

Article

Optimized Control of a Hybrid Water Pumping System Integrated with Solar Photovoltaic and Battery Storage: Towards Sustainable and Green Water-Power Supply

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Abstract: This article presents the modeling and optimization control of a hybrid water pumping system utilizing a brushless DC motor. The system incorporates battery storage and a solar photovoltaic array to achieve efficient water pumping. The solar array serves as the primary power source, supplying energy to the water pump for full-volume water surrender. During unfavorable weather conditions or when the photovoltaic array is unable to meet the power demands of the water pump, the battery discharges only at night or during inadequate solar conditions. Additionally, the photovoltaic array can charge the battery on its own when water distribution is not necessary, negating the need for external power sources. A bi-directional charge control mechanism is employed to facilitate automatic switching between the operating modes of the battery, utilizing a buck-boost DC–DC converter. The study incorporates a control system with loops for battery control and DC voltage control within the bidirectional converter. The water cycle algorithm adjusts four control parameters by minimizing an objective function based on tracking errors. The water cycle optimization is compared to other methods based on overshoot and settling time values to evaluate its performance, showcasing its effectiveness in analyzing the results.



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Keywords: hybrid water pumping system; photovoltaic; optimization; brushless DC motor; bi-directional control; water cycle algorithm

1. Introduction

A brushless DC motor (BLDC) driver for solar photovoltaic (SPV)-powered water pumping has recently gained more attention as it is highly efficient, easy to maintain and drive, and compact [1,2]. Due to its intermittent nature, SPV power causes unreliable and intermittent water pumping; bad climatic conditions and the absence of sunlight cause the entire water pumping system to shut down. In addition, PV installation and other resources are not used where water pumping is not required. If full water distribution is desired continuously due to these troublesome situations, external power support is required. In remote locations, a diesel generator is often used as a backup supply [3,4]. Recently however, it has been recommended that diesel generators should not be used, to maintain a pollution-free environment and reduce threats to energy security. Thus, the only solution left as a power backup is to use battery storage. A battery-powered SPV hybrid power supply provides enough power for a reliable water pumping system [3].

With increasing demands for electricity, power saving has become a serious problem. BLDC motors play a serious role in this issue as energy-efficient motors with high power density, high efficiency, high power factors, and a high torque/inertia ratio compared to asynchronous motors [4]. This motor has replaced the asynchronous motor in many applications, including water pumping. In recent studies, it has been proposed that a cost-effective, simple, and powerful BLDC motor driver should be used for SPV hybrid

water pumping systems. Transducer models such as Zeta converters are used to extract the maximum usable power from the SPV array [5]—as do positively interleaved Luo converters (I-Luo), which increase the output with minimal switching losses [6]. Studies carried out in MATLAB/Simulink have studied these converters under different operating conditions, demonstrating the efficient operation of dynamic and steady-state water pumping [7]. A BLDC motor can be used to maximize the power transmitted by the PV array and increase the reliability of the pumping system [8]. It is predicted that suitable PV techniques, pumps, motors, and appropriate optimization algorithms will benefit researchers in the effective design, control, and performance improvement of solar water pumping [9].

This study used a power flow control bidirectional boost converter [10,11] to charge/discharge a battery store. The control was based on whether the battery needs to be charged/discharged according to the availability of SPV power and water demand. The battery produced power during the day. On the other hand, when there was SPV power, the battery is charged. When all the power required for the water pump was supplied from the SPV array, pumping water was necessary, and the battery was non-functional. The proposed system functioned as a charging source for the battery; an SPV array and an external power source were not required. In this case, the full benefit was obtained from both the motor pump system and the PV installation. The bidirectional power flow provided bidirectional power flow through a collective capacitor placed on the DC bus of the voltage source inverter (VSI). The DC link voltage of the VSI was regulated so that the BLDC motor speed was kept at a nominal value. However, with the gain constants obtained with the traditional proportional integral (PI) controller, full-rated control could not be achieved; it was kept at the full nominal value by adding the optimization algorithm and was also kept at the constant value by applying optimization to the PI controller where the current battery value was controlled, as well as the PI controller where the DC-link voltage was also controlled at the same time. This application allows water to be pumped at full capacity [3].

This article proposes the modeling and optimization of a BLDC motor-driven pumping system based on an SPV battery hybrid power supply. It aims to improve the grid's power quality by using a water cycle optimization (WCO)-based proportional-integral (PI)-compensated design for grid-connected solar photovoltaic-fed BLDC. The novelty and practical importance of this research is the use of one of the best optimization algorithms—the WCO algorithm, which provides current and voltage control by optimization; furthermore, instead of using a conventional AC motor, a DC motor is used in the water pumping system. Although it is costly, considering the increase in efficiency, it can be calculated by how many years the cost can be recovered. As a result, a DC motor and optimization algorithms were used for better water pumping in the water pumping system, and efficiency was increased thanks to bidirectional charge control. Which performance criteria are preferred in the study and which functions are minimized are clearly given in Section 2.3. The formulas are explained one by one, and a flow chart showing the optimization steps is also given. In the study, the gain constants were found according to the conventional method PI, calculated according to the damping coefficient; then, the genetic algorithm (GA), the bacteria foraging algorithm (BFA), and the water cycle algorithm (WCA)—which is one of the best optimization algorithms—were used, and the results were compared with the results of the three algorithms and the conventional method. In the results, it can be seen that the WCA algorithm provided better optimization. By applying the optimization techniques suggested in the study to the control parameters in the most appropriate way, a good improvement in power quality was achieved, compared to the study results presented by Kumar and Singh.

This article is organized as follows: The proposed system and the methods used are described in Section 1. Section 2 describes the results and discussion of the system. Conclusions are given in Section 3.

2. Materials and Methods

2.1. SPV Battery-Based Hybrid Water Pumping System

The configuration of the modeled and optimized hybrid water pumping system is shown in Figure 1. Battery storage via an SPV array and a bidirectional buck-boost converter formed a collective DC bus. This common DC bus powered a BLDC motor pump through a VSI. An incremental conductance (InC) technique was used to perform the MPPT of the SPV array through the DC–DC step-up converter. A buck-boost converter acted as a charge controller for the battery. The converter acted as a part step-up converter (when the battery was discharged), and the battery supplied the common DC bus. A VSI performed the electronic commutation of the BLDC motor. A centrifugal water pump was connected to the shaft of the BLDC motor with three internal Hall Effect sensors to generate Hall signals for commutation [3].

