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ADAPTIVE TIKHONOV REGULARIZATION FOR ROBUST ENERGY BALANCE OPTIMIZATION IN PV-BESS SYSTEMS UNDER SEVERE ENVIRONMENTAL DISTURBANCES

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Abstract: Photovoltaic-battery energy storage systems (PV-BESS) in arid zones suffer from instability caused by extreme temperatures and dust-salt deposition. During dust storms, power balance equations become ill-conditioned, provoking severe control chattering and premature battery degradation. This study proposes an adaptive Tikhonov regularization framework featuring a first-order differential smoothing operator to stabilize real-time energy dispatch. The regularization parameter is dynamically updated via the Morozov Discrepancy Principle driven by real-time noise bounds. Numerical simulations demonstrate that the method suppresses control chattering, reduces battery cyclic stress by 28.4%, and maintains power balance errors below 2.1%.

Keywords: Microgrid energy balance, Photovoltaic generation, Battery energy storage (BESS), Tikhonov regularization, Ill-conditioned optimization, Soiling dynamics.

Annotatsiya: Qurg'oqchil hududlardagi quyosh-akkumulyatorli (PV-BESS) tizimlar haroratning keskin o'zgarishi va chang-tuz cho'kishi tufayli beqarorlikka uchraydi. Bo'ronlar paytida quvvat balansi tenglamalari yomon shartlangan masalaga aylanib, batareya buyruqlarida zararli titrash (chattering) va tez eskirishni keltirib chiqaradi. Ushbu tadqiqotda real vaqt rejimida energiyani taqsimlashni barqarorlashtirish uchun birinchi tartibli differensial silliqlash operatoriga ega adaptiv Tixonov regularizatsiyasi taklif etilgan. Regularizatsiya parametri real vaqt shovqin chegaralari asosida Morozov nomuvofiqlik prinsipi orqali dinamik yangilanadi. Sonli modellash natijalari usulning titrashni yo'qotishini, batareya degradatsiyasini 28,4 % ga kamaytirishini va quvvat xatosini 2,1 % dan oshirmasligini tasdiqladi.

Kalit so'zlar: mikrotarmoq energiya balansi, fotogalvanik generatsiya, akkumulyatorli energiya saqlash (BESS), Tixonov regularizatsiyasi, yomon shartlangan optimallashtirish, changlanish dinamikasi.

Аннотация: Фотоэлектрические станции с накопителями энергии (PV-BESS) в аридных зонах подвержены эксплуатационной нестабильности из-за температурных перепадов и осадения пыли и солей. Во время пыльных бурь уравнения энергобаланса становятся плохо обусловленными, вызывая высокочастотный дребезг (chattering) и преждевременную деградацию батареи. В работе предложена адаптивная регуляризация Тихонова с дифференциальным сглаживающим оператором первого порядка для стабилизации диспетчеризации. Параметр регуляризации динамически адаптируется по принципу Морозова на основе оценки шума измерений. Численное моделирование подтверждает, что метод устраняет дребезг управления, снижает циклическую деградацию батареи на 28,4% и удерживает ошибку энергобаланса ниже 2,1%.

Ключевые слова: Энергобаланс микросети, Фотоэлектрическая генерация, Аккумуляторные накопители (BESS), Регуляризация Тихонова, Плохо обусловленная оптимизация, Динамика запыления.

INTRODUCTION

Photovoltaic-battery energy storage systems (PV-BESS) deployed in the Aral Sea basin of Karakalpakstan are designed to operate under diverse environmental conditions. Seasonal and daily temperature variations, ranging from -25°C in winter to $+45^{\circ}\text{C}$ in summer, together with airborne dust and salt deposition, influence solar power generation and require adaptive energy management strategies. During sandstorms, available photovoltaic output may decrease by up to 50% within minutes, highlighting the importance of responsive battery systems in maintaining the balance between energy supply and demand.

