JOURNAL OF RENEWABLE ENERGY AND SMART GRID TECHNOLOGY

Vol. 21, No. 1, January-June 2026

Control of Bi-directional Converter for charge-discharge battery using PI With Modified PSO

Rifqi Firmansyah[1*], Habib Brilian Wicaksono[1], Gul Ahmad Ludin[2], Naufal Maulana Fahmi[1], Ali Nur Fathoni[1], Rudi Uswarman[3]

[1]Department of Electrical Engineering, Universitas Negeri Surabaya, Surabaya 60231, Indonesia
[2]Department of Electrical Power Engineering, Kabul Polytechnic University, Kabul 1005, Afghanistan
[3]Department of Electrical Engineering, Institut Teknologi Sumatera, Lampung 35365, Indonesia
***Corresponding author's email**: rifqifirmansyah@unesa.ac.id

Article info:

Received: 19 August 2025
Revised: 29 October 2025
Accepted: 3 December 2025
DOI:
10.69650/rast.2026.263584

Keywords:

Bi - Directional Converter
DC - DC Converter
Metaheuristic Optimization
Battery Charge - Discharge
Proportional - Integral

ABSTRACT

Increasing demand for renewable energy integration and efficient energy storage solutions have highlighted the critical role of battery. Batteries serve as essential components in energy systems, storing excess power for various applications, and backup power solution. However, achieving control for battery is challenging due to stability of charge and discharge, changing load condition, and battery state of charge fluctuation. To ensure efficiency of battery, accurate control of bi-directional converter is required. Bi-directional Converter facilitates the power flow required for this process but controlling battery charge discharge accurately. Among the many control methods, the Proportional-Integral (PI) controller is widely used for regulating the charge-discharge operation. However, selecting optimal PI parameters is non-trivial and greatly affects systems performance. This study proposes an enhanced control strategy for a bidirectional converter using PI controller optimized by a modified Particle swarm optimization (PSO) algorithm. The proposed method incorporates a dynamic re-randomized mechanism to overcome premature convergence in a standard PSO, improving its ability to escape local minima. Additionally, a penalty function is applied to restrict the search within a defined stable range for the controller gains. The performance of the system is evaluated based on the Integral of Time-Weighted Absolute Error (ITAE) criterion to minimize transient and steady-state errors. Simulation result using MATLAB/Simulink demonstrate that modified PSO-based PI controller significantly improves system performance-reducing overshoot, enchanting settling time, and maintaining stability under different operation modes (charge and discharge). This method offers a practical and efficient solution for optimizing converter control in battery-based energy storage systems.

1. Introduction

The increasing integration of renewable energy sources and smart grids has heightened the demand for efficient energy storage systems. Batteries serve as crucial energy storage units, ensuring stable power supply and improving grid resiliency. Demand for efficiency energy bi-directional converter is essential component in battery management system, with play in crucial role enabling smooth charge-discharge transition between battery and power grids or loads [1–3]. However, there are issues related to the performance of the output value, which is affected by uncertainty of parameter that vary over time in bi-directional [1] especially for charge and discharge battery condition.

Previous research by [4] used the application of PID for Bi-directional converter. The article examines a bi-directional converter DC-DC with dual operational modes: charge-discharge. This facilitates power transfer both to and from energy storage systems. The control of bi-directional converter used proportional integral derivative (PID) control is central to the work, optimizing both the rise time, settling time, and steady-state error during the system operation. Despite contributions, PID control is only applied to the discharge mode and leaving the charge mode unaddressed. In addition, the Ziegler-Nichols tuning method used for PID is effective but lacks further refinement.

Study conducted by [5] "Design and Performance Analysis of PID Controller for Extended Output Voltage Charge-Discharge Converter", it was explained that the implementation of a conventional PID controller in a charge-discharge converter system faces several significant limitations. One of the key issues highlighted is the presence of a large overshoot during transient response, as well as a relatively long settling time before reaching steady state conditions. These drawbacks result in undesirable system behavior, particularly when there are sudden changes in load or output voltage reference. Under such dynamic conditions, PID control tends to produce oscillatory responses or delayed stabilization, which can affect the overall performance and reliability of the system. The study emphasized the need for more adaptive and optimized tuning strategies that can maintain fast, accurate, and stable control performance under various operating scenarios.

Research by [6] has successfully implemented the topology of Bi-directional converter DC-DC based control logic. In this research, providing the mathematical model from converter was obtained through averaging technique can analyze performance and converter efficiency. Managing bidirectional DC-DC converters in real world applications like EV/HEV involves significant complexity due to mode switching, component parasitic, and nonlinear battery dynamics. Proper control strategies, including small-signal modeling and digital switching logic, are essential to stabilize converter operations and extend battery life.

Another Research about mathematics bidirectional model by [7] concluding that bi-directional DC-DC converter can used by 2 modes; charge and discharge. And bi-directional transmission energy makes it important in microgrid systems. Implemented PID is effective for stabilization busbar voltage, with accurate current control > 5% and efficiency of work more than 90% in charge mode as well as 95% in discharge mode.

The research by [8] bidirectional converter serves as a crucial solution for managing energy flow between power source and batteries. This type of converter enables two-way energy transfer, making it possible to both store excess energy and supply the stored energy to the load when needed such a topology, typically operating in charge-discharge modes, has been widely implemented to enhance the overall efficiency of power flow within energy storage systems. The bidirectional nature of the converter allows it to dynamically adapt to the system's demands, whether during energy accumulation or distribution phases.

Research by [9] the design of bidirectional converter effectively manage the energy flow during charging and discharging, using the PID controller with optimization GA (genetic algorithm) to minimize system errors. Specifically focusing on reducing the integral time absolute error (ITAE). Result of the article conclude that an optimized PID controller has a better system performance compared to traditional manual tuning method.

Discusses the importance of minimizing component losses, enhancing system performance for highlights the complexity and cost-efficiency of using bi-directional converter compared to traditional system that involve multiple stage of energy conversion [10].

A study conducted by [11] with entitled "Particle Swarm Optimization-based PID Controller Design for DC–DC Charge converter", explores the application of the particle swarm optimization (PSO) algorithm for tuning PID controllers in charge converter systems. The research highlights the critical lore of PID control parameters in determining the performance of control systems, particularly in reducing transient effects such as overshoot and steady state error. To address these challenges, the authors employed PSO to effectively identify the optimal set of PID parameters. Additionally, the study discusses common issues encountered in PI controllers, notably the wind-up phenomenon, which occurs when the control error remains nonzero for extended periods, leading to degraded system response. The use of PSO not only improves tuning efficiency but also enhances the controller's ability to respond accurately under dynamic conditions.

The Proportional–Integral (PI) controller was used in this study because it can guarantee system stability and optimal system performance that is linked with a fast transient response and high steady-state accuracy, even in the event of disturbances from external sources or system parameter variations [18]. The PI controller is thus best for systems requiring precise regulation and robustness. To further improve its performance, the Particle Swarm Optimization (PSO) algorithm is employed to optimize the parameters. PSO has been widely known as being easy to implement, having a high convergence rate, and possessing good global search ability, which enable it to effectively calculate the optimal values of the PI gains [21]. The combination of PI and PSO thus provides a simple yet effective control method with a balance of accuracy, stability, and computational complexity.

2. Non-Isolated Bi-directional converter

There are two types of bidirectional DC-DC converter circuits, one of which is a non-isolated bidirectional converter. In general, a one-way DC-DC converter can be converted into a bidirectional converter with the replacement of diodes on the controllable switches in its structure. Bidirectional converters are designed to support both phases, i.e. charge mode and power discharge mode, thus allowing for smooth energy flow according to specification and operational requirements. In practice, the voltage level in energy storage units is usually kept at a relatively low range. This is done as a measure to minimize potential safety risks and ensure safe operation of the system [12].

A bidirectional converter can be obtained by sequentially connecting two basic converters: a step-down (buck) converter and a step-up (boost) converter. In a stable state, the conversion ratio of the output voltage to the input is the product of the ratios of the two converters connected sequentially (assuming that the switches on both converters have the same ratio) [13].