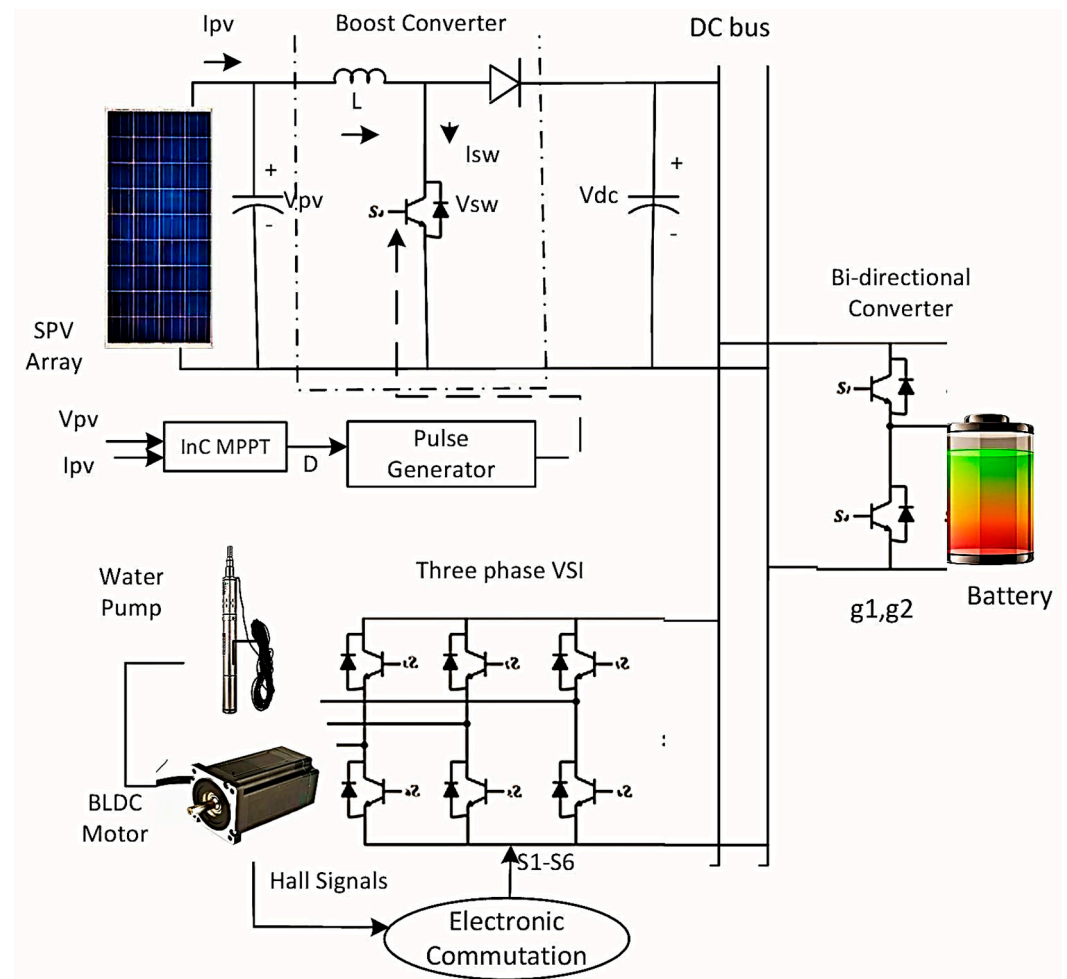


Figure 1. SPV-battery based hybrid water pumping system.

The magnitude of the initial BLDC motor stator current was controlled by running the VSI in Pulse Width Modulation (PWM) mode for a predefined time. Again, when the engine was started, the inverter was driven by fundamental frequency pulses—providing minimal switching loss and improved conversion efficiency. A SPV battery-based hybrid pumping system with a brushless DC motor driver was simulated on the MATLAB/SIMULINK platform, and optimization was applied to the DC link voltage and battery current PI controllers in the bi-directional converter part. Furthermore, to prove the claims made, a comparison with the conventional controller and basic genetic algorithm and a powerful optimization tool—the bactericide algorithm—was made through the simulation results, and the efficiency of the water cycle algorithm was evaluated. Various control methods

were implemented onto the suggested water pumping system to achieve the desired results. The conversion efficiency of an SPV cell is less than 20%. The absence of an effective MPPT leads to highly inefficient solar power generation. To make the best use of the installed PV array, INC is the most popular technique, because of its excellent tracking performance under dynamic conditions [5–12]. The proposed system also distorts this technique, with a fixed distortion size and rate according to the duty ratio and power slope selected as the control parameter. The bidirectional power change between the storage and the DC bus is shown in Figure 2; this was achieved through a DC–DC step-up converter [10,11] using a bidirectional power flow control. The DC bus voltage (V_{dc}) was regulated at the rated DC voltage of the BLDC motor—i.e., 110 V—by a voltage regulator. Charge/discharge current of the battery; The IB was controlled by a current regulator. A PI controller was utilized as the current and voltage regulator and was converted into a PWM pulse to further increase the duty ratio and converter corresponding to the regulator.

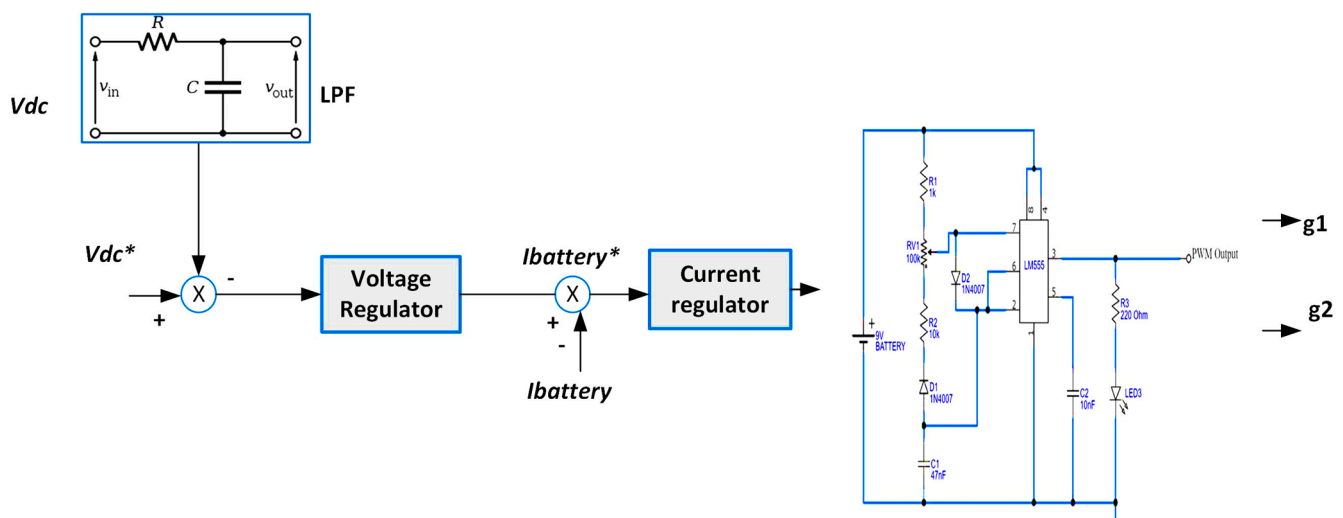


Figure 2. Bi-directional charge controller for battery storage.

The buck-boost bi-directional converter was run simultaneously in either boost mode or buck mode. The DC bus voltage controlled the operating mode. When solar radiation decreased or completely disappeared (at night), a drop in the DC bus voltage occurred.

The controller kept the voltage level at its set value by operating the converter in boost mode and allowing power flow from the battery to the DC bus—thus draining the battery. Only the g2 device was activated in this mode, while an anti-parallel diode g1 completed a boost converter circuit. The DC link voltage rose when water pumping was not required, but SPV power was available. The PI controller then maintained the voltage level at its set value by operating the converter in buck mode and enabling power flow through the power stream.

