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Queen honey bee migration (QHBM) optimization for droop control on DC microgrid under load variation

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Abstract

Transmission line impedance in DC microgrids can cause voltage dips and uneven current distribution, negatively impacting droop control and voltage stability. To address this, this study proposes an optimization approach using heuristic techniques to determine the optimal droop parameters. The optimizcv ation considers reference voltage constraints and virtual impedance at various load conditions, particularly resistive. The optimization problem is addressed using two techniques: queen honey bee migration (QHBM) and particle swarm optimization (PSO). Simulation results show that QHBM reaches an error of 0.8737 at the fourth iteration. The QHBM and PSO algorithms successfully optimized the performance of the DC microgrid under diverse loads, with QHBM converging in 5 iterations with an error of about 0.8737, and PSO in 40 iterations drawn error is 0.9 while keeping the current deviation less than 1.5 A and voltage error less than 0.5 V. The deviation of current control and virtual impedance values are verified through comprehensive simulations in MATLAB/Simulink.

Keywords: DC microgrid; droop control; PSO; QHBM.

I. Introduction

Researchers are currently exploring the integration of renewable energy sources into distributed systems, which offer advantages in terms of stability [1][2], reliability [3], efficiency [4], and power quality [5][6] compared to traditional generators. In distributed systems, various components operate at different voltage levels, necessitating the use of droop control to regulate devices in specific areas, including sparsely powered DC microgrids [7][8]. The main objective of droop control is to ensure accurate power distribution to connected loads, enabling efficient operation and optimal utilization of available resources [9]. Previous studies have focused on achieving proper power sharing in converter systems. Control methods such as feeder flow [10][11] are employed to interconnect parallel systems. Droop control is widely accepted and

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effective in achieving optimal load balancing in microgrid systems [1]. Traditional droop controllers used in DC microgrids rely on two primary parameters: output impedance r_i and reference voltage V_{ref}. The impedance r_i is selected individually for each DC source based on its rated current, allowing for current distribution to the load according to its maximum generating capacity [12]. A proportional current division is essential to prevent the overloading of other sources and ensure voltage stability [13]. Although droop control methods are widely used for current sharing, they have limitations when operating under heavy load conditions [14][15]. The presence of transmission line impedance leads to voltage drops in the line [1], significantly impacting the performance of the droop controller, particularly in achieving balanced current sharing within the DC microgrid. The application of droop control faces challenges when used with renewable energy sources like solar power plants, primarily due to their fluctuating power output [16][17]. As a result, direct utilization of droop control based on solar panel outputs is not feasible, and it is typically limited to stationary sources such as batteries for providing power to the DC microgrid [18]. The main purpose of employing droop control in renewable energy sources is to ensure dynamic stability rather than focusing solely on load sharing and steady-state operation [3].

Numerous methods have been proposed in the scientific literature to address the challenges associated with traditional droop control methods for example to reduce torque ripple [19][20][21], for switching reluctance motor [22][23][24], and on controllers [25][26]. Traditional methods often suffer from suboptimal load distribution and voltage sag issues, significantly impacting system performance [4][5]. This journal article introduces a new method for DC microgrids using fixed droop parameters based on conventional droop control. However, the main difference lies in the approach to parameter selection. To enhance overall control system performance, it is crucial to gather comprehensive information that influences microgrid behavior and incorporate it into the parameter selection process. The parameters used for droop control include reference voltage V_{ref} and virtual impedance r_i. The primary aim of this study is to utilize heuristic techniques to determine the optimal values of these parameters [27], optimize load performance [28][29], and achieve efficient operation in microgrids [30][31].

The main objective of this study is to find the optimal value of the droop parameter that minimizes both the current sharing error and voltage drop resulting from load variations. To achieve this goal, an optimization formula [13] is used to compute the optimal parameter values using heuristic algorithms. The study aims to minimize both the total error in current distribution and the voltage drop, resulting in improved system performance, especially under varying load conditions. QHBM algorithm [32] is introduced as a valuable tool for finding ideal values for setting the droop parameters in DC microgrids.