Bidirectional converters could increase or decrease voltage levels in buck-boost operation. This device is made to provide power flow in two directions, which means it can charge the battery (charge mode) or remove power from the battery (discharge mode). The reference current is used to measure the charging current entering the battery. Similarly, in discharge mode, the current flowing from the battery is measured and compared with the reference current to ensure that the power discharged matches the power required by the system. This adjustment process continues until the battery reaches a certain limit of the charging process (state of Charge, SOC) indicating the available battery capacity [9].

In fig. 1 provides voltage to the load. If the voltage supplied by Vin exceeds the load requirement, the remaining power will be used to charge the battery. Conversely, if the voltage supplied is insufficient for the load, the load will switch its source from the battery. Thus, the voltage continuity at the load will be maintained according to Vin and the battery [14].

2.1 Mode Buck / Charge

In charge mode, the output voltage V_{batt} is smaller than the voltageV_{in}. This serves to reduce the DC voltage level from V_{in} to V_{batt} (charge). The way the circuit works can be divided into two stages.

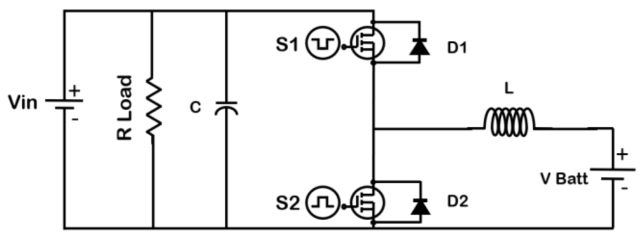

Fig. 1 Bidirectional Converter.

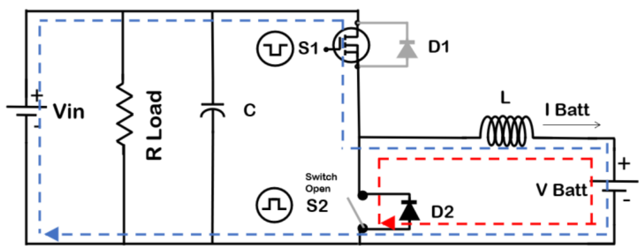

Fig. 2 Charge mode.

2.1 Mode Buck / Charge

In charge mode, the output voltage V_{batt} is smaller than the voltageV_{in}. This serves to reduce the DC voltage level from V_{in} to V_{batt} (charge). The way the circuit works can be divided into two stages.

(1) Switch 1 ON

The first stage begins when MOSFET S1 is ON at t = 0. The increasing input current flows through the inductor filter L, and MOSFET S2 is OFF. In this state diode 1 (D1) and diode 2 (D2) will enter reverse bias mode; causing the input voltage (V_{in}) to be used to charge the battery and make it charge mode until it reaches the voltage (V_{batt}) [4,15]. In this condition, the difference between the voltages V_{in} and V_{batt} will be equal to the voltage on the inductor, shown by the blue line in Figure (2.2). The voltage through the inductor can be written with the equation

$$L\frac{di_L}{dt} = V_{in} - V_{batt} \tag{1}$$

(V_L) is shown as the voltage on the inductor. In equation (), the voltage on the inductor will be equal to the voltage difference between the incoming voltage (V_{in}) and the voltage on the battery (V_{batt}).

(2) Switch 1 OFF

In stage 2, the two MOSFETs are both in the OFF state D1 is still in reverse bias mode, while D2 enters forward bias mode [4]. The current in the inductor is shown by the red line in Figure 2, thus dissipating the energy stored in the inductor to the battery with a voltage V_{batt}. The inductor voltage equation at this stage is written as follows

$$L\frac{di_L}{dt} = -V_{batt} \tag{2}$$

In equation 6,the voltage on the inductor (V_L) is equal to the voltage on the battery (V_{batt}). By applying the volt second balance principle of the inductor in equation (1) and equation (2), the voltage on the battery can be written as

$$V_{batt} = D.V_{in} \tag{3}$$

Which is where the output voltage of the charge mode (V_{batt}) is the duty cycle (D) multiplied by the incoming voltage (V_{batt}).

In Figure 2 illustrated, MOSFET S1 remains in the ON state, while MOSFET S2 is in the OFF state. This operation involves the main component that plays a role in energy storage. That component is the voltage on the inductor. This component works to support the charging process with optimal efficiency in the charge mode [16].

2.2 *Mode Boost / Discharge*

In discharge mode, the voltage at V_{in} is greater than V_{batt}. This mode is the discharge mode of a battery, or the voltage transition from low voltage level to high voltage level. The way the circuit works can be divided into two stages.

(1) Switch 2 ON

The first stage is when the voltage starts through V_{batt} to the inductor (L). Then MOSFET S2 will be ON at t = 0 while MOSFET S1 will be OFF. Both D1 and D2 become reverse biased. The input current will increase flowing through the inductor and produce inductor current [4,15]. In the state shown by the red line in Figure (3), the inductor charges energy from the battery. The inductor voltage operation at steady state can be written in equation 4

$$L\frac{di_L}{dt} = V_{batt} \tag{4}$$

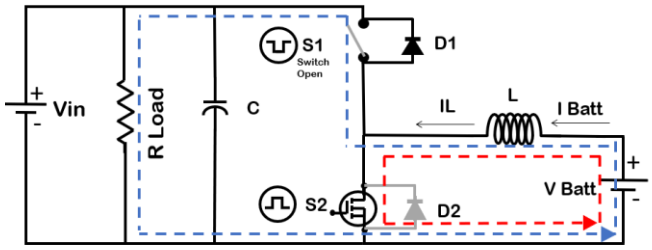

Fig. 3 Discharge Mode.

Table 1 Bidirectional converter specification.

Converter Components	Value
Battery	$24\,V, 50\,Ah$
DC Source Voltage	$48\,V$
Inductor (L)	$5.76e-4H$
Capacitor (C)	$1.083e-3F$
Switching Frequency (f)	$10kHz$
Duty cycle	50%

While the output of the discharge capacitor C stores energy to the $R\ load$. The current flowing into the capacitor during steady state operation is given in equation 5

$$C\frac{dV_c}{dt} = -\frac{V_{out}}{R_{load}} \tag{5}$$

Where the current of the capacitor (I_C) is the output voltage (V_{out}) divided by the load (R_{Load}).

(2) Switch 2 OFF

The second mode starts when MOSFET S2 is OFF. The current flowing through the transistor will flow through L, C, and R_{Load}. In this state, D1 will be forward biased while D2 will remain in the reverse bias state. The current stored in the inductor will flow to D1 and C just as in Figure 3. The diode rectifies the flowing current and prevents the current from returning after going through the capacitor. The inductor current drops until the MOSFET and S2 are reactivated in the next cycle [4,15,17]. Thus, giving the required load current for R_{Load}, the inductor voltage and capacitor current can be written in the equation below

$$L\frac{di_L}{dt} = V_{batt} - V_{out} \tag{6}$$

$$C\frac{dV_c}{dt} = i_L - \frac{V_{out}}{R_{load}} \tag{7}$$

$L\frac{di_L}{dt} = V_{batt} - V_{out}$Equation 4 and equation 6 output voltage against load resistance can be written as

$$V_{out} = \frac{V_{batt}}{(1-D)} \tag{8}$$

Where the output voltage of the discharge mode (V_{out}) is the battery voltage (V_{batt}) divided by the duty cycle (D) reduced by 1.

By applying the balance principle in equations 5 and 7, the inductor current can be written as

$$i_L = \frac{V_{out}}{R_{load}(1-D)} \tag{9}$$

In Fig. 3 for discharge mode, the battery releases power to the $Rload$ connected at the DC bus. The converter works in discharge mode to raise the output voltage. Switch S2 remains in ON mode and switch S1 is in OFF state. Energy from the battery is discharged through the inductor, temporarily stored and released to the output with a higher voltage [16]. Here are the bidirectional converter parameters for charge and discharge obtained from calculations and experiments.