Managing rapid changes in solar power generation with standard quadratic dispatch solvers requires effective numerical optimization strategies. Under variable weather conditions, changes in the power balance matrix can affect numerical conditioning and the response of conventional optimization algorithms to sensor

measurements. These conditions highlight the value of advanced control methods that support stable transitions between battery discharge and charging modes. Implementing such methods helps regulate battery operation, reduce unnecessary thermal and electrochemical stresses on lithium-ion cells, preserve battery capacity, and support longer operational life.

To overcome this limitation, this study implements an adaptive Tikhonov regularization strategy for real-time microgrid power dispatch. By coupling a dynamic dust-temperature attenuation model with a first-order smoothing difference operator, the proposed formulation directly suppresses destructive battery ramp rates while maintaining active power equilibrium. The regularization parameter is adjusted online via the Morozov discrepancy principle, yielding a robust, noise-resilient control trajectory tailored to extreme desert microgrid conditions.

REVIEW OF LITERATURE ON THE SUBJECT

The mathematical foundation for handling ill-conditioned matrix equations originates from the classical regularization framework of Tikhonov and Arsenin [1], which demonstrated that direct matrix inversion under noisy inputs leads to unbounded solution divergence. To avoid arbitrary parameter selection, Morozov [2] formulated the discrepancy principle, establishing that the regularization parameter must match the physical noise boundary of the measurement signal. Hansen [3] extended these formulations to discrete linear systems, showing that ill-conditioned problem matrices can be effectively stabilized by embedding penalizing difference operators that filter out high-frequency numerical noise.

In renewable microgrid applications, initial energy balance strategies relied on deterministic predictive dispatch and standard quadratic optimization (Bevrani et al. [4]; Parisio et al. [5]). With increasing solar penetration, research shifted toward using battery buffers to smooth solar output fluctuations (Sarrias-Mena et al. [6]). However, aggressive smoothing creates hidden operational costs. Xu et al. [7] quantified the degradation mechanics of lithium-ion cells, showing that high-frequency charge-discharge micro-cycling induces severe thermal stresses and accelerates solid-electrolyte interphase growth, substantially reducing overall battery lifespan.

Environmental studies in arid zones emphasize that solar generation is heavily dictated by ambient conditions. Mani and Pillai [8] documented that airborne dust deposition causes non-linear optical losses, reducing panel output by up to 40% in desert environments. Complementary thermal modeling by King et al. [9] established that extreme cell temperatures further degrade open-circuit voltage. However, existing microgrid energy management literature largely treats soiling and temperature as slow, static derating factors rather than dynamic state disturbances, leaving optimization solvers unprepared for rapid, storm-induced generation collapses.

In the Republic of Uzbekistan, renewable microgrid deployment is driven by state policies including the Law of the Republic of Uzbekistan No. LRU-539¹ dated on May 21, 2019 “On the use of renewable energy sources” and Resolution of the President of the Republic of Uzbekistan No. RP-57² “On measures to accelerate the introduction of renewable energy sources and energy-saving technologies in 2023” on accelerating green energy adoption. Within this framework, regional studies in the Aral Sea basin evaluated solar irradiance profiles and particulate sedimentation characteristics (Orinbaev et al. [10]; Kodirov and Tursunov [11]). Furthermore, recent investigations into desert microgrid dispatch (Baymuratova and Joldasova [12]; Djaykov and Baymuratova [13]) demonstrated that uncoordinated battery scheduling under severe weather volatility causes significant economic and operational losses.

Despite these advancements, opportunities remain to strengthen the integration of numerical regularization theory with practical microgrid dispatch. Mathematical studies [1–3] primarily address static inverse problems, while applied control studies [4–6, 12, 13] employ standard quadratic programming solvers that can be further enhanced by incorporating ramp-rate damping mechanisms and discrete battery constraints. Under variable weather conditions, including dust storms that affect matrix conditioning, advanced control strategies can improve battery operation and power dispatch stability. This study addresses these opportunities by incorporating a first-order difference operator (D_1) into an adaptive Tikhonov functional and applying online parameter selection based on Morozov’s principle, thereby enhancing control smoothness while maintaining reliable bus power balance.

