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SIMULATION AND PERFORMANCE ANALYSIS OF PID-TYPE ITERATIVE LEARNING CONTROL IN THE LABORATORY LINE TESTING OF CYLINDRICAL CELL BATTERIES

Abstract: *The increasing demand for reliable rechargeable energy storage systems has strengthened the need for accurate laboratory testing procedures for cylindrical cell batteries. Laboratory and pilot-line testing stations repeatedly perform charging, discharging, voltage verification, capacity estimation, and internal resistance measurements. These operations require precise current and voltage regulation because even small transient deviations may affect cell classification, aging analysis, and safety evaluation. This work presents a simulation-based study of PID-type Iterative Learning Control (PID-type ILC) for repeated laboratory line testing of cylindrical cell batteries. The proposed approach combines the classical proportional-integral-derivative control structure with an iterative learning mechanism that updates the control input after each repeated cycle using the previous tracking error. A simplified MATLAB model of a cylindrical battery charging process was developed using state-of-charge dynamics, internal resistance, terminal voltage estimation, actuator saturation, and a repeated finite-time testing interval. The simulation evaluates the controller response over successive cycles and analyzes current tracking, voltage behavior, control effort, state of charge, and error convergence. The results demonstrate that PID-type ILC can reduce tracking error over repeated cycles and improve the repeatability of laboratory battery testing. The method is especially relevant for automated quality-control lines where many cells are tested under similar protocols. The proposed simulation can serve as a preliminary digital model before experimental implementation on a real battery testing bench.*

Key words: *cylindrical cell battery, PID control, iterative learning control, laboratory testing, charging simulation, MATLAB, battery quality control, renewable materials.*

1. Introduction

Rechargeable batteries are a central component of modern electric transportation, consumer electronics, autonomous equipment and distributed power across the global infrastructure. Among the developed and already available formats, cylindrical cells remain as one of the most widely used battery formats on the globe due to their geometry that supports standardized manufacturing, mechanical and thermal stability and efficient packaging [1, 2]. Popular formats such as 18650, 21700, and 4680 cells are used in large battery packs where thousands of individual cells must demonstrate consistent electrical performance and safety characteristics.

Transition towards sustainable and safe energy systems is also changing the direction where battery research is heading. In addition to improving energy density and cycle life, researchers are actively studying renewable materials for separators, binders and other additives of known battery components known this day. Carbon derived from biomass such as lignin, cellulose, rice husk, coconut shells and other agricultural residues become considered as a possible new research route for lower-cost and resource-efficient electrode materials [3]. Although material development is important, practical application of those batteries depends heavily on reliable laboratory testing methods that can measure performance in a repeatable and controlled manner.

Battery testing process is not a single measurement – but a sequence of constantly repeated operations. A typical laboratory or pilot-line may include constant current and voltage charging, discharge capacity testing and open circuit rest periods, thermal monitoring and resistance estimations (Fig. 1). These tests are often repeated across many cells, or over many cycles of the same cell. Because the procedure is repetitive, the control system does not have to treat every cycle

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as though it were entirely new. Instead, it can learn from earlier tracking errors and perform better in the next repetition [4-6].

Classical proportional-integral-derivative control is widely used in industrial systems because it is simple, transparent, and effective at regulating current, voltage, temperature, and actuator output [7,8]. In a battery testing station, a PID controller can regulate the charging current or terminal voltage by comparing the desired setpoint with the measured value. However, classical PID control mainly responds within the current operation. It does not automatically retain the error pattern from a previous test cycle and use it to improve the next one. This limitation becomes especially important when the same testing protocol is repeated many times.

Iterative Learning Control is designed for systems that perform repeated, finite-duration tasks. Its basic principle is straightforward: the control input for a new iteration is corrected using the tracking error measured in the previous one [4-6]. When this idea is combined with PID-type correction, the resulting controller uses the proportional, integral, and derivative components of the previous-cycle error to update the input trajectory for the next cycle [5]. This approach is well suited to laboratory battery testing because charge and discharge profiles are often repeated under similar conditions.

