JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 13(4), DECEMBER, 2025
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

Proportional Integral Controller for Two-Stage Battery Control Based on Graylag Goose Optimization Algorithm

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ABSTRACT

This research presented the development of an optimized proportional Integral controller for two-stage battery system using Graylag Goose Optimization (GGO) algorithm. Battery management involves regulating charging and discharging processes to maximize efficiency and extend battery lifespan. Proportional Integral (PI) control technique is one of the classical control techniques that have been widely used for the regulation of battery charging and discharging processes. However, PI controller is able to stabilize the battery state of charge to some certain degree, but the root mean square error (RMSE) with respect to battery current control is not satisfactory due to uncertainties during the process of charging and discharging processes of battery. Thus, there is need to improve on the performance achieved with PI control technique in order to maximize efficiency and extend battery lifespan. To address this, this research presents an approach based on an optimized proportional Integral controller for two-stage battery system in order to enhance the regulation of battery charging and discharging processes while preventing energy overloads or deep discharges which would compromise the life of the battery itself. This problem was addressed in this research by developing optimized proportional Integral controller for two-stage battery system using Graylag Goose Optimization (GGO) algorithm. Firstly, model of bi-directional converter for charging the two-stage battery system model was developed in Simulink. Then the PI controller was designed and the cost function was formulated in terms of PI gains before applying on the developed Simulink model. The performance of the developed optimized PI system was evaluated using battery reference control of in RMSE as performance metrics. The simulation results when the nominal current and load voltage were within the desired range of 20A and 48V showed that the developed GGO-PI obtained RMSE of 0.731. This resulted in 7.31% improvement in RMSE when compared to that of SISO-Fuzzy logic technique. This implies that the developed GGO-PI has a good battery reference control. This clearly shows the effectiveness of the developed controller in stabilizing the system as fast as possible.

ARTICLE INFO
Article History
Received: October, 2025
Received in revised form: November, 2025
Accepted: November, 2025
Published online: December, 2025

KEYWORDS
Battery Management Systems, Electric Vehicle Charging, Proportional Integral Controller, Renewable Energy Integration, Graylag Goose Optimization (GGO)

INTRODUCTION

Electric vehicles (EV) and renewable energy systems (RES) have grown rapidly due in part to the need to lessen environmental pollution and reliance on nonrenewable resources [1]. Since they are regarded as the main energy storage source for RESs and EVs, batteries are crucial. Lithium-ion batteries (LIB) are especially

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promising due to their superior performance and steadily declining cost [7]. However, LIBs are typically subjected to a variety of abusive circumstances and function in a tough environment.

In addition to causing anomalous temperature rises that might result in gas production or even thermal runaway, combustion, and explosion, overloading, external heat transfer, overly fast charging, and internal/external short circuits can also shorten battery life [10]. As a result, batteries need to be properly handled to guarantee their security and increase their lifespan 13-14]. A battery management system (BMS) is needed to not only monitor all kinds of battery states, but also to ensure that battery performance meets the demands of the vehicle throughout the battery service life [2]. A key aspect of battery management involves regulating charging and discharging processes to maximize efficiency and extend battery lifespan [8]. Several control systems have been developed to automate the battery control based on proportional integral derivative, fuzzy logic controller, sliding mode controller, and proportional integral controller [3].

Proportional Integral (PI) controller is one of the conventional techniques commonly used for battery control due to their simplicity and effectiveness. The battery has a hysteretic loop and nonlinear charging circuit [9]. The traditional PI setting approach involves a complex setup procedure [6]. The empirical formula and several experiments require the PID settings to be adjusted. Realizing the perfect parameter setting is challenging [11]. The control system has a long response time and a large overshoot, and it cannot meet the requirements of the current control [4].

The accurate control of the charging parameters (charge voltage and current) of the lithium battery can shorten the charging time, improve the charging efficiency of the battery, prolong the service life and reduce the cost [12]. Therefore, it is of great significance to the PI parameter tuning of the battery charging circuit [5]. In this research, an optimized proportional Integral controller for two-stage batteries model was designed in order to enhance performance in regulating charging and discharging processes. In order to achieve enhance the performance of the PI, the PI gains was optimized using Graylag Goose Optimization (GGO) algorithm.

