Delta t / E_N$, with SOC constrained within [0.1, 0.9];

③ Diesel minimum stable output ($\geq 30\%$ rated power), ramp rate, and startup/shutdown count constraints;

④ To handle uncertainty, a robustness budget parameter Γ is introduced to limit the number of uncertain variables simultaneously taking worst-case values. The model is solved in MATLAB with Yalmip/Gurobi, and the 96-interval optimization converges within 1 minute.

2.4 Intra-Day MPC Rolling Optimization

PV forecast errors accumulate over time, causing deviations when the day-ahead plan is executed intra-day. The intra-day layer adopts MPC: a 15-min rolling period and a 4-h prediction horizon, re-solving at each roll. The objective tracks the day-ahead plan while penalizing deviations in diesel output and storage SOC:

$$\min J = \sum_{k=0}^{N_p} [\omega_1 \cdot (P_{DG}(k) - P_{DG}^{day(k)})^2 + \omega_2 \cdot (SOC(k) - SOC^{day(k)})^2 + \omega_3 \cdot |P_{ess}(k)|] \quad (2-2)$$

where N_p is the prediction horizon; ω_1 and ω_2 are tracking weights; ω_3 is the storage action cost weight. Simulations show that with a 4-h horizon and moderate tracking weights, the maximum diesel ramp rate is reduced from 100 kW/min (without correction) to 42 kW/min, and the SOC swing range is narrowed to 0.3–0.8, balancing tracking accuracy and economy.

2.5 Real-Time PQ Impulse Smoothing and Braking Energy Recovery

The real-time layer performs no optimization calculation; instead, it acts according to predefined control rules within 100 ms. The storage converter operates in PQ mode, with the real-time power reference given by:

$$P_{\text{ess_ref}}(t) = P_{\text{PV}}(t) + P_{\text{DG_ref}}(t) - P_{\text{L}}(t) \quad (2-3)$$

where $P_{\text{ess_ref}}(t)$ is the diesel reference dispatched by the intra-day layer; $P_{\text{PV}}(t)$ and $P_{\text{L}}(t)$ are measured PV output and drilling load. Through this control law, the storage tracks the net load fluctuation in real time, so that the diesel output always follows the reference without being disturbed by the impulse component.

The real-time controller uses a dual-loop structure: an outer power loop (bandwidth 10 Hz) and an inner current loop (bandwidth 1 kHz), ensuring power tracking within 100 ms. To protect the battery, discharge power is limited to 50% of rated when $\text{SOC} > 0.85$, and charge power is limited to 50% of rated when $\text{SOC} < 0.15$ —a "soft limit" strategy that protects the storage while maintaining compensation capability.

During downward drilling, the drillstring accelerates under gravity and the drawworks switches to generating mode, producing braking energy. Conventional schemes dissipate this energy in braking resistors. In this work, the LTO storage absorbs braking energy: during downward drilling, the converter operates in rectifier mode to store the drawworks generation, and releases the energy during subsequent upward pulls. This function leverages the high-rate charging capability of LTO batteries and is a distinct advantage over flywheels: flywheels only provide short pulse compensation, whereas LTO batteries simultaneously fulfill both

energy-level and power-level functions.

3. Simulation Analysis

3.1 Case Setup

A 50DB drilling rig well site in an oilfield is used as the case study, simulated in MATLAB/Yalmip/Gurobi. The system comprises a PV array, a 1.725 MW/0.424 MWh LTO storage system, and a diesel generator. Five typical daily scenarios are generated using Latin Hypercube Sampling and K-medoids clustering, covering summer sunny days, tripping-heavy operation, spring/autumn, winter low-output, and extreme fluctuation conditions, with probability weights of 0.25, 0.20, 0.20, 0.20, and 0.15, respectively. The simulation time step is 15 min for the day-ahead/intra-day layers and 1 ms for the real-time layer.