The aim of this work is to develop and analyze a MATLAB simulation of PID-type Iterative Learning Control for laboratory line testing of cylindrical cell batteries [9]. The focus is not on detailed electrochemical modeling, but rather on a control-oriented representation of the charging process, tracking accuracy, and cycle-to-cycle learning behavior [10, 11]. The study examines how the controller improves current tracking over repeated test cycles and how that improvement can support stable, repeatable laboratory battery measurements.

Unlike a conventional single-cycle PID implementation, the proposed framework explicitly uses the tracking error from the previous finite-duration test cycle to update the command trajectory for the next cycle. The contribution of this study lies in the implementation and analysis of this PID-type ILC strategy within a simplified control-oriented model of cylindrical-cell laboratory testing, with simultaneous evaluation of current tracking, RMS error convergence, terminal voltage, and state-of-charge behavior. The developed approach provides a preliminary digital-control framework for subsequent experimental implementation on a physical battery testing system (Figure 1).



Figure 1 – General concept of a laboratory line for cylindrical cell testing with PID-type ILC control

2. Methodology

2.1. Object of Study: Cylindrical Cell Battery Testing

This study focuses on a cylindrical rechargeable cell tested on a laboratory production line. In real testing stations, cells are placed in holders, connected to programmable charge-discharge channels, and monitored using sensors for voltage, current, temperature, and sometimes pressure or impedance. As the predefined test profile is applied, the system records how the cell responds. The resulting data are then used for cell grading, defect detection, capacity evaluation, and process validation [10].

The operation examined here is a repeated constant-current charging phase. This phase is especially representative because it appears in formation, capacity testing, and routine charge verification [1, 10]. The target charging current serves as the reference trajectory, while the actual current is treated as the controlled output. To reduce the tracking error between the desired and measured current, the controller adjusts the charger command. The same testing interval is assumed to repeat over multiple cycles. These cycles may correspond either to repeated tests on the same

cell or to sequential tests of similar cells manufactured under the same technological conditions. In either situation, the process is repetitive and finite in duration, which makes the use of ILC a reasonable choice [4-6]. When the iterations represent different cells rather than repeated tests of the same cell, the effectiveness of ILC depends on the cells and tester dynamics remaining sufficiently similar. Significant cell-to-cell variations in internal resistance, capacity, temperature, or initial state of charge may reduce the transferability of the learned command. Such variations should therefore be considered during future experimental implementation of the proposed control strategy.

2.2. Control-Oriented Battery Model

To keep the simulation easy to interpret and well suited for controller analysis, we chose a simplified, control-oriented battery model [10, 11]. The model captures the key elements: state of charge, open-circuit voltage, internal resistance, and the charger's first-order current response together with the battery system. It does not represent every electrochemical process taking place inside the cell, but it is more than adequate for examining tracking behavior and how the controller learns over time [1, 12].

The open-circuit voltage is approximated as a linear function of the state of charge. During charging, the terminal voltage is obtained by adding the ohmic voltage drop created by the internal resistance. The state of charge is then updated based on the charging current and the cell's nominal capacity [10-12].

The simplified equations are given below:

$$Voc(t) = Vmin + (Vmax - Vmin)SOC(t),$$
$$Vt(t) = Voc(t) + I(t)Rint,$$
$$SOC(t + \Delta t) = SOC(t) + I(t)\Delta t \,/\, (Cnom \cdot 3600).$$

Here, Voc is the open-circuit voltage, Vt is the terminal voltage, $I(t)$ is the charging current, Rint is the internal resistance, Cnom is the nominal capacity in ampere-hours, and Δt is the simulation time step. Voltage and current limits are included to imitate safety constraints used in real testing equipment.

2.3. PID Control Principle

The classical PID controller calculates the control signal using the present, accumulated, and predicted trend of the error. For a reference value r(t) and measured output y(t), the error is defined as e(t) = r(t) - y(t). The continuous PID control law can be written as [7,8]:

$$u(t) = K_p\, e(t) + K_i\backslash int_0\hat{}t\, e(\backslash tau)\backslash, d\backslash tau + K_d\backslash frac\{de(t)\}\{dt\}$$

The proportional term provides immediate correction, the integral term removes steady-state error, and the derivative term reacts to the rate of error change. In battery testing, PID control may be applied to charging current, voltage, discharge current, or chamber temperature. The controller output may represent a charger current command, power electronics duty cycle, or electronic load command.