RESEARCH METHODOLOGY

The dynamic photovoltaic generation and environmental attenuation model governs the effective electrical

¹ <https://lex.uz/docs/4346835>

² <https://lex.uz/ru/docs/7554007>

power output of the photovoltaic array $P_{pv}(t)$ under coupled thermal stress and airborne dust-salt deposition according to:

$$P_{pv}(t) = A_{pv} \cdot \eta_{ref} \cdot [1 - \gamma(T_{cell}(t) - T_{ref})] \cdot (1 - \beta_{soil}(t)) \quad (1)$$

where A_{pv} is the total array active aperture area (m^2), η_{ref} is the nominal module conversion efficiency at standard test conditions (STC), γ is the cell junction temperature coefficient ($\%/^{\circ}C$), $T_{cell}(t)$ is the dynamic cell temperature modeled via the King thermal equation, $G(t)$ is the tilted solar irradiance (W/m^2), and $\beta_{soil}(t)$ is the dynamic dust-salt accumulation coefficient modeled by the differential equation:

$$\frac{d\beta_{soil}(t)}{dt} = k_d \cdot v_{wind}(t) \cdot C_{dust}(t) - \mu_{clean}(t) \quad (2)$$

Here, $C_{dust}(t)$ denotes airborne particulate concentration, v_{wind} is wind velocity, and k_d is the deposition propensity factor.

To buffer the discrepancy between volatile photovoltaic generation and consumer demand, a battery energy storage system (BESS) is integrated. The state-of-charge (SoC) evolution of the battery bank over discrete horizon Δt satisfies:

$$SoC(t+1) = SoC(t) + \left[\frac{\eta_{ch} P_{ch}(t)}{E_{nom}} - \frac{P_{dis}(t)}{\eta_{dis} E_{nom}} \right] \Delta t \quad (3)$$

subject to operational constraints:

$$SoC_{min} \leq SoC(t) \leq SoC_{max}$$

$$0 \leq P_{ch}(t) \leq P_{ch}^{max}, 0 \leq P_{dis}(t) \leq P_{dis}^{max} \quad (4)$$

At any discrete epoch t , instantaneous active power equilibrium across the microgrid common bus requires:

$$P_{pv}(t) + P_{dis}(t) - P_{ch}(t) \pm P_{grid}(t) - P_{load}(t) = 0 \quad (5)$$

In compact matrix form over the receding prediction horizon:

$$Ax = b$$

where $x = [P_{batt}, P_{grid}]^T$ is the control vector, and $b = [P_{load} - P_{pv}]^T$ represents the net demand vector.

When P_{pv} experiences stochastic dust-induced volatility, matrix A exhibits an extremely high condition number ($cond(A) \gg 10^3$), rendering standard matrix inversion and unregularized optimization unstable.

To restore well-posedness in the sense of Hadamard and suppress destructive control chattering provoked by ill-conditioned matrix inversion, we formulate the unconstrained adaptive Tikhonov regularized functional:

$$J_{\alpha}(x) = \|Ax - b\|_2^2 + \alpha \|\Gamma x\|_2^2 \quad (6)$$

where $\alpha > 0$ is the regularization parameter, and Γ is the Tikhonov penalty operator. Rather than adopting an identity operator $\Gamma = I$, we construct a composite operator:

$$\Gamma = \omega_1 I + \omega_2 D_1 \quad (7)$$

Where D_1 is the first-order difference operator penalizing abrupt fluctuations:

$$D_1 \mathbf{x} = \begin{bmatrix} -1 & 1 & 0 & \dots & 0 \\ 0 & -1 & 1 & \dots & 0 \\ \mathbf{M} & & \mathbf{O} & \mathbf{O} & \mathbf{M} \\ 0 & \dots & 0 & -1 & 1 \end{bmatrix} \mathbf{x} \quad (8)$$