The DC bus was linked to the battery, thus charging the battery. In this case, the g1 device was activated when the g2 anti-parallel diode joined to complete the buck converter circuit. On the other hand, when the SPV array produced enough power to run the pump at full efficiency, the battery was inoperable. Thus, the battery did not charge/discharge. The voltage on the DC bus was kept at 110 V; it did not matter if the battery was charged/discharged, or idle.

2.2. Electronic Commutation of the BLDC Motor

Electronic commutation refers to the commutation of the currents flowing from the windings of the BLDC motor in such a way that a symmetrical direct current of 1200 is drawn from the DC bus of the VSI and placed in the center of the back EMF (Electro-Motive

Force) [1,2,13]. Three internal Hall Effect sensors generate a special combination of Hall signals (H)–H3) based on the rotor position over a 60° range.

The speed of the BLDC motor is controlled by regulating the DC bus voltage of the VSI at the nominal DC voltage of the BLDC motor. A bidirectional power flow control provides control by regulating the DC bus voltage and thus the operating speed—providing the exact amount of power needed to pump water at full capacity. The BLDC motor driver proposed by [14] provides simple and cost-effective control by eliminating the phase current sensors.

2.3. Water Cycle Algorithm for Optimization

The water cycle algorithm (WCA) used for optimization was the algorithm known as the water cycle, which was created based on the movement of water [15]. Raindrops and snow accumulating on mountains or hills continue to collect in the sea, which flows to form a river or stream. In addition, water evaporates and is carried into the atmosphere. When it condenses in cold conditions, it returns as rain and forms clouds. In the first optimization case, a raindrop's initial population in the search space is generated, and the optimization objective function of the algorithm is created [15,16]. The optimum solution is the sea with the best raindrops.

$$\text{Raindrops} = [x_1, x_2, x_3, \dots, x_N] \quad (1)$$

N symbolizes the number of variables and the size of the optimization problem. Since it contains four parameters of two PI controllers, the Raindrop vector $N = 4$ for the optimum control design and the vector in (1) is given as:

$$[x_1, x_2, x_3, x_4] = [K_{p1}, K_{i1}, K_{p2}, K_{i2}] \quad (2)$$

The parameters of the Raindrop vector (9), x_i ($i = 1 \dots 6$), are between the lower bound and upper bound as:

$$l_b \leq x_i \leq u_b \quad (3)$$

where l_b represents the lower and u_b is the upper limit.

The WCA algorithm creates a raindrop population, such as a size matrix represented by ($N_p \times N$), and is initial.

$$\begin{aligned} \text{Population} &= \begin{bmatrix} \text{Raindrops}_1 \\ \text{Raindrops}_2 \\ \vdots \\ \text{Raindrops}_{N_p} \end{bmatrix} \\ \begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^{N_p} \end{bmatrix} &= \begin{bmatrix} x_1^1 & \dots & x_N^1 \\ \vdots & \ddots & \vdots \\ x_1^{N_p} & \dots & x_N^{N_p} \end{bmatrix} \end{aligned} \quad (4)$$

where X^i is the position of the Raindrops _{i} , N_p is the population size, and $i = 1, \dots, N_p$.

The location of the raindrops is randomly generated and expressed as:

$$X^i = l_b + (u_b - l_b) \times \text{rand}(1, N) \quad (5)$$

The cost of the raindrops, C_i , is calculated using the cost formula:

$$C_i = F(X^i) \quad (6)$$

where $i = 1, \dots, N_p$ and F is the objective function.

In this work, the Integral time square error formula (ITSE) was selected as the cost function using Equation (7). The goal of the objective function is to minimize the errors (e_v , e_b) of the current and voltage regulators, where w_v and w_b are weight coefficients.

$$F(X) = [w_v \quad w_b] \begin{bmatrix} \int_0^T te_v^2 dt \\ \int_0^T te_b^2 dt \end{bmatrix} \quad (7)$$

In Figure 1, the hybrid water pumping system is simulated and applied the objective function in (7), run using the values of the raindrop's position $X^i = [x_1^i, x_2^i, \dots, x_N^i]$ appointed to the PI control parameters, such as:

$$[K_{p1}, K_{i1}, K_{p2}, K_{i2}] = [x_1^i, x_2^i, x_3^i, x_4^i] \quad (8)$$

C_i are classified in ascending order. N_{sr} is the best raindrop number assigned to one sea and several rivers (N_r).

$$N_{sr} = N_r + \underbrace{1}_{\text{sea}} \quad (9)$$

where the raindrop sea has the lowest cost value between the minimum cost values.

The optimal solution in the algorithm is the sea position. N_{st} includes streams that are likely to flow into rivers or straight into the sea. The remaining population is applied as:

$$N_{st} = N_p - N_{sr} \quad (10)$$

It is ensured that the streams are divided into seas or rivers according to the flow density, provided as (9), (10).

$$NS_n = \text{round} \left\{ \left| \frac{C_n}{\sum_{i=1}^{N_{sr}} C_i} \right| \times N_{st} \right\}, \quad n = 1, 2, \dots, N_{sr} \quad (11)$$

where NS_n , the number of streams flowing into a certain sea or rivers.

Streams move to rivers while rivers move to the sea and streams; the updated positions for the rivers are given as:

$$\begin{cases} X_{\text{stream}}^{i+1} = X_{\text{stream}}^i + \text{rand} \times C \times (X_{\text{river}}^i - X_{\text{stream}}^i) \\ X_{\text{river}}^{i+1} = X_{\text{river}}^i + \text{rand} \times C \times (X_{\text{sea}}^i - X_{\text{river}}^i) \end{cases} \quad (12)$$

where for C , the best value is 2, and must be greater than 1; $\text{rand} \in [0 \quad 1]$.

The new positions' costs are expressed by (6)–(8). If the stream's cost is less than a river's, their places are changed. The same is done for the river and sea locations, with the least costly river location being the sea. A rapid convergence of optimization is avoided by performing evaporation for seawater to flow streams or rivers into the sea. This operation is subject to the following requirements:

$$\text{if } |X_{\text{sea}}^i - X_{\text{river}}^i| < d_{\max} \quad (13)$$

Managing the raining process and evaporation. Where $d_{\max}$ is a small number ($\rightarrow 0$), $N_{sr} - 1$, $i = 1, 2, \dots$. The expression indicating that the river reaches the sea is at any distance less than $d_{\max}$. Accordingly, evaporation occurs, and sufficient evaporation initiates the precipitation process. When $d_{\max}$ is a small value, the search density near the sea increases. A large value decreases the call while near the sea. Accordingly, the search density close to the sea can be checked with the updated $d_{\max}$:

$$d_{\max}^{i+1} = d_{\max}^i - \frac{d_{\max}^i}{\text{max_iter}} \quad (14)$$

where $i = 1, 2, \dots, \text{max_iter}$; max_iter is the maximum iteration number.