2.4. PID-Type Iterative Learning Control

PID-type Iterative Learning Control extends the PID idea from single-cycle feedback to repeated-cycle learning [4-6]. The method updates the next control input trajectory by using the error measured during the previous iteration. The update law used in this study is:

$$u_{k+1}(t) = u_k(t) + K_p e_k(t) + K_i \int_0^t e_k(\tau)\, d\tau + K_d \frac{de_k(t)}{dt}$$

Here, is the iteration number, is the command trajectory used during the kth testing cycle, and ek(t) is the tracking error from that cycle. The proportional learning term corrects direct error, the integral learning term compensates accumulated bias, and the derivative learning term responds to changes in the error trajectory [5,6]. After each cycle, the next control trajectory is corrected and constrained by actuator saturation limits.

The main advantage of this method is that the controller can gradually improve the entire time profile of the control input. Instead of only reacting to the present error, the system uses previous information to anticipate repeated deviations. In a battery laboratory line, this behavior is useful when the same protocol is applied to many cells and the tester dynamics remain similar.

2.5. Simulation Procedure

The simulation was carried out in MATLAB (Fig. 2) using a discrete-time model [9]. The time step was kept small enough to capture detailed transient behavior during the first minute of testing. Each cycle followed the same reference current profile. The first cycle began with an initial charger command. Once the current response and the error had been calculated, the resulting error

trajectory was used to adjust the control input for the next cycle [4-6]. This procedure was repeated over twenty cycles (Table 1). Twenty learning iterations were used as a fixed evaluation horizon. This number was sufficient to capture the rapid initial reduction in tracking error and the subsequent approach to a nearly steady RMS-error level, while maintaining a compact simulation interval for comparative analysis.

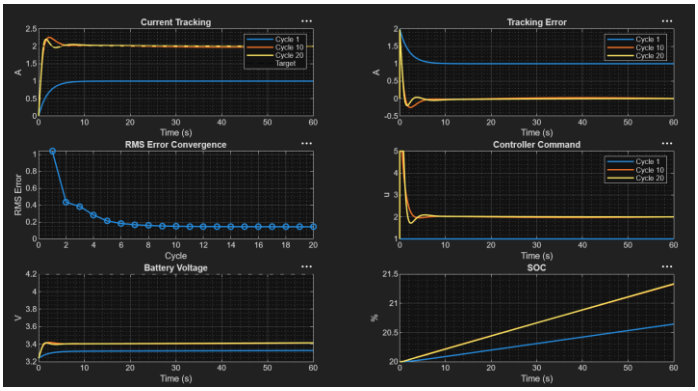


Figure 2 – MATLAB simulation flowchart of the repeated PID-type ILC battery testing process

Table 1 – Main simulation parameters used in the PID-type ILC model

Parameter	Symbol / value	Purpose
Simulation time	60 s	Finite testing interval
Time step	0.01 s	Detailed transient resolution
Nominal capacity	2.5 Ah	SOC calculation
Initial SOC	20%	Initial battery state
Internal resistance	0.08 Ω	Terminal voltage calculation
Reference current	2 A	Target charging value
Number of cycles	20	ILC learning iterations
Voltage limit	4.2 V	Charging safety constraint
Proportional learning gain	K_p=0.35	Direct error correction
Integral learning gain	K_i=0.02	Accumulated error compensation
Derivative learning gain	K_d=0.01	Transient error correction
Charger command saturation	U_{min}=0 U_{max}=5	Actuator constraint

The analysis focused on the following performance indicators: current tracking response, tracking error, root-mean-square error, maximum absolute error, controller command evolution, terminal voltage, and state-of-charge progression. Together, these indicators help determine whether the controller improves the repeatability of the test and whether the charging process stays within safe operating limits.