3. Methods

3.1 PI Controller

The theoretical function of the PI controller system is to keep the process variable to reach the target value by considering the difference between the reference value and the actual value. The P controller is responsible for reducing the error by responding quickly to changes, while the I controller is responsible for eliminating the error in the long run by integrating the error value over time. The combination of the two results in a PI that enables the system to achieve optimal performance with fast response and high accuracy, despite disturbances or changes in system parameters [18].

Proportional controllers have the advantage of accelerating the response to reach its steady state price, while the disadvantage is that they cannot perfectly reduce the magnitude or disturbance that hits the control system, and the system response always has a steady state error. The Integral controller is able to achieve a steady state without error lies in the slowness of the high response in the initial response with the merger of the two components of the P and I controllers into PI this allows for control with better behavior.

The PI control signal is used to provide feedback on the voltage output value of the Bidirectional DC-DC converter by controlling the duty cycle. In this case, the PI controller uses certain constants, namely the proportional constant (K_p) and Integral Constant (K_i), in regulating the system response. The main objective of using a PI controller is to minimize the error value between the allowable value and the actual value of the voltage output and adjust the duty cycle accurately. The formula of the PI controller can be shown in equation 10 [19] :

$$u(t) = K_p\left[e(t) + \frac{1}{\tau_i}\int e(t)\, dt\right] \tag{10}$$

Where K_p is the proportional parameter, τ_i is the time constant of the integrator, and $e(t)$ is the error value of the system. Both are parameters that can be changed according to design specifications.

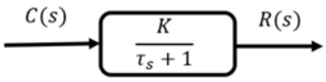

Fig. 4 First Order System.

To get the desired system response approach, a first-order system can be used. Figure 4 is a first-order system, a first-order system is a system characterized by the highest rank of the denominator of the transfer function is one [20,21].

$$\frac{C(s)}{R(s)} = \frac{K}{\tau s + 1} \tag{11}$$

where K is the process of gain, which is the ratio of steady state and reference, and τ is the time constant. Where τ is the time obtained from c(τ) when it reaches 63.2% of the steady state.

$$K = \frac{Yss}{Xss} \tag{12}$$

$$c(\tau) = 0.632.Yss \tag{13}$$

Alternatively, when time (t>τ) can use the equation

$$y(t) = Y_0 + (Y_{ss} - Y_0)(0.632) \tag{14}$$

Where for Y0 is the initial voltage, and Yss is the voltage at steady state. After using the first-order approach, further determination is made using PI parameters. The values of K_p and K_i can be found using the equation below [20].

$$K_p = \frac{\tau i}{K.\tau^*} \tag{15}$$

It is said that the value of $\tau i = \tau$ because the slow process has a large value, while τ* is the desired closed-loop time constant. After knowing the value of K_p, the search for the value of Ki is shown in equation 16.

$$K_I = \frac{K_p}{\tau i} \tag{16}$$

To obtain the appropriate or optimal parameters, the K_p and K_i values are optimised using the PSO optimisation method during simulation.

3.2 Particle Swarm Optimization

Trial and error or Ziegler-Nichols methods are often applied in finding the parameters of PI controllers, but both methods have shortcomings in terms of accuracy and time efficiency. Conventional approaches in tuning PI controllers generally rely on certain models with simpler orders. However, these tuning rules are often ineffective, especially in dealing with unbalanced or unstable systems. The conventional PI controller tuning process usually requires numerical calculations to achieve optimal parameters. To overcome this limitation, PSO methods have been increasingly used in recent decades. PSO enables more effective optimization of PI parameters in complex and non-linear systems. The advantages of PSO include simple implementation, fast convergence time, and better global exploration capability [21].

PSO combines local search and global search techniques to find a solution. PSO is designed to tackle complex problems by forming a population of particles whose positions are randomized at the start of the process. Each particle is a representation of a potential solution to the problem being solved. The algorithm then evaluates the suitability of each particle, which is used to assess the extent to which the particle can solve the problem at hand. During the optimization process, each particle updates its speed and position based on its individual experience as well as the collective information of the entire swarm. By combining personal data and social knowledge, the particles are directed to potential areas in the search space. This collaboration allows the group to effectively explore different areas. As well as the utilization of areas that are considered promising or show better potential solutions.

$$v_i = w \,. v_i + c_1.r_1.(pbest_i - x_i) + c_2\,.r_2.(gbest - x_i) \tag{17}$$

$$x_i = x_i + v_i \tag{18}$$

v_i is the velocity of the particle, with w being the inertia of the particle where the value for this is 0.9, while c_1 is the learning coefficient of each particle, c_2 is the global learning coefficient with r_1 and r_2 random numbers from 0-1 to maintain the randomness of the solution search. Meanwhile $pbest_i$is the i-th particle's best solution during the process, and $gbest$ is the best solution of all particles. After knowing the velocity of each particle, $x_1$or the position of the particle is updated. This formula is evaluated every iteration for all particles, so gradually the population will converge to the optimal solution.

(1) PSO Initialization

It starts by randomly assigning initial positions of particles based on a distribution in the search space. Each particle is placed in space based on parameters relevant to the optimized problem. This process ensures an even initial distribution of particles to effectively explore the search space.

(2) Fitness Evaluation

Fitness evaluation is the process of assessing the suitability of each particle individually. At this stage, the fitness value is calculated based on criteria that are determined and set according to the problem being solved. The purpose of this evaluation is to measure the extent to which each particle can solve the problem or achieve the desired target.

(3) Update Individual Data

At this stage, the latest fitness value is compared with the previous value. Furthermore, the P_{best} (personal best) value is updated if the current fitness value is better, then the value is updated as P_{best}. And the current particle (x_1) is stored as position Pi, which represents the individual's best solution so far.

(4) Global Best Identification

Of all the particles in the swarm, the particle with the highest fitness value is identified as the global best solution ($gbest$). And the position of the particle is also recorded as Pg, which guides the whole swarm to move closer to the optimal solution in the next iteration.

(5) Update Velocity and Position

The velocity and position of each particle is updated using an equation that considers the velocity and position of the $Pbest$ and $gbest$. These changes allow particles to move in a more optimised direction based on individual and collective information. Iterations are performed until convergence criteria are met (maximum number of iterations and solution accuracy).

A PI controller is added to minimize the influence of environmental conditions. PSO is used to optimize the K_p and K_i parameters in the PI controller algorithm so that the closed-loop control system can operate with maximum efficiency. The ITAE function optimisation algorithm results in faster solution time. Smaller steady state error, and minimal overshoot through PSO-based parameter optimization [22].

$$\boldsymbol{ITAE}\ (\boldsymbol{e}) = \int_0^T t\ |e(t)|dt \tag{19}$$

Where $e(t) = r(t) - y(t)$ is the error between the reference signal and the system output, t is the simulation time, and T is the total simulation time. The choice of ITAE as the objective function imposes a large penalty on the error at the final time, so that the system will have fast, stable, and minimal overshoot response characteristics. Several Particles are randomly initialized in the search which represents K_p and K_i, respectively. The optimised parameters will be applied to the bidirectional converter system in charge and discharge operating modes.

n the block diagram, V_{ref} is an input value that represents the target or desired output voltage of the converter. This value becomes the reference for the control system in maintaining output stability. The reference voltage is compared with the actual output voltage to produce an error signal e(t), representing the difference between the actual and target conditions, which is then used by the controller to correct the system.

To regulate the system a PI controller is used, the purpose of which is to generate a control signal based on the error e(t). The PSO module is used to find the optimal condition of parameters K_p and K_i by minimising certain objective functions such as ITAE or error values in the system. PSO adjusts the position and velocity in the solution space to obtain the best parameters based on system performance evaluation. This optimisation is done before the simulation is run.

The bidirectional converter block is the plant system or the physical system being controlled. Bidirectional Converter regulates the flow of power between the source and the battery either in charge mode or in discharge mode. The signal from the PI is used to adjust the duty cycle so that the output voltage matches the reference.