The flow of new raindrops at different locations, expressed as such, creates the raining process:

$$X_{\text{stream}}^{\text{new}} = l_b + (u_b - l_b) \times \text{rand}(1, N) \quad (15)$$

The algorithm will proceed until max_iter is reached. The sea location will be found as the most suitable solution. These values will be used for K_p , K_i (10) and to minimize objective functions, focusing on the battery current or DC-link voltage control (V_{dc}) following errors (l_b). The SPV-battery based hybrid water pumping system given in Figure 3 was simulated and controlled. Conventional, GA, and BFA WCA methods were used to optimize the PI control parameters for DC-link voltage and current control of the simulated hybrid water pumping system, as shown in Figure 4. The flow diagram of the WCA used for optimization is shown in Figure 5.

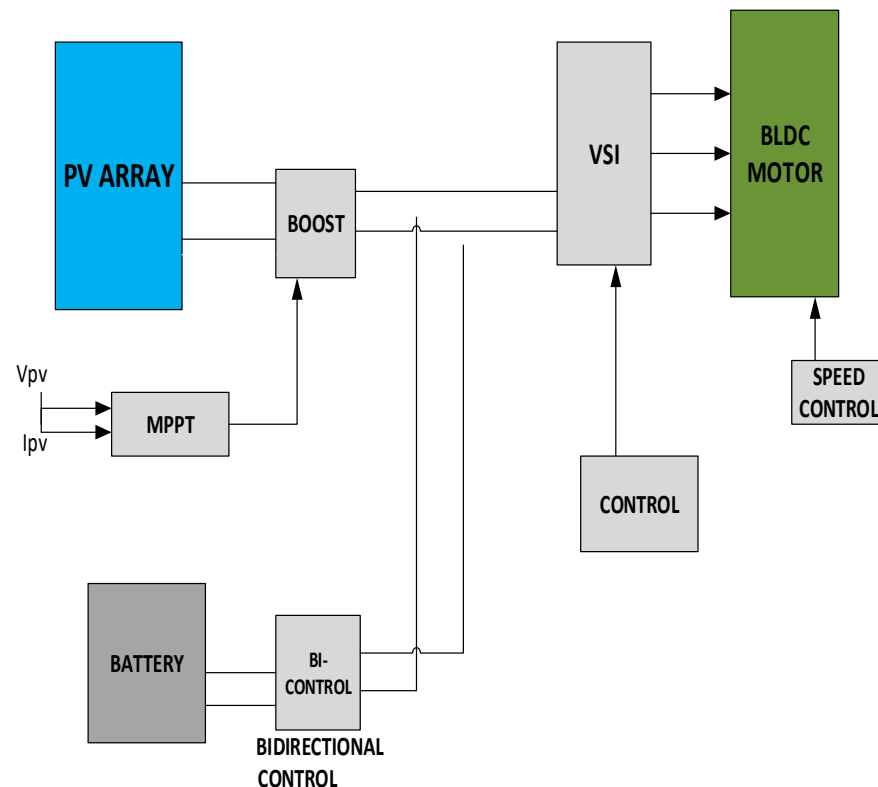


Figure 3. Modelling of the hybrid water pumping system in MATLAB/Simulink R2022a.

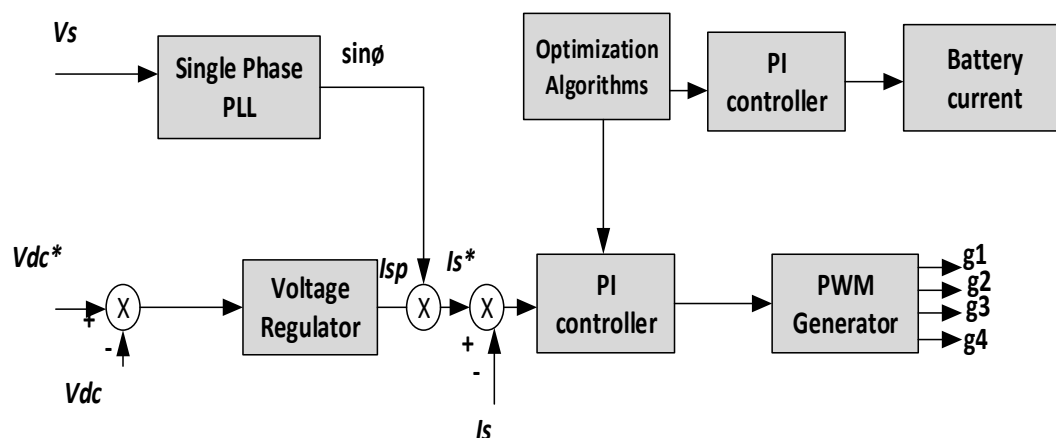


Figure 4. Optimization PI control parameters for DC-link voltage control and battery current control.