3. Results and Discussion

3.1. Current Tracking Across Iterations

A clear sign of how well the controller performs is how accurately it tracks the current (Fig. 3). During the first cycle, the charging current does not match the reference value right away because the initial command trajectory has not yet been tuned. The largest error appears during the transient stage of the response, as the system climbs from zero current toward the desired charging level [7, 8].

After several iterations, the PID-type ILC update adjusts the command trajectory based on the error observed in earlier cycles [4-6]. As a result, the later cycles reach the target current faster and with less tracking error. Comparing the first, fifth, tenth, and twentieth cycles makes the learning effect easy to see. The response becomes sharper and more consistent because the controller has effectively learned the approximate command required to offset the system's slow dynamics.

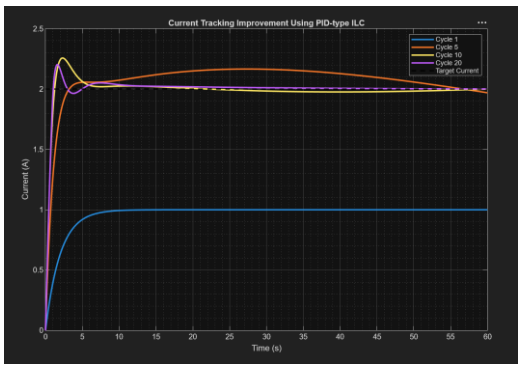


Figure 3 – Current tracking response for selected learning cycles: Cycle 1, Cycle 5, Cycle 10, and Cycle 20

3.2. Error Convergence

Figure 4 shows that the tracking-error profile changes substantially as the learning process progresses. The first cycle is characterized by a relatively large positive error because the charger response does not immediately reach the 2 A reference current. By Cycles 5 and 10, the magnitude of the error is markedly reduced, although transient over- and under-correction remain visible. By Cycle 20, the tracking error is concentrated mainly within the initial transient period and remains close to zero during most of the testing interval.

This trend is further confirmed by the RMS tracking error presented in Figure 5. The RMS error decreases from approximately 1.04 A during the first iteration to about 0.14 A by the twentieth iteration, corresponding to an overall reduction of approximately 86%. The largest improvement occurs during the first several iterations, after which the RMS error approaches a nearly steady level. This behavior demonstrates progressive cycle-to-cycle learning and diminishing tracking-error corrections.

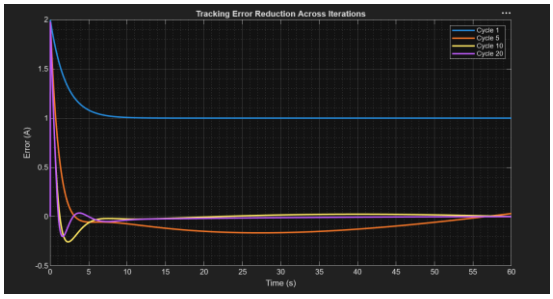


Figure 4 – Tracking error reduction during selected cycles of the laboratory battery testing simulation

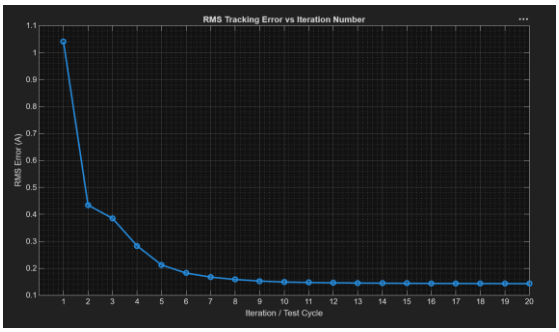


Figure 5 – RMS tracking error convergence as a function of iteration number

3.3. Controller Command Evolution

The learned controller command illustrates how the input trajectory shifts from one cycle to the next (Fig. 6). During the first cycle, the command is relatively simple and does not fully make up for the dynamic lag in the charger-battery system. As learning progresses, the command becomes better matched to the process dynamics. In practical terms, the controller starts applying a command that more effectively anticipates the charging current the system needs.

Just as importantly, the command must stay within physical limits. In the simulation, saturation constraints were included to prevent unrealistically large or negative charger commands. This mirrors the behavior of real battery testing equipment, where current, voltage, and power outputs are restricted by hardware capabilities and safety settings.