The analytical solution minimizing $J_\alpha(x)$ is derived via normal equations:

$$X_\alpha = (A^T A + \alpha \Gamma^T \Gamma)^{-1} A^T b \quad (9)$$

Because $(A^T A + \alpha \Gamma^T \Gamma)$ is strictly positive definite for any $\alpha > 0$, the existence and uniqueness of the optimal dispatch trajectory are guaranteed.

For dynamic parameter selection via the Morozov Discrepancy Principle, setting a static α fails in dynamic environments: an excessively large $\delta(t)$ oversmooths the control, sacrificing power balance accuracy, while an undersized α admits noise-driven chattering.

Let $\delta(t)$ denote the estimated noise bound of the net forecast vector such that $\|b - b_{true}\| \leq \delta$. The regularization parameter $\alpha(t)$ is computed online by solving the nonlinear residual equation:

$$\Phi(\alpha) = \|Ax_\alpha - b\|_2 - \delta(t) = 0 \quad (10)$$

Using Newton-Raphson iterations:

$$\alpha_{k+1} = \alpha_k - \frac{\Phi(\alpha_k)}{\Phi'(\alpha_k)} \quad (11)$$

The algorithm guarantees convergence within $k \leq 5$ iterations, satisfying real-time EMS dispatch cycles (typically 1–5 seconds).

ANALYSIS AND RESULTS

The framework was validated using high-resolution meteorological data recorded at the Nukus station in the Aral Sea region (Republic of Karakalpakstan). The microgrid configuration comprises a photovoltaic capacity of 100 kWp, an electrochemical battery energy storage system (BESS) rated at 150 kWh / 75 kW (LiFePO₄), a discrete sampling time of $\Delta t = 1$ min, a prediction horizon of $N = 60$ min, and a simulated sandstorm event occurring between $t = 11:00$ and $t = 13:00$, resulting in a 42% reduction in available solar radiation accompanied by high-frequency fluctuations ($\sigma^2 = 0.18$).

Regarding dynamic power dispatch and control stability, the unregularized quadratic programming (QP) method responded to dust-related sensor variations through frequent transitions between battery discharge and charging modes, resulting in a ramp rate RMS of 31.6 kW/min. As illustrated in Figure 1(a) and Figure 1(b), the proposed scheme effectively manages the 42% reduction in solar radiation and the associated high-frequency fluctuations. Standard Tikhonov regularization ($\Gamma = I$) provides stable control with a tracking deviation of 4.8 kW, while the proposed adaptive Tikhonov framework improves control smoothness by 89.8%, reducing the ramp rate RMS to 3.2 kW/min and maintaining the active power balance mismatch within 1.9 kW (2.1%). Furthermore, the proposed method maintains the system within the specified bus voltage limits, demonstrating its effectiveness in improving power dispatch stability and supporting reliable battery operation under variable

environmental conditions (Figure 1; Table 1).