The authors of this study contributed to formulating the droop control parameter optimization problem by considering reference voltage and virtual impedance constraints. They were also instrumental in designing a comprehensive simulation case study in MATLAB/Simulink to verify the proposed method. The authors made a significant contribution by introducing the use of the QHBM algorithm to determine the optimal droop parameters in microgrid DC systems. The authors show that QHBM is superior to other heuristic techniques, such as PSO, in terms of convergence speed and accuracy of the resulting solution. Overall, the author successfully implemented and proved the effectiveness of the latest heuristic optimization technique, QHBM, for the problem of determining control parameters in the DC microgrid electrical system. This research is expected to be useful for the development of better control methods in DC microgrids

Here are some comparative references that are similar to this research: Authors [33] used PSO for droop control parameter optimization with the aim of accurate load sharing and voltage regulation and considered the effect of transmission line impedance. In [6], adaptive droop control to the boost converter by considering load and voltage variations to optimize converter operation. A study conducted by [34] used adaptive droop control to balance the state of charge of batteries in a DC microgrid by taking into account load variations. Authors [35], proposed a modified droop control for low-voltage DC microgrid by considering load variation and transient response optimization. In [36], reviewed the droop control method for DC microgrids and discussed the challenges and improvements of the method.

Although several previous studies have optimized droop control parameters, this research has several differences and novelty compared to these studies. One of the main differences is the use of the QHBM algorithm, which has never been used before for droop control parameter optimization in DC microgrids. This research shows the superiority of QHBM over PSO in terms of convergence speed and accuracy of the optimization solution. In addition, the optimization problem formulation in my study specifically considers the constraints of reference voltage and virtual

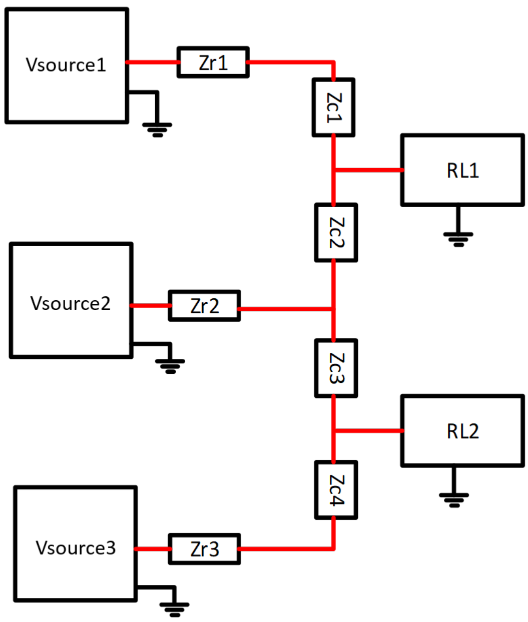

Figure 1. DC microgrid system.

impedance, which have not been explicitly described in previous studies. Thus, although the topic of droop control parameter optimization has been studied before, my research makes new contributions both in terms of the algorithms used and the optimization problem formulation for the case of DC microgrid. This research improves and complements previous research on the same topic.

II. Materials and Methods

A simulation of the DC microgrid framework was conducted to assess the viability of utilizing QHBM calculation to find the optimal value. Figure 1 illustrates the arrangement of two-device DC microgrid system loads and three DC sources. The system starts with a static DC source of 100 V, which is then stepped down to 48 V using a buck converter before being supplied to the loads. Each buck converter has a different maximum current: 3A, 3A, and 6A. All converters have a PI control system, as shown in Figure 2. For this study, Line impedance's impact on converter output current and voltage is disregarded. QHBM and PSO algorithms are used to evaluate performance and are also simulated. The current and voltage errors are calculated, ensuring that the global voltage does not exceed 2.4 V.