LITERATURE REVIEW

This section explains some basic concept related to this work. Numerous studies have been proposed in this context for example [15] presented the electric vehicle's battery management concept and execution. Preventing misuse and damage to the battery cells was the primary goal of the project. In their work, implementation of active clamp forward converter for active cell balancing, design a new BMS platform based on available dedicated integrated circuits and microcontrollers targeting fast sampling, high accuracy, low consumption and low cost were carried out. The BMS topology and active forward converter was simulated in or CAD, TINA software and MATLAB Simulink software.

The simulation of the active forward converter showed that for an input voltage of 40V the output voltage was 3.3V, with an efficiency of 90%. The ripple in the converter is limited to less than 5%. The BMS topology is reviewed and the PCB was printed, then the PCB is tested with connecting battery stack for both charging and discharging process of active cell balancing. Also [16] designed genetic-fuzzy proportional Integral (fuzzy-PI) technique for two-Stage battery Control. Since the fuzzy-PI controller only works with linear systems, the proposed method linearized the Bi-directional conveter model using a gap metric before using it .The proposed method used the triangle membership function with L, M, and H as its linguistic variables.

The recommended controller outperformed the other controller in terms of DC voltage regulation, battery voltage and battery reference control after the proposed two stage battery model was simulated and the results were compared with classic fuzzy-PI. But the reported battery voltage was rather high. In [17] presented an optimum control theory-based energy management strategy (EMS) for a battery-supercapacitor hybrid power system. A lithium-ion battery, a super-capacitor, and related

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bidirectional DC/DC converters make up the hybrid power system. In order to determine the power reference for the battery and super-capacitor while maintaining stable voltage and optimal performance, the suggested EMS computes adaptive gains utilizing the load following control approach and the salp swarm algorithm.

The first-principles approach is used to create the DC/DC converter model, which calculates the necessary gains to get the desired power. The fact that the developed algorithm takes disturbances into account increases the power elements' life expectancies and supplies the power system with the required power. [18] presented design and control of a two-stage onboard battery charger (OBC) for the low-voltage electric vehicle (LVEVs). The charger in this study has a high-power factor and can function over a broad variety of AC input voltages. A bridgeless AC-DC converter with constant input current characteristics at the front end is used in the developed charger.

An isolated Cuk DC-DC converter was used at the charger's back end to implement and regulate various battery charging modes using constant voltage (CV) and constant current (CC) charging profiles. Battery current control with regard to DC voltage regulation, battery voltage, and battery reference control are some of the parameters on which the performance is compared with other modern power factor correction (PFC) topologies. The overall operational analysis and efficacy of the design were confirmed through both simulations and experimental implementation. In [19] work on battery protective Electric Vehicle charging management in renewable energy system using Fractional Order Proportional Integral Derivative (FOPID) controller.

The Neural network (NN) controller and Linear Quadratic Regulator (LQR) were also employed the designed for the controlling of the battery stage of charge/discharge. Through simulation in MATLAB/Simulink, the performance of the proposed controller was contrasted using that of NN and LQR controllers using DC voltage regulation, battery voltage and battery reference control as performance matrices. When compared to NN and LQR, the suggested controller showed superior DC voltage regulation and battery voltage. Their study addressed the problems of severe hypoglycemia and instability in basal level tracking with this modification. However, their work did not adequately address the issue of reference battery control.

Similarly, [20] designed the Single Input Interval Type 2 Fuzzy Logic Proportional Integral (SIIT2FLPI) controller, designed for regulating a battery using a two-stage control approach. In the proposed technique, the lithium battery model was designed in MATLAB/Simulink prior to using the SIIT2FL-PI controller in order to enhance the regulation procedures for charging and discharging batteries. Since it can only work on linear system. The proposed two-stage battery model was simulated and the result was compared using a traditional PI controller where the proposed controller outperformed the other controller in terms of RMSE of 31% improvement in battery current control with respect to DC voltage regulation, battery voltage and battery reference control.