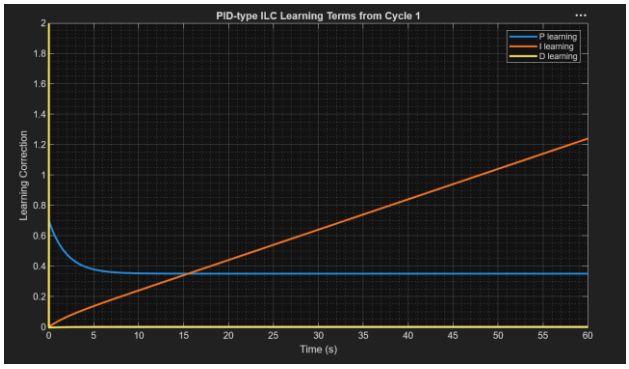


Figure 6 – Evolution of the learned charger command over repeated PID-type ILC cycles.

3.4. Voltage and State-of-Charge Behavior

Terminal voltage is one of the most important safety indicators in battery testing (Fig. 7). As the state of charge increases, and as current moves through the cell's internal resistance, the simulated voltage rises gradually. Throughout the interval examined, the voltage curve stays below the defined maximum voltage limit. This suggests that the improvement in current tracking does not compromise the basic safety requirement of charging.

The state-of-charge response increases smoothly over the one-minute test interval (Fig. 8). Because the simulation covers only a short period compared with a full charging process, the increase in SOC remains moderate. Even so, the SOC curve is still useful because it shows that the battery model responds consistently to the charging current and that the repeated cycles remain physically reasonable.

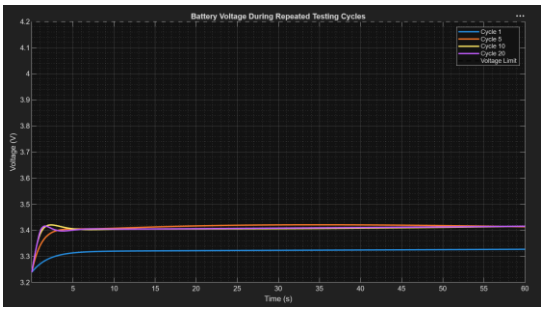


Figure 7 – Terminal voltage response during repeated cylindrical cell testing cycles

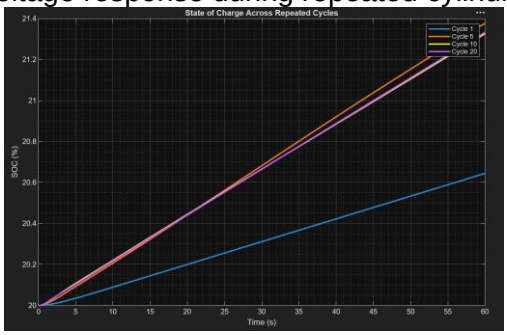


Figure 8 – State-of-charge progression during the simulated laboratory charging interval

3.5. Relevance for Laboratory and Pilot-Line Testing

The results obtained through simulations support the suitability of PID-type ILC for laboratory line testing of cylindrical cells [4-6]. In such systems, the same procedures are repeated for many cells,

and high repeatability is often more valuable than aggressive one-time control action. By reducing cycle-to-cycle error, the controller may improve the reliability of capacity measurements, internal resistance estimation, and grading decisions [10, 11].

This approach is also relevant for batteries based on renewable or bio-derived materials [3]. New material systems often require careful laboratory validation because their electrochemical properties, internal resistance, and aging behavior may differ from conventional cells [1, 2]. A more repeatable testing control method makes it easier to distinguish real material performance from measurement variation caused by poor control accuracy.

The presented simulation is intentionally simplified and should be treated as a preliminary control study (Table 2). A real cell has nonlinear voltage-SOC behavior, temperature-dependent resistance, aging effects, hysteresis, and electrochemical diffusion phenomena. However, the simplified model is useful for demonstrating the learning principle and for preparing future implementation in MATLAB/Simulink or on a physical battery analyzer.