3.2 Day-Ahead Dispatch and PV Consumption

Taking the summer sunny scenario (S1) as an example, PV output is concentrated between 06:00 and 18:00, with a noon peak of about 500 kW. The day-ahead optimization shows that the diesel generator runs at full load during the night when PV is zero; as PV rises during the day, the diesel gradually reduces output to prioritize PV consumption. The LTO storage charges during 12:00–15:00 when PV is abundant, with an average charging power of about 95 kW and SOC rising from 0.1 to 0.9; it discharges during the evening load peak to supplement the diesel output. This "charge at noon, discharge in the evening" pattern effectively improves PV consumption, with a weighted PV curtailment rate below 5% across the five scenarios.

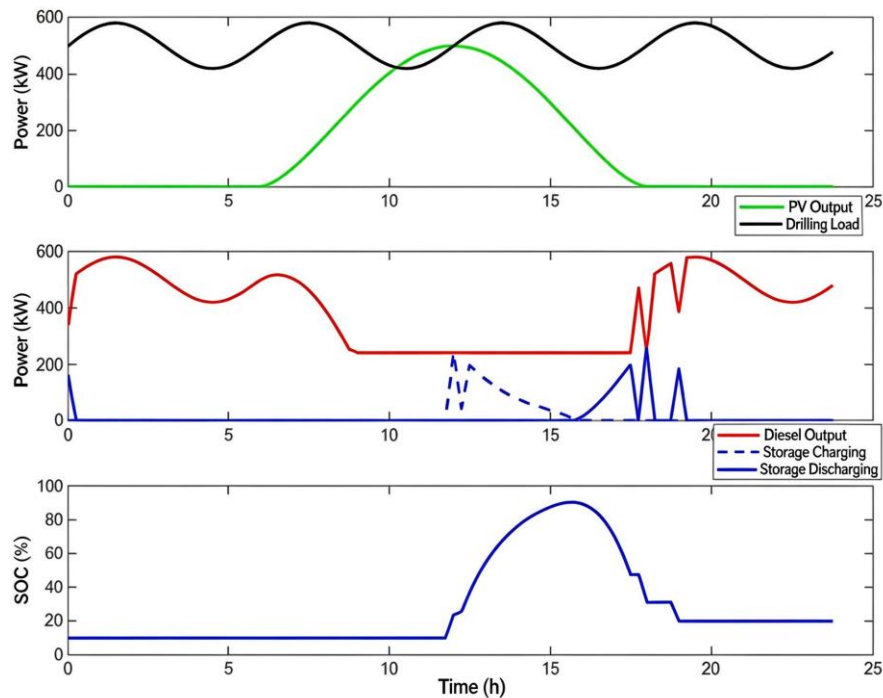


Fig. 2 Day-ahead dispatch schedule and SOC trajectory for a typical sunny day

3.3 Intra-Day MPC Correction Effect

A $\pm 10\%$ PV forecast error is superimposed on the day-ahead plan to simulate intra-day rolling optimization. Without intra-day correction, the diesel output rises rapidly during cloud-cover periods, with the maximum ramp rate exceeding 100 kW/min—beyond the dynamic capability of the diesel. With MPC correction, the diesel output becomes smooth, the ramp rate is controlled within 50 kW/min, and PV forecast deviations are absorbed by the storage. Meanwhile, SOC swings are narrowed from deep discharge (down to 0.15 without correction) to the 0.3–0.8 range.

Compared with the two-layer scheme (day-ahead + real-time only), the three-layer dispatch reduces the daily cost of scenario S1 from 20,433 yuan to 16,536 yuan, a reduction of about 19%. The cost saving comes mainly from avoiding unnecessary storage cycling and inefficient diesel operation caused by forecast deviations.

3.4 Real-Time Impulse Smoothing Performance

Taking the tripping scenario (S2), a 4-min tripping process is simulated. Without storage, the impulse load causes diesel output to swing violently between 300 and 700 kW, with ramp rates exceeding 200 kW/min. With the 1.725 MW LTO storage, the impulse component is handled by the storage, and the diesel output smoothly tracks the 500 kW reference, with fluctuations controlled within ± 50 kW. The converter discharges about 400 kW during the upward impulse and charges about 300 kW during the downward swing.