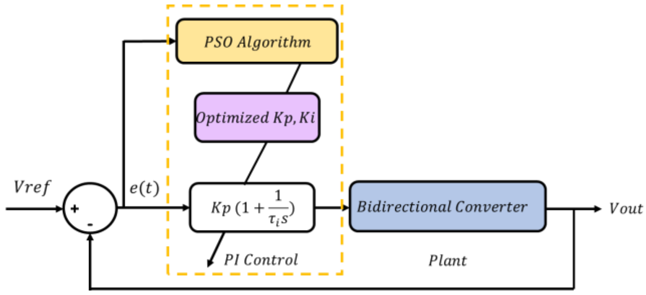

Fig. 5 Block Diagram PI-PSO bidirectional converter.

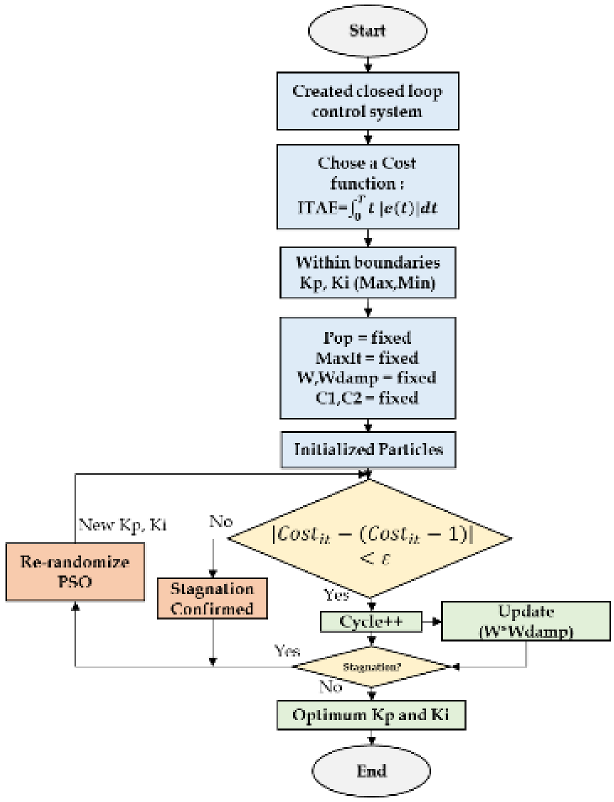

Fig. 6 Flowchart modified PSO.

The actual voltage of the system is measured and used as feedback. Its value is monitored to ensure compliance with the reference value and assessed based on system dynamics performance such as rise time, overshoot, and stability.

Figure 6 flowchart of the Modified Particle Swarm Optimization (PSO) procedure for optimal tuning of PI controller gains (K_p and K_i) in bidirectional DC-DC converter system. The process begin with the creation of a close loop control system and the selection of the ITAE (integral time weighted absolute error) performance index as the cost function. Initial boundaries for the proportional and integral gains are defined, followed by the initialization of PSO parameters and including the number of particle population, maximum iteration (maxIt), inertia weight (w), damping ratio (Wdamp), and acceleration coefficients (C1, C2). Particles are then initialized randomly within the search space. During the iterative process, the algorithm checks for stagnant by evaluating whether the change in cost function between successive iterations falls below a predefined threshold (ε). Is stagnation is confirmed the particle is re-randomized to escape the local optima. Otherwise, the inertia weight is updated, and the iteration continues. The process repeat until convergence is archived, resulting in the optimal set of K_p and K_i that minimizes the ITAE, thereby enhancing the dynamic performance of the converter.

4. RESULT AND DISCUSSION

In the results and discussion will discuss the comparison of bidirectional converter system performance in three conditions. Namely in conditions without a controller, using a conventional PI, and using a PI that has been optimized with the PSO algorithm. The purpose of this test is to evaluate the effectiveness of PSO optimization on improving system performance, especially in terms of transient response, overshoot, recovery time and steady state error. Tests were carried out in several scenarios, namely fixed reference, changing reference, input changes, and system disturbances, both in charge mode and in discharge mode.

Fig. 7 and Fig. 8 is the convergence result graph of the PSO algorithm of charge and discharge mode. We can see that 80 iterations were performed. It can be seen that the fitness value decreases significantly over 80 iterations.

This indicates that the optimization process has successfully found the best ITAE result for the PI controller. Figure 9 and Table 3 show the comparison of bidirectional converter charge modes in three different conditions, namely without controller, using conventional PI, and using PI controller optimized with PSO algorithm (PI-PSO). The three conditions show significant differences in terms of response speed and the ability to reach the reference voltage.

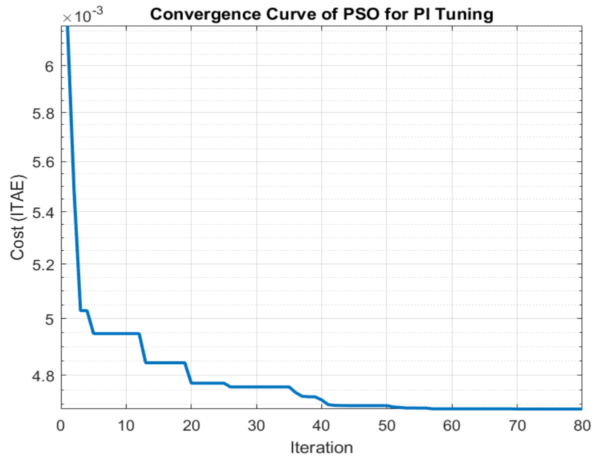

Fig. 7 ITAE Charge.

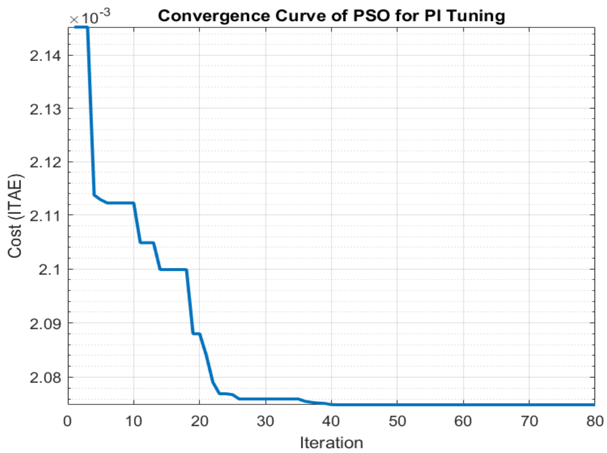

Fig. 8 ITAE Discharge.

Table 2 PI-PSO Value convergence.

Mode	Best Cost	K_p	K_i
Charge	0.00468	60.019	305.05
Discharge	0.002074	0.4012	154.208

Table 3 Performance of PI-PSO, conventional PI, and No controller in charge mode.

System	Maximum Overshoot (V)	Rise time (s)	Oscillation (V)	
			Min	Max
No Controller	0.0000	0.000	25.521	25.531
Conventional PI	25.9841	0.958	25.9761	25.9839
PI-PSO	25.9838	0.707	25.9763	25.9835

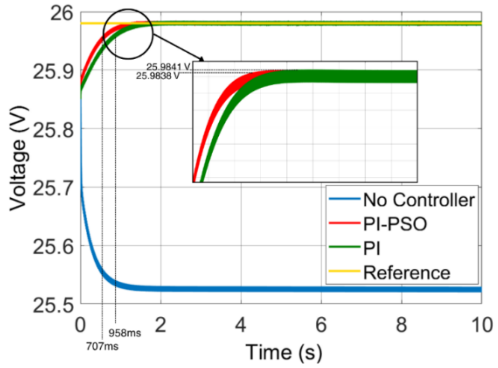

Fig. 9 Mode Charge Performance.

In the condition of no-control, the system shows very limited performance. The output voltage is only 25.53V whereas the expected reference voltage is 25.98V. There is no overshoot or rise time which means that the system is unable to provide an active response to changes in the reference. Although the voltage oscillation is small, this condition does not reflect a responsive and imprecise system. So, it is not feasible for battery charging processes that require stability, in contrast to conditions that have been controlled using PI.

When the system was given a conventional PI controller, the performance improved significantly. The output voltage successfully reaches the reference value with a recorded rise time of 0.819 seconds. And there are still small oscillations between 25.9761V to 25.9839V, this shows the system is starting to be responsive. The conventional PI controller is good enough in directing the output close to the reference value, but still needs improvement especially in terms of response speed and oscillation minimization.