Table 2 – Interpretation of main simulation outputs

Output graph	Meaning	Expected interpretation
Current tracking	Actual current compared with reference current	Later cycles should approach the target faster
Tracking error	Difference between reference and actual current	Error amplitude should decrease with learning
RMS error	Average tracking quality over one cycle	A downward trend shows learning convergence
Controller command	Input sent to the charger model	Command becomes optimized while staying within limits
Battery voltage	Terminal voltage during charging	Voltage must remain below the safety limit
SOC	Charging progress of the cell	SOC should increase smoothly and consistently

4. Conclusion

This work presents a simulation study of PID-type Iterative Learning Control applied to laboratory line testing of 18650-type cylindrical cells [4-6]. The study focuses on repeated constant-current charging, which is one of the most important operations in battery formation, its capacity evaluation, and other quality control procedures [10].

The MATLAB model that was developed included a simplified representation of battery voltage, internal resistance, state-of-charge dynamics, actuator limits, and a repeated finite-time testing cycle [1, 2, 9-12]. After each cycle, the PID-type ILC algorithm updated the charger command using the proportional, integral, and derivative components of the previous tracking error [5, 6]. The simulation results showed that the controller improves tracking performance over repeated cycles. Current tracking becomes more precise, the tracking error decreases, the RMS error steadily converges downward, and the controller command gradually develops into a more effective input trajectory.

At the same time, voltage and state-of-charge behavior stay within reasonable operating limits. These results suggest that PID-type ILC could be valuable for automated laboratory and pilot-line battery testing, especially when the same protocol is repeated across large numbers of cylindrical cells. The method can help create more repeatable measurement conditions and may improve the reliability of cell grading and performance analysis.

Future research should examine nonlinear electrochemical battery models, temperature effects, experimental validation on a real battery analyzer, and applications involving cylindrical cells made from renewable or bio-derived materials [1-3, 12].

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МОДЕЛИРОВАНИЕ И АНАЛИЗ ЭФФЕКТИВНОСТИ PID-ТИПОВОГО ИТЕРАТИВНОГО ОБУЧАЮЩЕГО УПРАВЛЕНИЯ ПРИ ЛАБОРАТОРНОМ ЛИНЕЙНОМ ТЕСТИРОВАНИИ ЦИЛИНДРИЧЕСКИХ АККУМУЛЯТОРНЫХ ЭЛЕМЕНТОВ

Рост спроса на надежные перезаряжаемые системы хранения энергии усилил необходимость в точных лабораторных методах испытания цилиндрических аккумуляторных элементов. Лабораторные и пилотные испытательные станции многократно выполняют операции зарядки, разрядки, проверки напряжения, оценки емкости и измерения внутреннего сопротивления. Эти операции требуют точного регулирования тока и напряжения, поскольку даже небольшие переходные отклонения могут повлиять на классификацию элементов, анализ старения и оценку безопасности. В данной работе представлено исследование на основе моделирования PID-типового итеративного обучающего управления для повторяющегося лабораторного линейного тестирования цилиндрических аккумуляторных элементов. Предлагаемый подход объединяет классическую структуру пропорционально-интегрально-дифференциального управления с механизмом итеративного обучения, который обновляет управляющее воздействие после каждого повторяющегося цикла с использованием ошибки отслеживания предыдущего цикла. Упрощенная MATLAB-модель процесса зарядки цилиндрического аккумулятора была разработана с учетом динамики состояния заряда, внутреннего

сопротивления, оценки клеммного напряжения, насыщения исполнительного устройства и повторяющегося конечного временного интервала испытания. В ходе моделирования оценивается отклик контроллера на протяжении последовательных циклов и анализируются отслеживание тока, поведение напряжения, управляющее воздействие, состояние заряда и сходимость ошибки. Результаты показывают, что PID-типовое ILC способно уменьшать ошибку отслеживания в повторяющихся циклах и повышать повторяемость лабораторных аккумуляторных испытаний. Метод особенно актуален для автоматизированных линий контроля качества, где большое количество элементов тестируется по схожим протоколам. Предложенная модель может служить предварительной цифровой основой перед экспериментальной реализацией на реальном стенде для испытания аккумуляторов.