The compensation effect is quantified by the diesel power standard deviation: 120 kW before compensation and 25 kW after, corresponding to a 79% reduction in power fluctuation. This outperforms the 40%–58% flywheel peak-shaving effect reported by Dai et al. , verifying the effectiveness of LTO batteries in independently compensating drilling impulses.

To examine the effect of storage rating, four configurations—0.5 MW, 1.0 MW, 1.725 MW, and

2.5 MW—are tested, as shown in Table 2.

Table 2 Impulse smoothing performance under different LTO storage ratings

Power rating / MW	Diesel Std / kW	Fluctuation reduction / %	Compensation evaluation
0.5	85	29	Insufficient
1.0	48	60	Adequate
1.725	25	79	Significant
2.5	22	82	Marginal gain

When the rating increases from 0.5 MW to 1.725 MW, the smoothing effect improves significantly; further increasing to 2.5 MW yields diminishing returns. This indicates that the 1.725 MW configuration is near saturation for drilling impulse smoothing, consistent with the demonstration project selection.

3.5 Braking Energy Recovery Analysis

The drawworks potential energy during downward drilling can be recovered ^[14]. Simulation results show that a typical downward drilling run recovers about 15 kWh, approximately 3.5% of rated storage capacity. Although the energy recovered per run is modest, with an average of 50 tripping cycles per well, the cumulative recovery reaches about 300 kWh, accounting for 2.5% of daily electricity consumption. The field measurements by Du et al. on offshore drilling platforms report a comparable recovery ratio, validating the engineering value of this approach.

3.6 Comprehensive Economic Analysis

The weighted average daily dispatch cost across the five typical scenarios is approximately 26,163 yuan. Among them, the extreme fluctuation scenario (S5) has the highest cost (35,534 yuan), while the summer

sunny scenario (S1) has the lowest (16,536 yuan under three-layer dispatch). By introducing the robustness budget parameter Γ to balance economy and robustness, simulations show that at $\Gamma = 0.7$, the daily cost is only 4.5% higher than the most economical case, the loss-of-power probability drops to 0.1%, and power balance is maintained under extreme scenarios—representing the optimal trade-off between economy and robustness.

From a life-cycle perspective, although the initial investment of LTO batteries is higher than that of NCM batteries, their cycle life exceeding 20,000 cycles extends the replacement interval by 5–10 years. Under the high-frequency cycling conditions at drilling sites, the whole-life cost is actually more favorable. Furthermore, braking energy recovery (about 300 kWh per well) and fuel savings from smoother diesel operation further improve system economy.

4. Conclusion

This paper addresses the severe impulse loads and the inadequate adaptability of conventional batteries in islanded drilling-well microgrids, and proposes a multi-time-scale optimal dispatch method centered on lithium titanate battery energy storage. Theoretical analysis and simulations lead to the following conclusions:

(1) Drilling load exhibits a distinct three-component structure. The impulse component oscillates quasi-periodically at 120–220 s with peaks up to 800 kW and requires fast storage compensation. LTO batteries are highly suited to drilling impulse conditions in terms of cycle life (>20,000 cycles), rate capability (5C–30C), temperature adaptability, and thermal safety.

(2) The proposed three-layer framework of "day-ahead MILP—intra-day MPC—real-time PQ control" achieves well-coordinated multi-time-scale operation: the intra-day MPC reduces the maximum diesel ramp rate from 100 kW/min to 42 kW/min, and the real-time layer completes impulse compensation within 100 ms, lowering the diesel power fluctuation rate by 79%.

(3) While smoothing impulses, the LTO storage recovers downward-drilling braking energy of about 300 kWh per well (2.5% of daily consumption). The three-layer dispatch reduces daily cost by about 19% compared with the two-layer scheme. Simulations indicate that the 1.725 MW/0.424 MWh LTO configuration is near saturation for impulse smoothing.

Future work may introduce supercapacitors to form a hybrid energy storage system for further extending LTO battery life, and validate the real-time control strategy through hardware-in-the-loop experiments under realistic converter and communication delay conditions.

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