The best performance is shown by the system using PI-PSO controller. The voltage not only reaches the precise reference value, but also does so in a shorter time, with a rise time of 0.562 seconds and also has a slightly higher overshoot of 25.9838V. The oscillation value of PI-PSO is the smallest compared to the others. With a stable voltage in the range of 25.9763V to 25.9835V. This shows that the optimization of K_p and K_i parameters through PSO can increase the response speed and produce a more stable system.

In charge mode the rise time of the PI-PSO system is recorded at 0.707 seconds, faster than the conventional PI with a rise time of 0.958 seconds or superior to 26.2% and much better than the system without a controller that does not show an active response. The overshoot of the PI-PSO is also very small at 0.0038V from the reference as well as smaller oscillations of about 7.7% than the conventional PI.

Figure 10 and table 4 present the simulation results of the bidirectional converter when the battery is in discharge condition. The analysis is carried out on four scenarios, namely without controller, with conventional PI controller, VNS-PI, and with PI-PSO controller. The evaluation is focused on three main parameters namely maximum overshoot, rise time and output voltage oscillation.

Table 4 Performance of PI-PSO, conventional PI, and No controller in discharge mode.

System	Maximum Overshoot (V)	Rise time (s)	Oscillation (V)	
			Min	Max
No Controller	84.11	0.00343	51.4	51.72
Conventional PI	67.37	0.002922	47.987	48.001
VNS-PI	64.41	0.002932	48.013	48.028
PI-PSO	64.41	0.002920	47.991	48.006

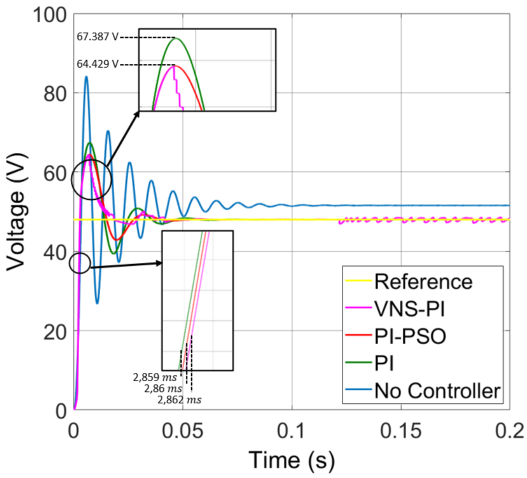

Fig. 10 Mode Discharge Performance.

In the no-control condition, the system shows a very unstable performance. It can be seen that the output voltage reaches a very high overshoot of 84.11 V, far exceeding the specified reference of 48V. Coupled with a rise time of 0.00343 seconds, this does not reflect excellence. Because the system is unable to effectively control the voltage spike. The oscillations that occur are also large, in the range of 51.4 V to 51.72 V, indicating that the system in this condition is very unstable and at high risk to the load components.

After being given a conventional PI controller, the system performance has improved. The output voltage is closer to the reference value with a maximum overshoot of 67.37 V, and the rise time becomes 0.002922 seconds. The oscillation range also decreased to 47.987 V and 48.001 V, which means that the system began to show stability and the ability to follow the reference voltage well. However, there is still a high overshoot and the response is not fully optimized.

Then, under the VNS-PI control system conditions, the system performance is better than the conventional PI controller. The output voltage can approach the reference value with a maximum excess of 64.41 V, and the rise time is 0.002932 seconds. The oscillation range is also reduced to 48.013 V and 48.028 V, which means the system stability shows improvement and the ability to follow the reference voltage is better.

The most significant improvement is shown by the PI-PSO controller system. Although the overshoot value is still the same as the VNS-PI control system 64.41 V, the rise time is slightly improved to 0.002920 seconds. The oscillation is also more stable between 47.991 V to 48.006 V, which indicates that the system can reach the reference voltage more smoothly, quickly, and with minimal fluctuations. The response becomes more precise, which indicates the success of the PSO method in optimizing the K_p and K_i values in the PI controller.

In discharge mode, the rise time obtained by the PI-PSO controller is 0.002920 seconds faster than the conventional PI (0.002922 seconds) or up to 0.07% faster than the PI, and also 0.000012 seconds faster than the VNS-PI control system, indicating excellent transient control capability. However, the overshoot in discharge mode is relatively larger due to the system characteristics that increase the battery output voltage. Nevertheless, the PI-PSO still shows improvement with a lower overshoot, which is 64.41 V, compared to the conventional PI (67.37 V), or 4.39% lower than the conventional PI.

Based on the simulation results and performance data, it can be seen that the PI-PSO controller provides significant improvements in terms of response speed (rise time) and voltage stability (oscillation) compared to the system without a controller, conventional PI, and also VNS-PI. These results prove that PI optimization using PSO successfully improves system performance, especially in accelerating response time and stabilizing the output voltage, both in charging and discharging conditions.

4.1. Reference Voltage Change

This section tests the performance of the bidirectional converter against gradual changes in the reference voltage value. The goal is to see the system's ability to adjust to the dynamics of the reference input, both in charge and discharge modes. Simulations were carried out in three conditions; without controller, with conventional PI, and with PI optimized with PSO (PI-PSO). The observed parameters include recovery time (trec) and voltage deviation from the reference value.

Fig. 11 and table 5 illustrate the system response when the reference value changes from 25.98V to 25.74V. At all stages of change, the system shows no response at all. This is indicated by the recovery time and voltage deviation values that remain 0.00 seconds and 0.00V. in other words, the system is unable to adjust to changes in the reference value and the output voltage is stagnant. This indicates the absence of dynamic control, so the system without controller is not reliable for operating conditions with changing references.

After the system is regulated by a conventional PI controller, the system can improve the condition of the output voltage. Seen when the reference rises to 26.22V at second 2, the system shows a recovery time of 1.744 seconds with a voltage deviation of 0.004V. Signaling a good response. However, when the reference is lowered to 25.74V at the 4th second, the recovery time becomes slower, which is 3.676 seconds with a voltage deviation of 0.006V. This shows that the PI system is able to follow changes in the reference, but the response is still slow and not entirely accurate especially when the reference decreases.

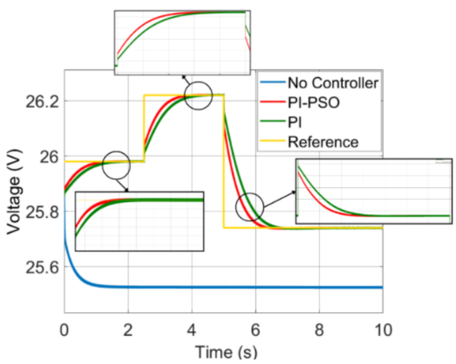

Fig. 11 Performance of reference voltage change PI-PSO, conventional PI, and No controller in charge mode.

Table 5 Performance of reference voltage change PI-PSO, conventional PI, and No controller in charge mode

No.	Vin (V)	R (Ω)	V_{ref}(V)	No Controller		PI		PI-PSO	
				t_{rec}(s)	ΔV(V)	t_{rec}(s)	ΔV(V)	t_{rec}(s)	ΔV(V)
1.	48	100	25.98	0.00	0.00	0.00	0.00	0.00	0.00
2.			26.22	-	-	1.744	0.004	1.262	0.004
3.			25.74	-	-	3.676	0.006	2.922	0.005

Table 6 Performance of reference voltage change PI-PSO, conventional PI, and No controller in discharge mode.

No.	Vin (V)	R (Ω)	V_{ref}(V)	No Controller		PI		PI-PSO	
				t_{rec}(s)	ΔV(V)	t_{rec}(s)	ΔV(V)	t_{rec}(s)	ΔV(V)
1.	25.85	100	48	0.00	0.00	0.00	0.00	0.00	0.00
2.			63	-	-	0.091	6.44	0.073	5.28
3.			33	-	-	0.066	12.34	0.052	10.70

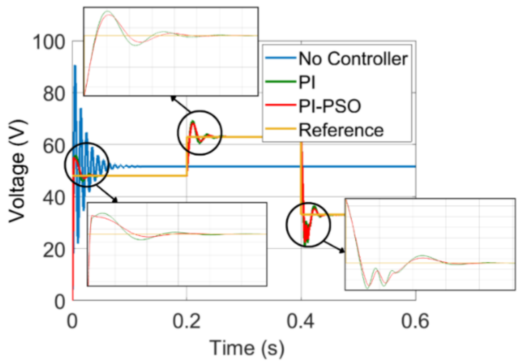

Fig. 12 Performance of reference voltage change PI-PSO, conventional PI, and No controller in discharge mode.