Ключевые слова: *цилиндрический аккумуляторный элемент, PID-управление, итеративное обучающее управление, лабораторное тестирование, моделирование зарядки, MATLAB, контроль качества аккумуляторов, возобновляемые материалы.*

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ЦИЛИНДРЛІК АККУМУЛЯТОРЛЫҚ ЭЛЕМЕНТТЕРДІ ЗЕРТХАНАЛЫҚ ЖЕЛІДЕ СЫНАУ КЕЗІНДЕГІ PID-ТИПТІ ИТЕРАТИВТІ ОҚЫТУШЫ БАСҚАРУДЫ МОДЕЛЬДЕУ ЖӘНЕ ӨНІМДІЛІГІН ТАЛДАУ

Қайта зарядталатын сенімді энергия сақтау жүйелеріне сұраныстың артуы цилиндрлік аккумуляторлық элементтерді дәл зертханалық сынау әдістеріне деген қажеттілікті күшейтті. Зертханалық және пилоттық желідегі сынақ станциялары зарядтау, разрядтау, кернеуді тексеру, сыйымдылықты бағалау және ішкі кедергіні өлшеу операцияларын бірнеше рет қайталайды. Бұл операциялар ток пен кернеуді дәл реттеуді талап етеді, себебі аз ғана өтпелі ауытқулардың өзі элементтерді жіктеу, қартаюды талдау және қауіпсіздікті бағалау нәтижелеріне әсер етуі мүмкін. Бұл жұмыста цилиндрлік аккумуляторлық элементтерді қайталанатын зертханалық желіде сынау үшін PID-типті итеративті оқытушы басқаруды қолдануға арналған модельдеуге негізделген зерттеу ұсынылады. Ұсынылған тәсіл классикалық пропорционалды-интегралды-дифференциалды басқару құрылымын алдыңғы қадағалау қатесін пайдалана отырып, әрбір қайталанатын циклден кейін басқару кірісін жаңартатын итеративті оқыту механизмімен біріктіреді. Цилиндрлік аккумуляторды зарядтау процесінің жеңілдетілген MATLAB моделі заряд күйінің динамикасын, ішкі кедергіні, қысқыш кернеуді бағалауды, атқарушы құрылғының қанығуын және қайталанатын шекті уақыттық сынақ аралығын ескере отырып жасалды. Модельдеу контроллердің бірнеше цикл бойындағы жауабын бағалайды және токты қадағалау, кернеу әрекеті, басқару әсері, заряд күйі және қателіктің жинақталуы мен азаюын талдайды. Нәтижелер PID-типті ILC қайталанатын циклдер барысында қадағалау қатесін азайтып, зертханалық аккумуляторлық сынақтардың қайталанғыштығын жақсарта алатынын көрсетеді. Бұл әдіс көптеген элементтер ұқсас хаттамалар бойынша тексерілетін автоматтандырылған сапаны бақылау желілері үшін ерекше маңызды. Ұсынылған модельдеу нақты аккумуляторлық сынақ стендінде эксперименттік іске асыруға дейінгі алдын ала цифрлық модель ретінде қызмет ете алады.

Түйін сөздер: *цилиндрлік аккумуляторлық элемент, PID басқару, итеративті оқытушы басқару, зертханалық сынау, зарядтауды модельдеу, MATLAB, аккумулятор сапасын бақылау, жаңартылатын материалдар.*

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МОДЕЛЬ СИСТЕМЫ ПРОГНОЗИРОВАНИЯ УРОЖАЙНОСТИ ЯБЛОНЕВЫХ САДОВ

Аннотация: *Прогнозирование урожайности яблоневых садов в горно-предгорных зонах Казахстана остаётся открытой задачей: классические агрономические методы субъективны, а методы компьютерного зрения требуют репрезентативных обучающих выборок, отсутствующих для региона. Предложены архитектура информационной системы прогнозирования урожайности и её интерпретируемое полумеханистическое расчётное ядро для сорта Апорт (Malus domestica cv. Aport) в микрозоне предгорий Заилийского Алатау. Ядро реализовано как четырёхзвенный*

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