PROPOSED METHODOLOGY

To designed PI controller in MATLAB/Simulink. The control scheme was developed in this section. It is made up of the integral and proportional part. The PI control law function can be state as:

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad (1)$$

The resulting Simulink model is showing below:

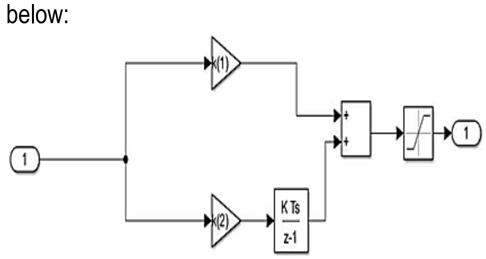

Fig.1: Simulink Model of PI Controller

Formulation of optimization problem

The control law in equation (1) was used to formulate the given weighting factor into an

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objective function in order to produce an optimized weigh for the controller input. The optimization problem's goal is to maximize gains while minimizing weight. kp and k_i, for integral time absolute error minimization between the control input $u(t)$. On the basis of equation (1), the cost function was developed. The boundaries for the system variables were determined by considering the range derived from the implementation of PI without utilizing GGO. The following constraints are used to select the best solution:

$$4 < k_p < 4.5 \quad (2)$$
$$43 < k_i < 44 \quad (3)$$

Therefore, k_p and k_i are the weighting factor's parameters that need to be optimized in order to fulfill the goal. Optimization of the weighting factor using GGO. The GGO algorithm was employed in this research to optimize the cost function parameters. Equation (1) serves as evaluation criteria for the optimality of the results obtained by GGO. The flowchart for evaluating the cost function using GGO is given in Fig.2.

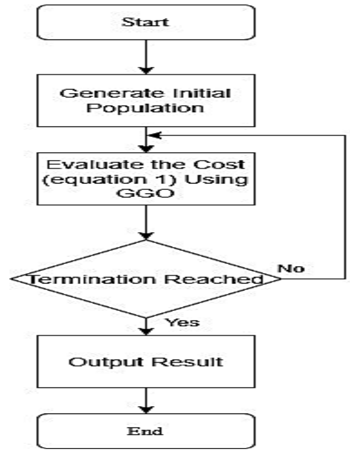

Fig.2: Flowchart of Objective Function Cost Evaluation.

Fig.2 shows the flowchart for evaluating the weighting factor cost. In the first step, a population of size N is created, and the weighting factor parameters' values are chosen at random using the limitations provided by equations (2 to 3). Afterward, the GGO's selection procedure is executed in a manner that seeks the ideal parameter combination to produce the greatest result. Goose life and goose behavior are the two algorithmic modes that are employed to find the objective function's optimum. It optimizes the cost function until the termination criteria are met. Table I provides the GGO parameters used in this study.

Table 1: GGO Parameters.

S/N		Parameters	Symbols	Values	Unit
1		Population	N	50	_
2		Dimension	D	3	_
3	Iterations	itr	10	_	
4	Step Movement	SM	2.5	M	

SIMULATION SETUP

The simulation parameters of the GGO-PI controller, battery model parameters are presented in this section.

A. Simulation environment and parameters

The simulation was carried out in MATLAB/Simulink 2022b environment. Table II presents the simulation parameters.

Table 2: GGO Parameters

S/N	Parameters	Symbol	Value
1	Population	N	50
2	Dimension	D	3
3	Iteration	Itr	10
4	Step Movement	SM	2.5

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B. Battery model

The lithium battery model utilized in the simulation setup is a crucial component for evaluating the performance of the proposed control strategy. It aims to capture the dynamic behavior and characteristics of lithium-ion batteries commonly used in various applications (electric vehicles and renewable energy systems). The lithium battery model incorporates key parameters such as nominal voltage, rated capacity, initial state of charge, and battery response time depicted in TABLE III.