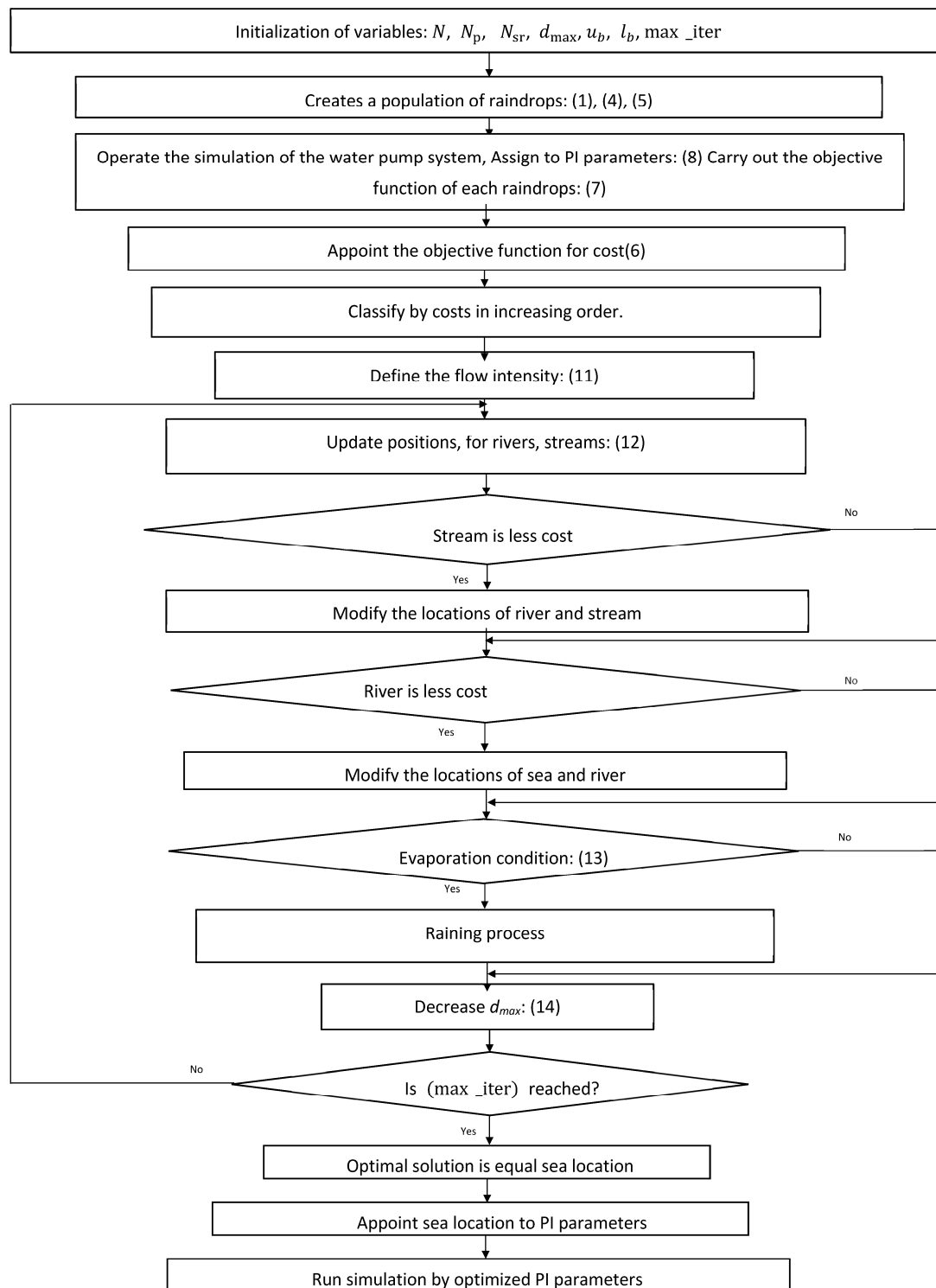


Figure 5. WCA optimization algorithm flowchart.

Optimization techniques were performed using the performance criteria detailed in [17–19], such as the integral squared error (ISE), integral time squared error (ITSE), integral absolute error (IAE), and integral time absolute error (ITAE). The parameters of the methods (techniques) used are given in Tables 1–3. The results were compared with other methods to demonstrate the superiority of the WCA method using WCA-based PI parameters in the SPV-battery hybrid water pump system. The parameters used for the hybrid system modeled in Simulink are given in Table 4 for the BLDC motor.

The parameters used for the solar PV system and bi-directional converter are given in Tables 5 and 6.

To appraise the parameters (K_p , K_i) and natural frequency (ω_n) of the PI controller—which is the traditional method—they were obtained using a quadratic equation by choosing the damping coefficient (ϵ) and the residence time (t_s) [20,21].

Table 1. GA technique parameters as detailed in [22–26].

Parameters	Quantity
Number of variables	4
Number of iterations (Generations)	100
Population size	50
Rate of mutation	0.01
Rate of cross over	0.8

Table 2. The BFA technique parameters [21].

Parameters	Quantity
Dimension of search space	4
Number of iterations	100
Bacteria number (S)	10
Chemotactic steps number (N_c)	5
Limits the length of swim (N_s) and Reproduction steps number (N_{re})	4
Probability for elimination/dispersion (P_{ed}) and Elimination-dispersal number (N_{ed})	2

Table 3. WCA technique parameters as detailed in [27,28].

Parameters	Quantity
Condition constant of evaporation (d_{max}):	10^{-16}
Rivers + sea (N_{sr}):	4
Iterations (max_iter)	100
Variables number (N)	4
Population number (N_p)	50

Table 4. BLDC motor pump parameters.

Parameters	Quantity
Pole	6
Speed	300 rpm
Stator resistance	0.37Ω
Stator inductance	1.0 mH
Voltage constant	$34 V_L / \text{krpm}$

Table 5. Solar PV array parameters.

Parameters	Quantity
Peak Power	1.92 kW
Open circuit voltage	126 V
MPP voltage	102 V
Short circuit current	22.4 A
MPP current	19 A

Table 6. Bi-directional converter parameters.

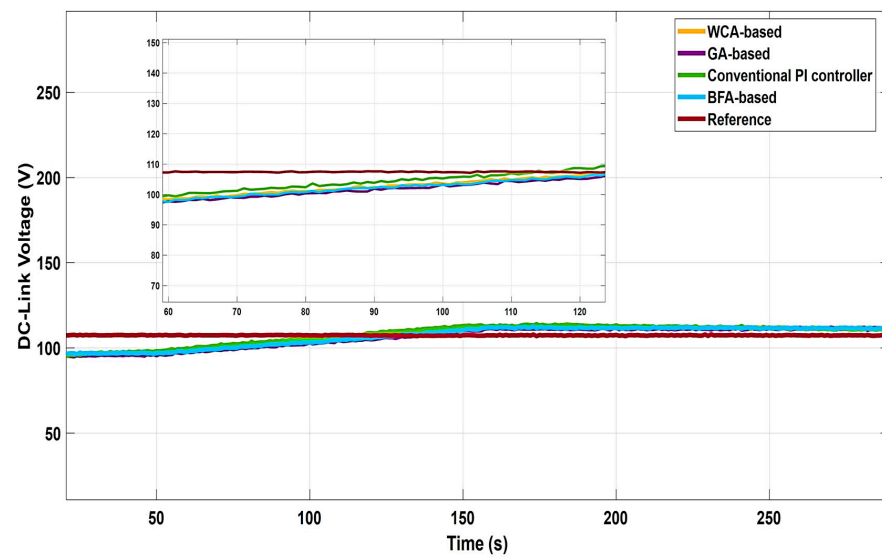
Parameters	Quantity
Boost inductor	3 mH
Bus capacitor	6000 μF

3. Results

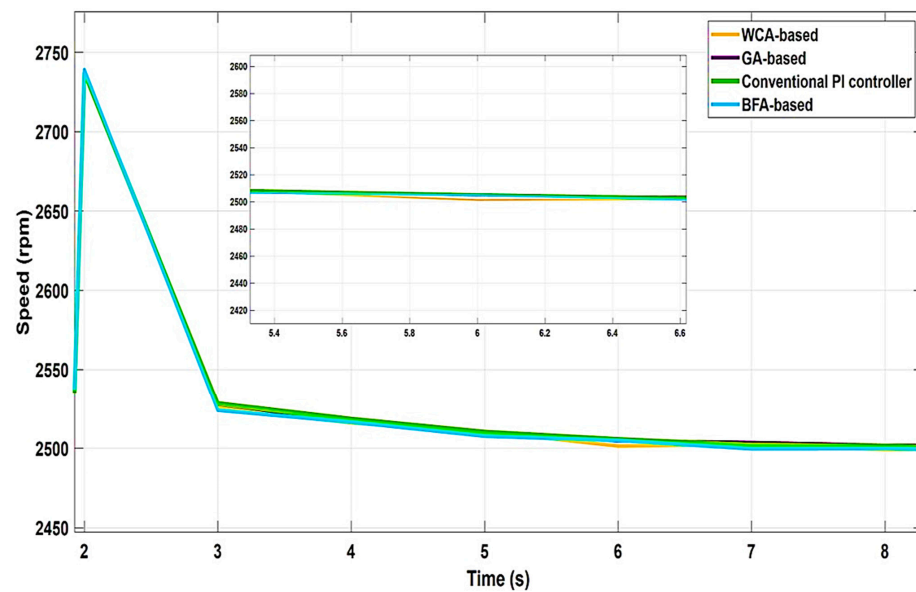
The proposed hybrid water pumping system was modeled and optimized, and the performance analysis performed, using MATLAB/Simulink toolboxes. A hybrid generation unit consisting of a 1.92 kW peak power and a 72 V SPV array was used, with a 300 Ah lead-acid battery feeding the 110 V 5.2 Nm BLDC motor pump at 3000 rpm. The GA, BFA, and WCA optimization algorithms were applied to utilize the ISE, ITSE, IAE, and ITAE; the iteration number was 100. The optimization process was conducted on a computer with an AMD Ryzen 7 4800 H processor with Radeon Graphics 2.90 GHz. The parameters obtained as a result of the optimization are given in Table 7. When evaluated in terms of average error detection criteria, the performance of the WCA was more effective than the GA or BFA and provided more effective picking and control. It was also effective as determined by the results of all the performance criteria. In the first case, the SPV-battery water pump system was run at a fixed 2500 rpm rotor speed. The aim was to determine the control performance by applying each algorithm method during the transitions. The control monitored the defined references for the DC-link voltage and battery current. Figure 6 shows the results of the tracking responses. Examining the results of the WCA method, while it was overdamped at the preferred settling time, the voltage responses of the GA and BFA-based PI control were underdamped, with a certain overshoot—as shown in Figure 6a. As a result of the dynamic analyses performed in Simulink in Figure 6a, in Table 8, while the over-shoot value was 8.9 in the DC-link voltage control provided with the PI constants—determined by the conventional method under constant speed—the overshoot value was 1.27 when the PI parameters were obtained using the WCA optimization algorithm. When the settling time was examined, it was reduced to 151.08 with the WCA-based method, while it was 160.5 in the conventional method. The WCA method had the best settling time, following the reference value for speed control in Figure 6b. In Figure 6c, it is seen that fluctuations were high in the conventional method and GA technique in terms of current control; these fluctuations were reduced with a good optimization tool such as the WCA. The BFA-based method appeared to have a better settling time, but was insufficient compared to the WCA-based method.