The best performance is shown by the PSO optimized PI controller. When the reference rises to 26.22V from second 2, the system takes only 1.262 seconds with a voltage deviation of 0.004V. when the reference drops to 25.74V at second 4, the recovery time decreases to 2.922 seconds with a deviation of 0.005V. PI-PSO performance has a faster response time, shows a more adaptive system and has a smaller voltage deviation. The result is that PI-PSO is more efficient in dealing with dynamic changes in reference changes.

In charge mode, the PI-PSO system recorded a shorter recovery time of about 27.61% than the conventional PI when the reference rose to a voltage of 26.22 V with no difference in voltage deviation. While at a voltage drop to 25.74 V PI-PSO has a recovery time shorter by 20.52% than the conventional PI and has a smaller voltage deviation of 16.67% than the conventional PI.

Fig. 12 and table 6 illustrate the capability of the output voltage system to dynamically change the reference value. In the condition without controller, the system is not able to respond to changes in reference at all. This is indicated by all parameters between recovery time and voltage deviation (ΔV) which is 0V. Signaling that the system has no control to adjust the voltage to the changing reference. As a result, the output voltage remains stagnant and far from the required value, which is not ideal for systems that require stability and adaptivity.

When the system is given a conventional PI controller, there is a significant improvement in performance. The system is able to respond to changes in the reference. For example, when the reference is increased to 63V at second 0.2 until the system shows a recovery time of 0.091 seconds and the voltage deviation reaches 6.44V. Meanwhile, when the reference is lowered to 33V at the 0.4 second, the recovery time becomes 0.066 seconds with a deviation of 12.34V. Although the conventional PI has been able to follow the reference changes, the system still experiences considerable overshoot and undershoot, and the response is not optimal in terms of speed and stability.

The most noticeable improvement occurs when a PI controller optimized with the PSO algorithm (PI-PSO) is used. At second 0.2 the reference was increased to 63V, the recovery time improved to 0.073 seconds and the voltage deviation reduced to 5.28V. While at the reference down to 33V at second 0.4, the recovery time becomes 0.052 seconds, and the deviation is only 10.70V. This shows that PI-PSO has a faster and more accurate response and is able to reduce overshoot and undershoot significantly.

While in discharge mode, PI-PSO produces a shorter recovery time of about 19.78% from PI and a smaller voltage deviation of 18% from conventional PI when the reference rises to 63V. While when the voltage drops to 33 V PI-PSO produces a recovery time of 21.21% from PI and a smaller voltage deviation from PI by 13.29%.

Based on simulations when the reference voltage changes, the PI-PSO controller shows better performance compared to the conventional PI and the system without a controller. This can be seen from the recovery time and lower voltage deviation. Overall, PI-PSO provides a faster response and is also able to stabilize the output voltage better when the system undergoes reference changes. This shows that the PSO algorithm successfully finds more optimal PI parameters in dealing with changes in transient conditions.

4.2. Input Voltage Change

This test is only performed in charge mode, the input voltage is changed by decreasing and increasing from the original input voltage. However, the reference and load voltages are constant. An example in this test is a photovoltaic system where the output produced is unstable because it is highly dependent on the intensity of sunlight. The simulation results of the performance seen in the first test are the recovery time (trec) and ΔV of the three controllers. Figure 13 and table 7 aim to evaluate the system response when there is a change in the input voltage, while the reference voltage remains constant. In the no-control condition, the system does not respond at all to changes in input voltage. Neither when Vin is increased to 96V at second 2 nor when Vin decreases to 36V at second 4, there is no output voltage adjustment. This can be seen from the recovery time and voltage deviation (ΔV) values which remain at 0 or no change at all. This condition indicates that the system does not have the flexibility or controllability of the source condition, which can lead to instability in the charge condition.

Table 7 Performance of input voltage change PI-PSO, conventional PI, and No controller in charge mode.

No.	Vin (V)	R (Ω)	V_{ref} (V)	No Controller		PI		PI-PSO	
				t_{rec}(s)	ΔV(V)	t_{rec}(s)	ΔV(V)	t_{rec}(s)	ΔV(V)
1.	48	100	25.98	0.00	0.00	0.00	0.00	0.00	0.00
2.	60			-	-	1.569	0.0049	0.996	0.0049
3.	36			-	-	0.026	0.0041	0.021	0.0039

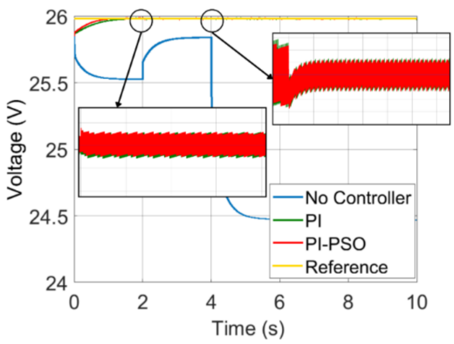

Fig. 13 Performance of input voltage change PI-PSO, conventional PI, and No controller in charge mode

With the use of a conventional PI controller, the system begins to show a response to changes in input. When Vin is increased to 60V at second 2, the system requires a recovery time of 1.569 seconds with a voltage deviation of 0.0049V against the reference. Conversely, when Vin is lowered to 36V, the recovery time becomes 0.026 seconds with a voltage deviation of 0.0041V. This indicates that the conventional PI has been able to maintain a relatively stable voltage, but the recovery time is still relatively slow, and the voltage deviation has not been fully minimized.

The best performance is shown by the system with PI-PSO controller. When Vin is increased to 60V, the recovery time is slightly shorter at 0.996 seconds and the voltage deviation is equally small at 0.0049V. When Vin drops to 36V at the 4th second, the recovery time becomes faster at 0.021 seconds with a smaller deviation of 0.0039V. This performance reflects better adaptive capability and higher system stability as the deviation remains very small even though the input voltage changes drastically.

From the simulation results, it is known that PI-PSO provides the best performance with a recovery time of 36.52% better than PI and with the same reduction in voltage deviation as the conventional PI when the voltage is increased to 60 V. Meanwhile, when the input voltage is lowered to 36 V, PI-PSO produces 19.23% better recovery time than conventional PI and produces 4.88% smaller voltage deviation than conventional PI.

The sensitivity analysis indicates that the buck converter's output remains remarkably stable despite fluctuations in the input voltage. Assuming $V_{ref} = 48\,V$ and $\Delta V_{in} = \pm 12\,V$, the output variation for the conventional PI controller under an input increase to $60\,V$ is only $\Delta V = 0.0049\,V$, giving a sensitivity of $S = 0.0004083\,V/V$ (approximately $0.00041\,V$ change in output per $1\,V$ change in input), or a relative deviation of just 0.01021% from V_{ref}. When the input decreases to $36\,V$, $\Delta V = 0.0041\,V$ ($S = 0.0003417\,V/V$, 0.00854%). The PI–PSO controller shows comparable sensitivity during voltage rise ($S = 0.0004083\,V/V$) but better resilience during voltage drops with $\Delta V = 0.0039\,V$ ($S = 0.0003250\,V/V$, 0.00813%). In other words, a 1 V change in supply only causes about $0.00033 - 0.00041\,V$ deviation at the output, confirming the system's high robustness against input disturbances, with PI–PSO performing slightly better under downward fluctuations.