Table 3: Battery Parameters

Parameters	Values
Nominal voltage	*24V*
Rated Capacity	*50Ah*
Initial state of charge	*80%*
Battery response time	*1s*
Battery nominal discharge current	*22A*

RESULTS AND DISCUSSION

The simulation results obtained based on the methodologies that addressed the research objectives are discussed and compared with the work of (Muritala *et al*., 2024) [20]. The results obtained from the simulations are presented in this section.

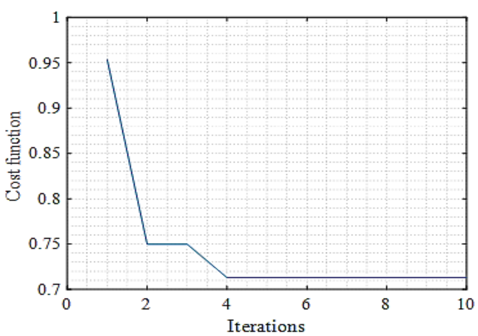

Fig.3: GGO Convergence plot on Benchmark

Fig.3 shows the convergence plot when GGO was applied on the PI cost function in order to obtain optimal gains parameters. It was observed from the Fig.3 above that, the algorithm converged at the 4th iterations.

The battery current in Fig.4 represents the rate at which energy is being transferred to or from the battery during charging or discharging.

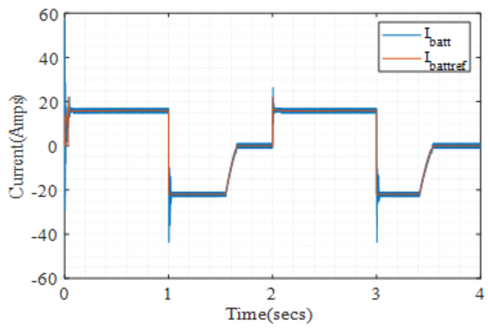

Fig.4: Battery Current

Fig.4 illustrates the battery current, which indicates the rate of energy transfer to or from the battery when it is being charged and discharged. The reference current shown represents the desired trajectory that the developed GGO-PI controller aims to track in the initial control stage, serving as the optimal target current. The battery charges when the voltage source switch (as shown in Figure 7) is active, and discharges when the switch is inactive. Monitoring the battery current is crucial for evaluating the state of charge, assessing battery performance, and maintaining the overall system's stability and safety. As seen in Fig.3, the error between the battery voltage and its reference voltage and the error between the DC voltage and the common load voltage define the GGO-PI controller's output.

Fig 5 shows the graphs of state of charge of battery obtained from simulation.

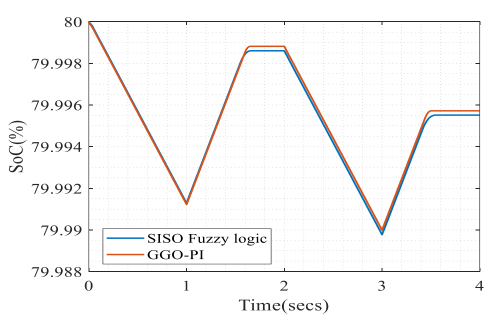

Fig.5: SOC of the Battery

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The battery SOC, which is represented as a percentage of its total capacity and measures the amount of electrical energy stored in the battery at any one time, is shown in Figure 4.3. This value reflects the remaining charge and indicates how much energy is available for use. As observed from the figure, the proposed GGO-PI controller enables a quicker SOC response during both the charging and discharging phases of the voltage switch controller. Unlike the Single Input Single Output (SISO-Fuzzy Logic) two-stage battery control technique, which also, ensures that the SOC during the charging and discharging state of the voltage switch controller within 79.99% - 80%

Fig.6 shows the graphs of load voltage obtained from simulation.