Table 7. Optimization statistical results.

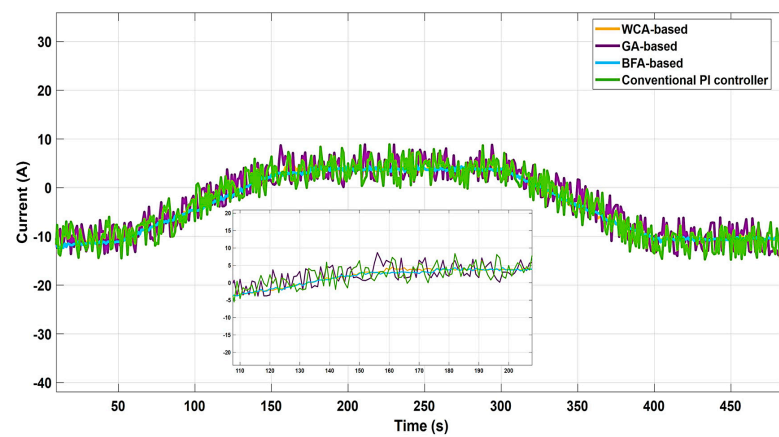
Performance Tests	Gain Parameters (Control)	Genetic Algorithm Optimization Technique	Bacteria Foraging Algorithm Optimization Technique	Water Cycle Optimization Technique
ITSE	DC-link voltage controller (K_{p1}, K_{i1}) Battery current controller (K_{p2}, K_{i2})	0.9674, 0.3701 0.3350, 0.8347	0.9991, 0.0712 0.5805, 0.9347	0.9981, 0.0194 0.5643, 0.9555
ISE	DC-link voltage controller (K_{p1}, K_{i1}) Battery current controller (K_{p2}, K_{i2})	0.9961, 0.0056 0.9756, 0.8414	0.9949, 0.0493 0.2099, 0.9861	0.9961, 0.0135 0.9766, 0.9834
ITAE	DC-link voltage controller (K_{p1}, K_{i1}) Battery current controller (K_{p2}, K_{i2})	0.9707, 0.2124 0.3302, 0.9255	0.9943, 0.0259 0.4196, 0.9898	0.9649, 0.0046 0.5870, 0.9724
IAE	DC-link voltage controller (K_{p1}, K_{i1}) Battery current controller (K_{p2}, K_{i2})	0.9815, 0 0.9693, 0.8278	0.9706, 0.0243 0.7482, 0.9421	0.9773, 0.0031 0.6111, 0.8928



(a)



(b)



(c)

Figure 6. (a) DC-link voltage. (b) speed, and (c) battery current (Tracking responses under a constant rotor speed with the optimization techniques).

Table 8. Dynamic performance results of the controllers.

PI Block	Based Controller	Overshoot	Settling Time (s)	Peak Values
DC-link voltage (under variable speed)	Conventional	45.12	112.5	195.2
	GA	36.92	111.1	183.4
	BFA	9.80	110.8	138.2
	WCA	6.02	108.5	134.01
DC-link voltage (under constant speed)	Conventional	8.90	160.5	113.3
	GA	7.44	155.8	112.1
	BFA	3.202	153.04	111.09
	WCA	1.27	151.08	110.01

In the second case, the SPV-battery hybrid water pump system was operated at variable speeds, and optimized PI parameters were used. As shown in Figure 7, at 2500 rpm at 0–120 s, 3000 at 120–260 s, and 2500 at 260–500 s, the BLDC motor system was operated under variable speed. The results shown in Figure 8 prove that in the case of conventional GA, BFA methods for DC-link voltage control were affected by speed changes from overshoot and settling times. WCA has proven to perform well and is a good optimization tool, as shown in Figure 8a–c; WCA-based PI controllers respond better to rotor speed changes in terms of settling time and overshoot compared to GA, BFA, and conventional controllers. Additionally, the controlled variables of the battery current and transient settling time—as shown in Figure 8—as well as the DC-link voltage were ahead of the WCA compared to other methods. In Figure 9, the fitness function resulting from the optimization for the performance criterion for ISE is given. The transition dynamic results from Figures 6a, 7a and 8a are shown in Table 8. As a result of the dynamic analyses performed in Simulink in Figure 8a, in Table 8, while the overshoot value was 45.12 in the DC-link voltage control provided with PI constants determined by the conventional method under variable speeds, the overshoot value is 6.02 when the PI parameters obtained as a result of the WCA optimization algorithm were used. When the settling time and peak values were examined, it was reduced to 108.5 settling time with the WCA-based method, while it was 112.5 settling time in the conventional method; it was reduced to a 134.01 peak value with the WCA-based method, while it was 195.2 with the conventional method. The WCA method had the best settling time in terms of following the reference value for speed control in Figure 8b. In Figure 8c, it is seen that fluctuations were high with the conventional method and GA technique in terms of current control; these fluctuations were reduced with a good optimization tool such as the WCA. The BFA-based method appeared to have a better settling time, but was insufficient compared to the WCA-based method. As a result, the optimization technique was used to tune four parameters of two simultaneous PI controllers by minimizing the cost function. A comparative analysis showed that the WCA technique gave better results in minimizing the overshoot and settling time. Wind, solar, voltage, and power control are essential in hybrid systems, and these controls are achieved using PI control. As such, the determination of PI parameters gains importance in order to provide the desired control and the optimization of these parameters; this is still being studied, and researchers are continuing to find the best optimization tool.