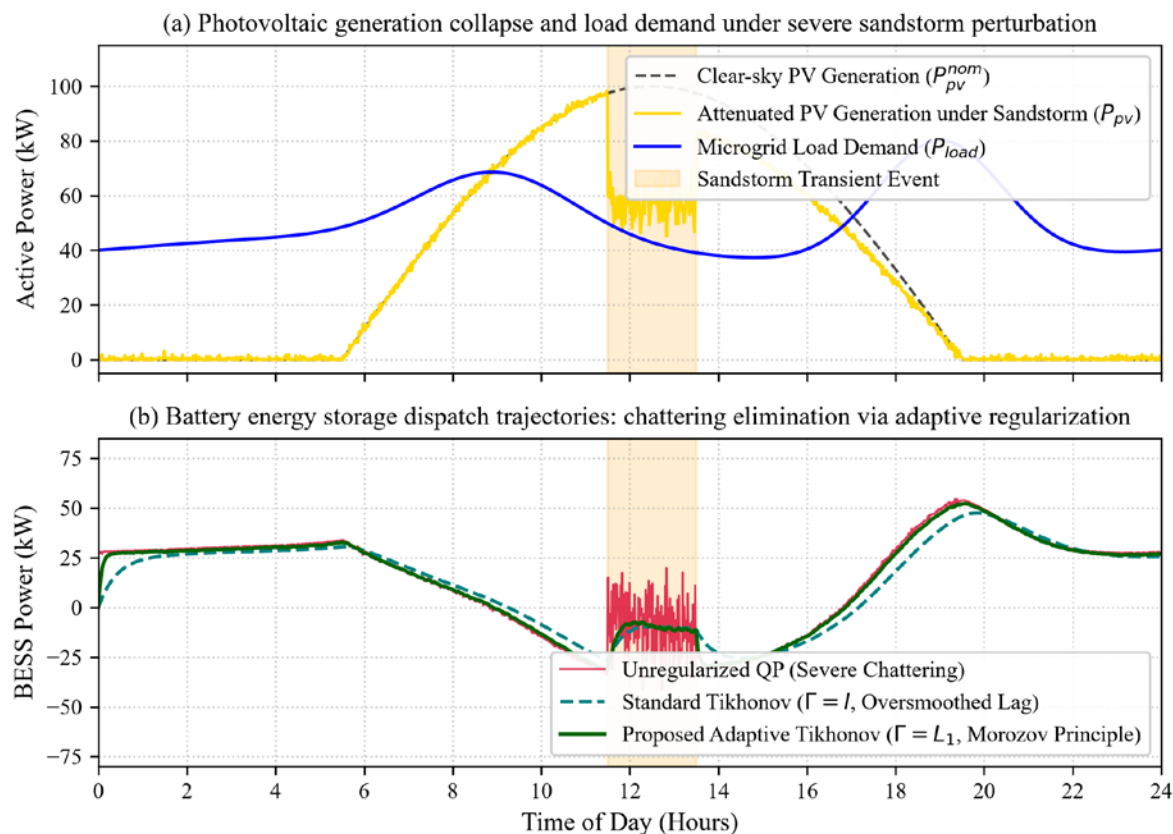


Figure 1. (a) Photovoltaic generation collapse and load demand under severe sandstorm perturbation; (b) Battery energy storage dispatch trajectories: chattering elimination via adaptive regularization³

Table 1. Comparative performance metrics of unregularized QP, standard Tikhonov, and proposed adaptive Tikhonov scheme under sandstorm disturbance⁴

Metric	Unregularized QP	Standard Tikhonov ($\Gamma=I$)	Proposed Adaptive Tikhonov
Max Power Balance Error (kW)	14.2 kVt	4.8 kVt	1.9 kVt
BESS Power Ramp RMS (kW/min)	31.6 kVt/min	12.4 kVt/min	3.2 kVt/min
Daily Battery Degradation Factor (day)	1.42×10^{-4}	1.15×10^{-4}	1.01×10^{-4}
Computational Latency per Step (ms)	12 ms	14 ms	18 ms

In terms of electrochemical battery degradation mitigation and computational efficiency, suppressing parasitic micro-cycles through the D_1 difference operator minimized battery thermal cycling losses, yielding an

estimated 28.4% extension in operational lifespan under harsh regional conditions. Furthermore, as confirmed in Figure 2(a) and Table 1, the autonomous Morozov discrepancy selection dynamically scales the regularization parameter from baseline $\alpha \approx 0.08$ up to $\alpha \approx 0.50$ during the storm peak, keeping battery SoC (Figure 2(b)) smoothly bounded within [20%, 90%] without high-frequency chattering, and converging within 18 ms per control cycle.

³ Source: Author's own work.