In terms of stability, the dynamic response clearly benefits from the PSO-based optimization. When the input rises to $60\,V$, the recovery time for the conventional PI controller is $1.569\,s$, while the PI–PSO controller stabilizes in only $0.996\,s$ - a 36.5% improvement. During a drop to 36 V, recovery improves from $0.026\,s$ to $0.021\,s$ (19.2% faster). The steady-state error is highest below $0.0049\,V$ ($\leq 0.01021\%$ of $48\,V$), and with the PI–PSO, the voltage error in drop events is decreased from $0.0041\,V$ to $0.0039\,V$ (4.88% improvement). The findings demonstrate that the PI–PSO controller enhances dynamic stability by improving settling time and damping but leaving or enhancing steady-state stability relative to the standard PI controller.

4.3. Disturbance

This section discusses the response of the bidirectional converter system to external fault conditions. The purpose of this test is to determine the durability and stability of the controller system in maintaining the output voltage during a disturbance. Simulations are carried out with three system conditions, namely without a controller, using a conventional PI controller, and using a PI controller optimized with the PSO algorithm (PI-PSO). Disturbance testing is carried out to test the extent to which the controller is able to maintain the stability of the output voltage when the system experiences sudden changes such as voltage spikes or drops. Simulation results show that the PI-PSO controller has the fastest and most stable response in returning the system to the reference state.

Fig. 14 and table 8 present the simulation results showing the system response when experiencing sudden disturbances or unexpected source fluctuations. In the condition without controller, the system does not show the ability to overcome the disturbance. This can be seen from the recovery time and voltage deviation values which are both zero. Which means the system is unable to readjust its output voltage after a disturbance. The voltage remains stagnant without any effort to recover to the reference value, indicating that the system is not suitable for dynamic applications that require voltage stability.

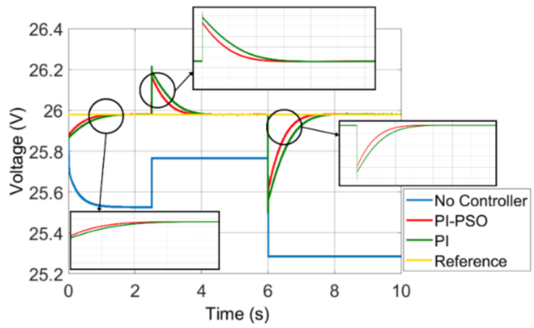

Fig. 14 Performance of disturbance PI-PSO, conventional PI, and No controller in charge mode.

Table 8 Performance of disturbance PI-PSO, conventional PI, and No controller in charge mode.

No.	V_{out} (V)	R (Ω)	V_{ref} (V)	No Controller		PI		PI-PSO	
				t_{rec}(s)	ΔV(V)	t_{rec}(s)	ΔV(V)	t_{rec}(s)	ΔV(V)
1.	25.98	100	25.98	0.00	0.00	0.00	0.00	0.00	0.00
2.	26.22			-	-	3.18	0.2379	2.08	0.2374
3.	25.74			-	-	3.42	0.4838	2.82	0.4828

Table 9 Performance of disturbance PI-PSO, conventional PI, and No controller in discharge mode.

No.	V_{out} (V)	R (Ω)	V_{ref} (V)	No Controller		PI		PI-PSO	
				t_{rec}(s)	ΔV(V)	t_{rec}(s)	ΔV(V)	t_{rec}(s)	ΔV(V)
1.	48	100	48	0.00	0.00	0.00	0.00	0.00	0.00
2.	63			-	-	0.042	15.008	0.038	15.006
3.	33			-	-	0.093	30.08	0.076	30.10

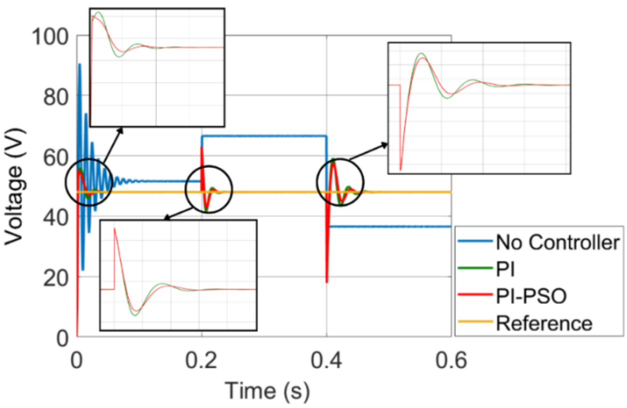

Fig. 15 Performance of disturbance PI-PSO, conventional PI, and No controller in discharge mode.

Meanwhile, the system with a conventional PI controller shows better performance when a disturbance occurs. The system was able to restore the voltage close to the reference value when the disturbance occurred at second 2.5. With a voltage of 26.22V, the recovery time for disturbances using conventional PI is 3.18 seconds and the voltage deviation reaches 0.2379V. As for the disturbance that occurred at the 6th second, with the disturbance reaching 25.74V, the recovery time on the conventional PI controller reached 3.42 seconds and the voltage deviation reached 0.4838V. It shows that the system is starting to be able to overcome the disturbance and return to stability even though the response is relatively slow and there is a slight overshoot. Thus, the PI controller is good enough but can still be improved, especially in terms of recovery speed.

Meanwhile, the PI-PSO controller shows the best performance in dealing with disturbances. The system with PI-PSO is able to respond faster and the voltage deviation is smaller when a disturbance occurs at second 2.5 with a recovery time of 2.08 seconds and a voltage deviation of 0.2374V. As for the disturbance that occurred at the 6th second, with a disturbance reaching 25.74V, the recovery time on the PI-PSO controller reached 2.82 seconds and a smaller voltage deviation of 0.4828V. from the analysis results show that the system is able to restore stability with a faster response and smaller deviation this is evidence that the optimization of parameters K_p and K_i using the PSO algorithm significantly improves the resilience and stability of the system against disturbances.

In charge mode, the PI-PSO system recorded a shorter recovery time of about 34.59% than the conventional PI when the reference rose to a voltage of 26.22 V with a smaller voltage deviation of about 0.21%. While at a voltage drop to 25.74 V PI-PSO has a recovery time shorter by 17.54% than the conventional PI and has a smaller voltage deviation of 0.21% from the conventional PI.

Fig. 15 and table 9 provide an overview of the system's ability to maintain voltage stability in the form of output when external disturbances occur. In the condition without a controller, the system does not show an adaptive response to disturbances. Recovery time and voltage deviation (ΔV) are recorded as 0, indicating that the system is completely passive and unable to adjust itself when a disturbance occurs. As a result, the output voltage is unstable and keeps deviating from the reference value.

When given a conventional PI controller, the system shows improvement. When a disturbance occurs at the second to 0.2 with a disturbance reaching 63V, the PI is able to restore the voltage towards the reference value with a recovery time of 0.042 seconds and a voltage deviation of 15.008V. As for the disturbance that occurred at the 0.4 second, with a disturbance reaching 33V, the recovery time on the conventional PI controller reached 0.093 seconds and a voltage deviation of 30.08V. This shows that the system begins to have adaptation and correction capabilities, but there are still shortcomings in terms of response speed and voltage deviation.

The best performance is shown by the system with PI-PSO controller. This system provides the fastest response, the system shows improvement. When a disturbance occurs at the second to 0.2 with a disturbance reaching 63V, PI-PSO is able to restore the voltage towards the reference value with a recovery time of 0.038 seconds and a smaller voltage deviation than the conventional PI of 15.006V. As for the disturbance that occurred at second 0.4, with a disturbance reaching 33V, the recovery time on the PI-PSO controller is faster reaching 0.076 seconds and a voltage deviation of 30.10V. Indicating that PI-PSO is able to respond quickly to disturbances and maintain voltage stability better than conventional PI.

While in discharge mode, PI-PSO produces a shorter recovery time of about 9.52% from PI and a smaller voltage deviation of 0.013% from conventional PI when the reference rises to 63 V. While when the voltage drops to 33 V PI-PSO produces a recovery time of 18.28% from the conventional PI. However, the voltage deviation is still superior to conventional PI by about 0.066% from PI-PSO.

Overall, PI-PSO is able to maintain system stability and suppress errors during disturbances in both charge and discharge modes. This indicates that tuning K_p and K_i through PSO provides better disturbance suppression power than conventional controllers.