Sensitivity analysis is a valuable technique used to assess the behavior and performance of a control and optimization power supply system. Sensitivity analysis helps us understand the impact of changes in various parameters on a system's outputs, such as its efficiency, stability, and cost. It can be observed how these parameters influence the system's performance by systematically varying these parameters within predefined ranges. Different power supply loss probability values of 0–7% were obtained. A sensitivity analysis of the reliability of these three different configurations in a water pump system is given in Figure 10. As shown in this figure, increasing system reliability (reducing the amount of loss of power supply probability) leads to an increase in Total Cost. The results of this study were more economical when a solar–battery hybrid system energy was used

in the water pumping system compared to other configurations. Therefore, the priority in building water pumping systems under actual conditions is to establish a solar power plant.

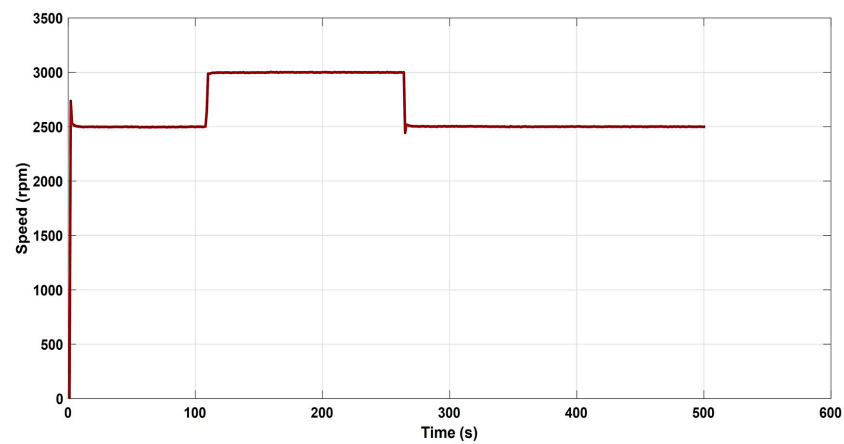


Figure 7. BLDC motor speed.

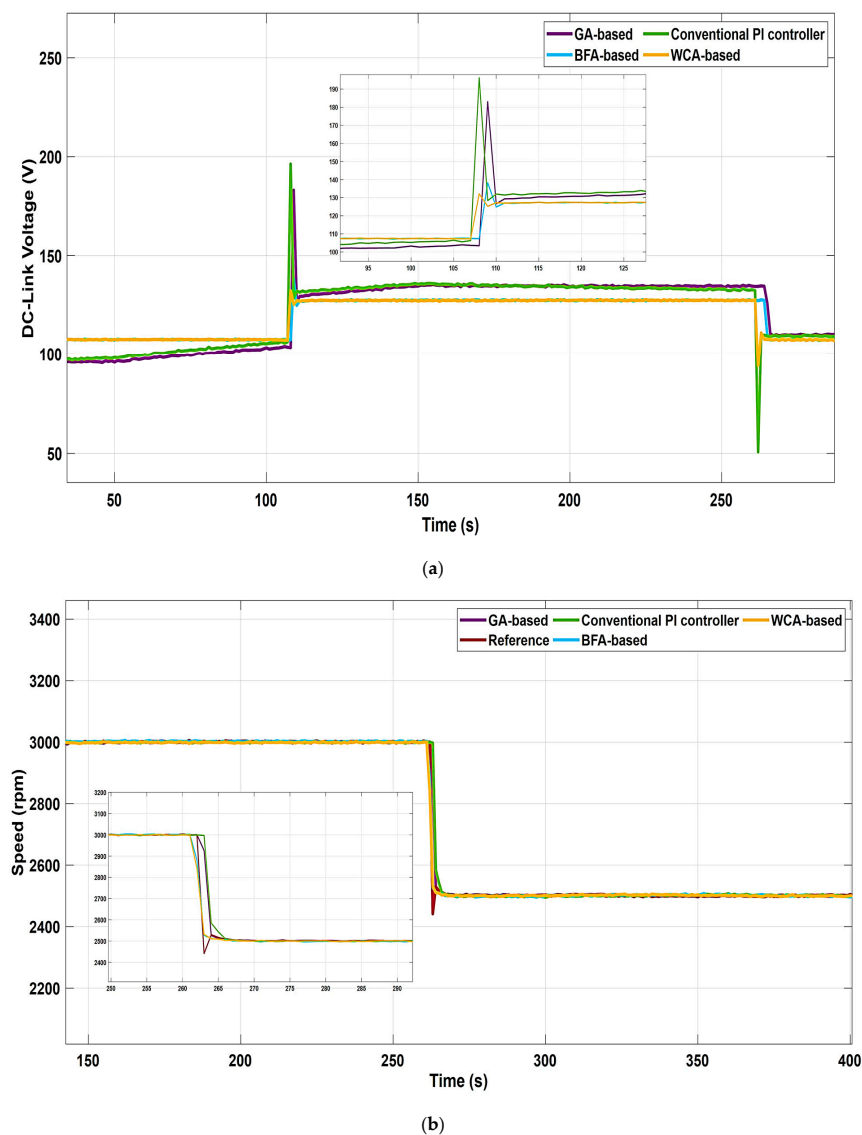
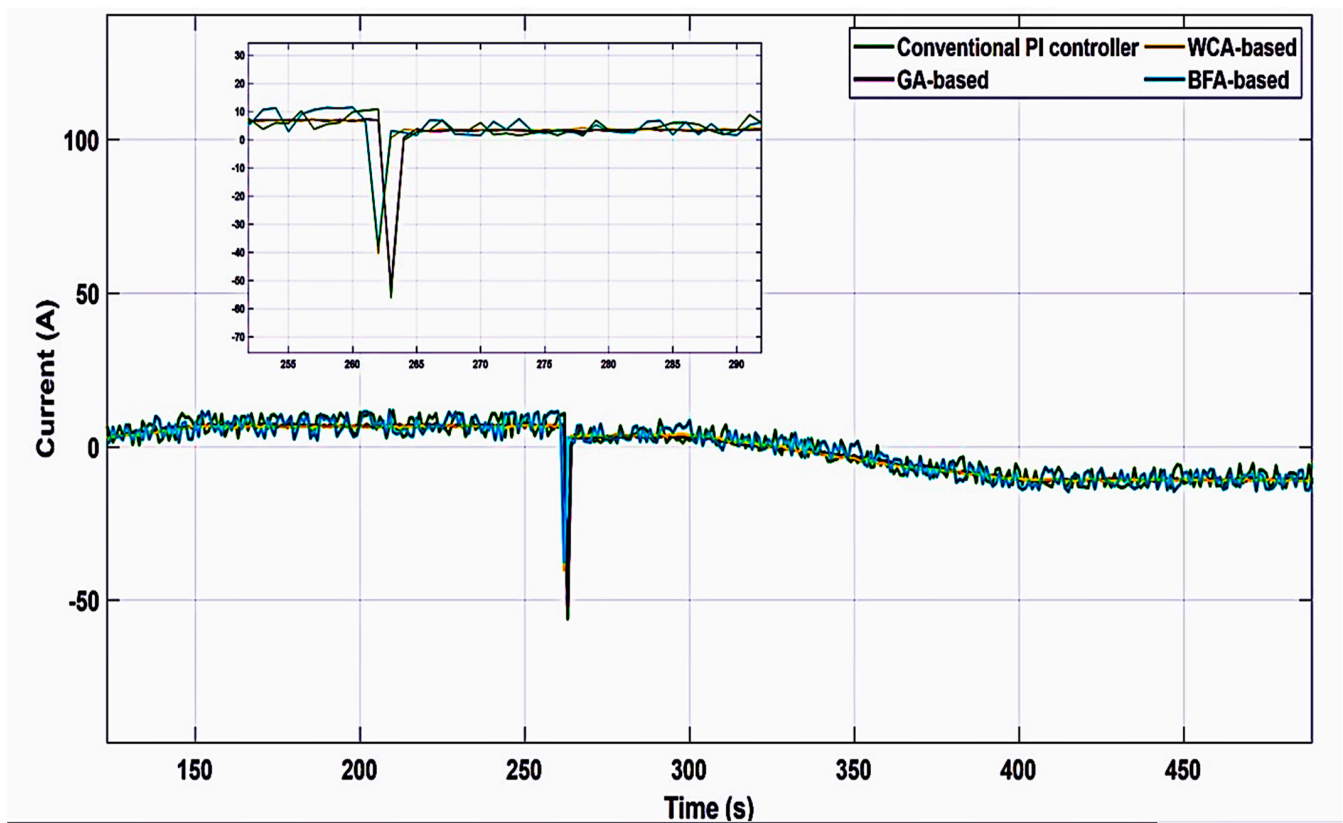