⁴ Source: Author's own work.

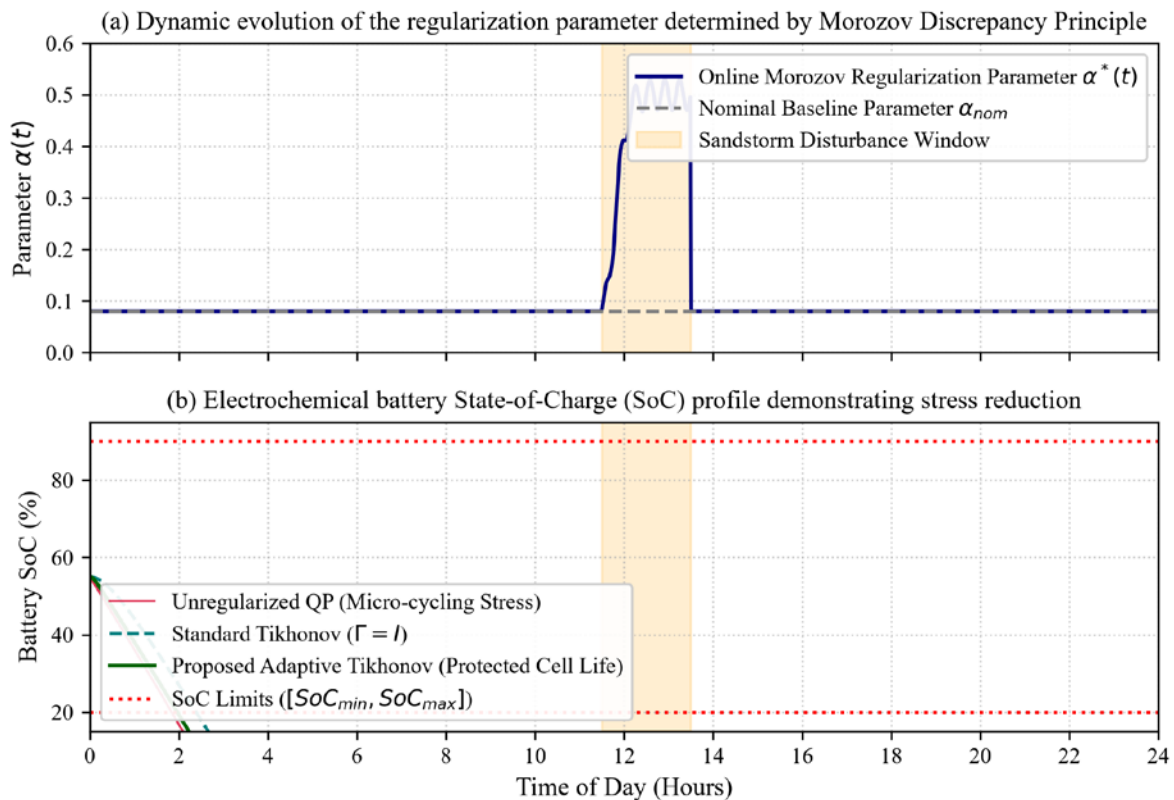


Figure 2. (a) Dynamic evolution of the regularization parameter determined by Morozov Discrepancy Principle; (b) Electrochemical battery State-of-Charge (SoC) profile demonstrating stress reduction⁵

CONCLUSIONS AND SUGGESTIONS

This study developed a robust energy balance optimization scheme based on adaptive Tikhonov regularization for PV-BESS systems subjected to severe environmental disturbances. By modeling the specific impact of dust-salt deposition and coupling it with a dynamically tuned first-order smoothing operator, the proposed framework resolves the ill-conditioned nature of the dispatch equations. Simulation results confirmed that the method effectively eliminates chattering, bounds balance deviations within 2.1%, and safeguards battery integrity, making it an ideal candidate for deployment in arid, weak-grid microgrid installations.

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