5. Conclusion

In charge mode, the results obtained K_p = 60.019 and K_i = 305.05, PI-PSO controller is able to accelerate the rise time with the rise time reduced from 0.958 seconds (PI) to 0.707 seconds (PI-PSO), and overshoot decreased from 25.9841V to 25.9838V. In addition, PI-PSO reduces the oscillation compared to conventional PI by 7.7%. The system achieves the reference voltage with better precision and shows improved system stability in battery charging mode.

In discharge mode, the results of K_p = 0.4012, K_i = 154.208 were obtained. The application of PI-PSO also provides optimal results by suppressing overshoot significantly with the result of overshoot decreasing from 55.83V to 50.12V and shortening the rise time with the result of rise time decreasing from 0.00117 seconds to 0.0011 seconds. In addition, the system output becomes smoother with smaller oscillations of up to 1.2% than the conventional PI, in accordance with the reference for efficient battery discharge.

The optimized PI controller using the Modified PSO Algorithm demonstrates superior performance compared to conventional PI controllers and without controllers. This improvement is mainly due to improvements in the optimization mechanism. Unlike the basic PSO, the modified version integrates a dynamic re-randomization process to prevent premature convergence and effectively avoid local minima. This allows the algorithm to continue exploring better combinations of K_p and K_i, especially in complex nonlinear system responses such as those found in bidirectional converters.

Acknowledgement

The authors would like to express gratitude to Lembaga Penelitian dan Pengabdian Masyarakat Universitas Negeri Surabaya (LPPM Unesa) for funding this work through the scheme collaborative basic research (Contract No. B/ 35086 /UN38.III.1/LK.04.00/2025).

Author Contributions

Rifqi Firmansyah: Methodology, Supervision, Validation, Writing – original draft. **Habib Wicaksono:** Conceptualization, Formal analysis, Writing – original draft. **Gul Ahmad Ludin**: Conceptualization, Methodology, Supervision. **Naufal Maulana Fahmi:** Conceptualization, Methodology, Writing – original draft. **Ali Nur Fathoni:** Software**,** Validation, Writing – review & editing. **Rudi Uswarman:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Reference

[1] Trinh, H. -A., Nguyen, D. G., Phan, V. -D., Duong, T. -Q., Truong, H. -V. -A., Choi, S. -J. and Ahn, K. K., Robust Adaptive Control Strategy for a Bidirectional DC-DC Converter Based on Extremum Seeking and Sliding Mode Control. *Sensors*. 23 (2023) 457, doi: https://doi.org/10.3390/s23010457.

[2] Li, X., Jiang, W., Wang, J., Wang, P. and Wu, X., An autonomous control scheme of global smooth transitions for bidirectional DC-DC converter in DC microgrid. *IEEE Transactions on Energy Conversion.* 36 (2021) 950–960, doi: https://doi.org/10.1109/TEC.2020.3020127.

[3] Vadivel, S. and Ragupathy, U. S., Modeling and design of high performance converters for optimal utilization of interconnected renewable energy resources to micro grid with GOLRS controller. *International Journal of Control, Automation and Systems*. 19 (2021) 63–75, doi: https://doi.org/10.1007/s12555-019-0498-2.

[4] Septiawan, F. R., Tahtawi, A. R. A. and Ilman, S. M., Control of bidirectional DC-DC converter with proportional integral derivative. *Journal of Fundamental Science Community*. 2 (2024) 164–169, doi: https://doi.org/10.59247/jfsc.v2i3.241.

[5] Wibawa, U., Mardiana, E. and Ardhenta, L. Design and performance analysis of PID controller for extended output voltage buck-boost converter. in *2020 10th Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS).* (2020) 31–36, doi: https://doi.org/10.1109/EECCIS49483.2020.9263458.

[6] Pramanik, R. and Pati, B. B., Modelling and control of a non-isolated half-bridge bidirectional DC-DC converter with an energy management topology applicable with EV/HEV. *Journal of King Saud University - Engineering Sciences*. 35 (2023) 116–122, doi: https://doi.org/10.1016/j.jksues.2021.03.004.

[7] Li, B. Y., Xu, C., Li, C. and Guan, Z., Working principle analysis and control algorithm for bidirectional DC/DC converter. *Journal of Power Technologies.* 97 (2018) 327–335.

[8] Trapti, G. and Sudeep, M., Control and Designing of Bidirectional DC-DC Converter. *International Journal of Research Publication and Reviews*. 05 (2024) 852–855.

[9] Adhikary, S. and Biswas, P. K. Optimization of PID tuning of DC-DC bidirectional converter control strategy for EV charger using GA and IoT based SOC estimation. in *2024 1st International Conference on Innovative and Sustainable Technologies in Energy, Mechatronics and Smart Systems (ISTEMS)*, 1–6, doi: https://doi.org/10.1109/ISTEMS60181.2024.10560127.

[10] Suresh, K. and Arulmozhiyal, Dr. R., Design and implementation of bi-directional DC-DC converter for wind energy system. *Circuits and Systems*. 07 (2016) 3705–3722, doi: https://doi.org/10.4236/cs.2016.711311.

[11] Debnath, A., Olowu, T. O., Roy, S., Parvez, I. and Sarwat, A., Particle swarm optimization-based PID controller design for DC-DC buck converter. 2021 North American Power Symposium (NAPS), (2021) 1–6. https://doi.org/10.1109/NAPS52732.2021.9654737.

[12] Zhang, H., Chen, Y., Park, S. -J., Kim and D. -H. A family of bidirectional DC-DC converters for battery storage system with high voltage gain. *Energies*. 12 (2019) 1289, doi: https://doi.org/10.3390/en12071289.

[13] Mohan, N., Undeland, T. M. and Robbins, W. P. *Power electronics*, *converters, applications, and design*. 3rd edn., John wiley & sons, 2003.

[14] Sarif, M. S. M., Pei, T. X. and Annuar, A. Z. Modeling design and control of bidirectional DC-DC converter using state-space average model. in *2018 Symposium on Computer Applications & Industrial Electronics (ISCAIE)*. (2018), 416–421, doi: https://doi.org/10.1109/ISCAIE.2018.8405509.

[15] Chatterjee, A., Patra, S., Samal, P., Jyoti, D. and Utsav, K. A. Investigation Analysis of a Bi-directional DC-DC Converter for EV Charging. in *2024 IEEE 1st International Conference on Advances in Signal Processing, Power, Communication, and Computing (ASPCC)*. (2024), 118–123, doi: https://doi.org/10.1109/ASPCC62191.2024.10881172.

[16] Pramanik, R., Mathematical modelling of non-isolated bi-directional DC-DC converter on transients and steady state response. *International Journal of Engineering Research & Technology(IJERT).* 4 (2015) 101–105.

[17] Rashid, M. H. *Power electronics handbook.* 2001 edn., Academic Press.

[18] Laoprom, I. and Tunyasrirut, S., Design of PI Controller for Voltage Controller of Four-Phase Interleaved Boost Converter Using Particle Swarm Optimization. *Journal of Control Science*

and Engineering. (2020) 9515160, doi: https://doi.org/10.1155/2020/9515160.

[19] Ogata, Katsuhiko. *Modern control engineering*. 5th edn., Pearson, 2017.

[20] Seborg, D. E., Edgar, T. F., Mellichamp, D. A. and Doyle III F. J., *Process dynamics and control.* 2nd edn., John Wiley & Sons, 2002.

[21] Premkumar, K., Vishnupriya, M., Thamizhselvan, T., Sanjeevikumar, P. and Manikandan, B. V., PSO optimized PI controlled DC-DC buck converter-based proton-exchange membrane fuel cell emulator for testing of MPPT algorithm and battery charger controller. *International Transactions on Electrical Energy Systems.* 31 (2021) e12754, doi: https://doi.org/10.1002/2050-7038.12754.

[22] Mühürcü, G., Kose, E., Muhurcu, A. and Kuyumcu, A. Parameter optimization of PI controller by PSO for optimal controlling of a Buck Converter's output. in *2017 International Artificial Intelligence and Data Processing Symposium (IDAP)*. (2017), 1-6, doi: https://doi.org/10.1109/IDAP.2017.8090234.