Figure 8. Cont.



(c)

Figure 8. (a) DC-link voltage, (b) speed, and (c) battery current (Tracking responses under variable rotor speeds with the optimization techniques).

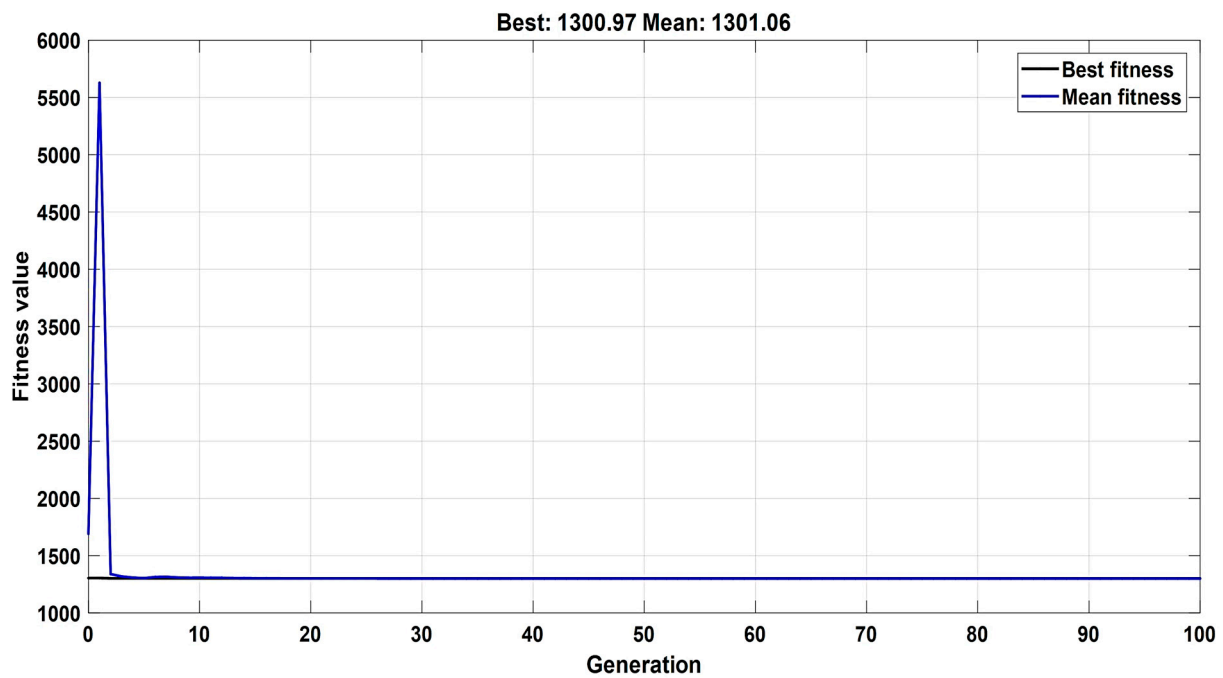


Figure 9. Fitness function resulting from the optimization of ISE.

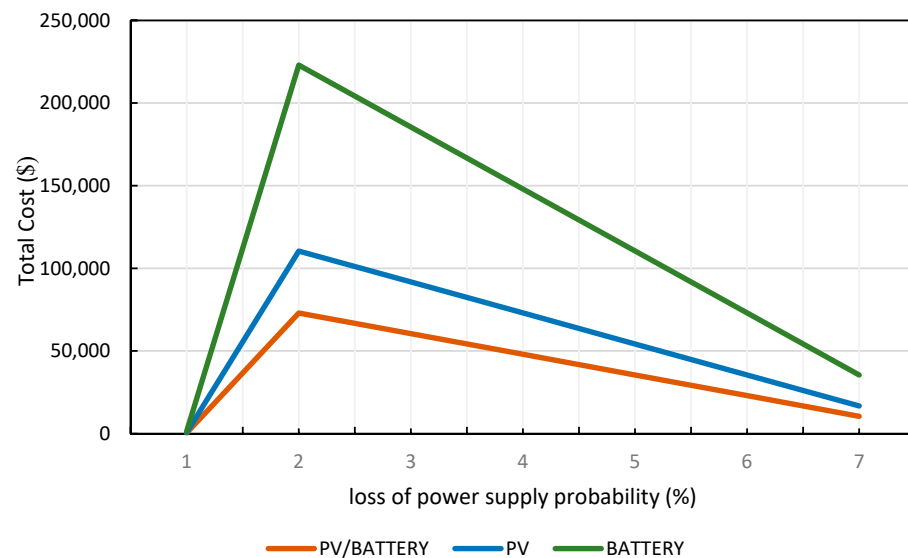


Figure 10. The sensitivity analysis of the reliability of the studied configurations.

4. Conclusions

An optimized control system was developed for an SPV battery hybrid water pumping system powered by a BLDC motor. The integration of the optimization algorithms allowed for the efficient operation of the pumping system, making full use of the SPV array and ensuring reliable performance. An energy flow control was implemented through a bidirectional boost converter to enable power transfer between the battery storage and the DC bus. Utilizing a cost-effective and compact sensor-based BLDC motor driver enhanced the overall affordability and size of the pumping system. Both current control and voltage control were achieved by applying optimization techniques. The proposed optimization approach significantly improved the efficiency of the water pumping system—making it particularly suitable for off-grid, remote, and isolated areas. With this study, a real-time measurement using OPAL-RT and a comparison of experimental and simulation results can be achieved in the future.

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