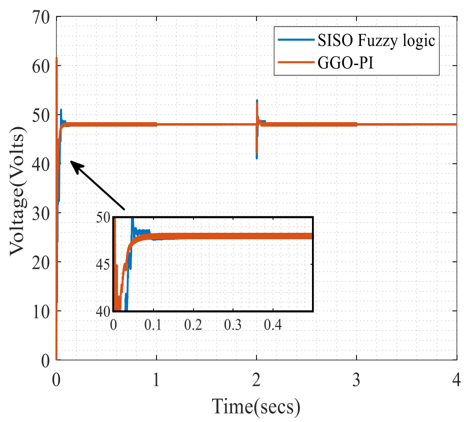

Fig.6: Load Voltage

The performance of the SISO fuzzy logic-based controller and the GGO-PI controller with respect to the load voltage is shown in Fig.5. As shown, the GGO-PI controller successfully tracks the reference voltage of 48V and stabilizes the battery system within 0.04 seconds. This highlights the GGO-PI controller's ability to deliver superior system performance under critical load conditions. In comparison, the SISO fuzzy logic-based controller also manages to follow the reference signal and achieves steady-state operation at 0.065 seconds, enabling continuous monitoring of the load voltage and adjusting the battery's discharge rate to keep the voltage around the desired 48V range.

Fig.7 shows the graphs of voltage source switch obtained from simulation.

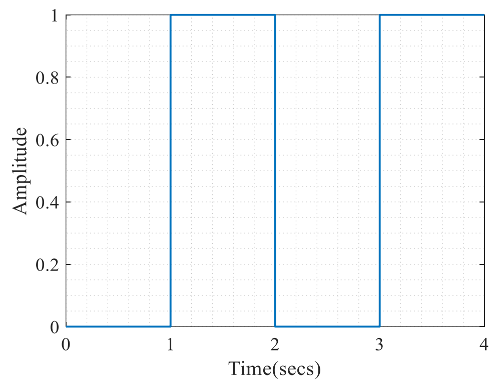

Fig.7: Voltage Source Switch

The voltage source switch is depicted in Fig.7 during the battery system's charging and discharging operations. Fig.7 showed that the charging process is started when the switch is switched on (one), allowing the battery to accept voltage from the voltage source. This enables the battery to sustain its state of charge (SOC) and restore its energy reserves. On the other hand, when the source voltage switch is turned off (zero), it disconnects the battery from the voltage source, preventing further charging. This is important to avoid overcharging the battery, leading to degradation, and reducing lifespan. Additionally, turning off the source voltage switch during certain conditions may be necessary to conserve energy or prevent damage to the battery system.

A. Performance evaluation

The performance of the controllers for the two-stage battery control system was assessed on the basis of root mean square error (RMSE) as reported in Muritala *et al*., (2024) [20]. The performance of the developed Graylag Goose Optimization Proportional Integral (GGO-PI) controller and SISO-Fuzzy logic controller based on DC voltage regulation, battery voltage and battery reference control with respect to the performance metric were presented in Table IV

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Table 4: Performance Metric

	RMSE		Percentage Improvement
	Developed GGO-PI	SISO-Fuzzy Logic	
DC Voltage Regulation	0.008	0.008	__
Battery Voltage	0.02	0.02	__
Battery Reference Control	0.7130	0.769	**7.3%**

Table 4.2 summarizes the performance comparison of the developed GGO-PI and that of SISO-Fuzzy logic reported in the work of [20]. It can be observed from the Table 4.2 above that, the developed GGO-PI has the overall improvement of good battery reference control of 7.31% in RMSE when compared to the work reported by [20]

CONCLUSION AND RECOMMENDATION

This research has presented the development an optimized proportional Integral controller for two-stage battery model. In Simulink, a two-stage battery model was developed PI and GGO were then used to adjust the gain parameters in an optimal battery control scheme. The MATLAB/Simulink software was utilized to the simulation in MATLAB2022b for the battery discharging rate to maintain the load voltage within the desired range of 48V. The performance evaluation of the results was carried out and compared to the two-stage battery system developed by [28] in terms of root mean square error (RMSE). The simulation results reveal that the developed GGO-PI has the overall improvement of good battery reference control of 7.31% in RMSE when compared to the work reported by [20].

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