The DC microgrid's intended voltage is 48 V, and the voltage deviation from the reference value V_{ref} using a 2.4 V or 5 % output voltage setting. The transmission line impedance was chosen to imitate a commonplace DC microgrid framework. The virtual resistance rdi for each source is determined using equation (2). The reference value is chosen as the global reference voltage V_{ref}. The droop parameters specified in Table 1 are then applied, and the simulation is done with a DC microgrid system. Table 2 is a comprehensive overview of the optimization parameters in a particular context. It is divided into three categories that are essential to the optimization procedure. The first section, parameters for equation (5), lists the values and ranges directly related to the selected formula, such as 48, 0.6, 45.5, and 0.1 to 1.0 in voltage or V units. PSO algorithm parameters, the second portion, lists fixed numbers such as 50 and 40, along with ranges relevant to the PSO algorithm, such as 0.4 to 0.9 and 0.2 to 0.6. The parameters for the QHBM method are outlined in the third section, QHBM method parameters. These include a fixed value of 1 and particular values for position queen, which are

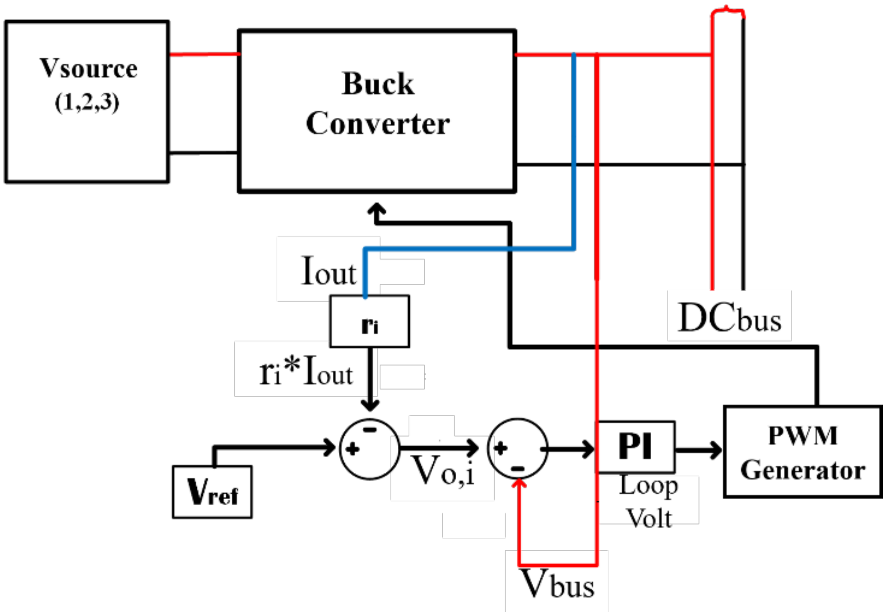

Figure 2. System droop control.

Table 1.
Table DC microgrid parameters.

Parameter	Symbol	Value
Converter	V_{in}	100 V
	$I_{o\ max}$	[3A, 3A, 6A]
	C	1500 μF
	L	0.75 mH
	f	20000 Hz
	Duty	0.45~0.55
Control parameter	K_p	0.05
	K_i	2.0
	V_{ref_con}	[48, 48, 48]
	r_{d_con}	[0.8, 0.8, 0.4]
	V_{ref_PSO}	[48.278, 48.487, 52.8006]
	r_{d_PSO}	[0.5756, 0.4372, 0.7505]
	V_{ref_QHBM}	[48.7299, 48.3019, 51.5418]
	r_{d_QHBM}	[0.7666, 0.3305, 0.3691]
Transmission line and load	Z_{s1}	0.01+(75 μH) Ω
	Z_{s2}	0.01+(75 μH) Ω
	Z_{s3}	0.01+(75 μH) Ω
	Z_{c1}	0.536 + (50 μH) Ω
	Z_{c2}	0.637 + (50 μH) Ω
	Z_{c3}	0.531 + (30 μH) Ω
	Z_{c4}	0.643 + (60 μH) Ω
	R_{load1}	9-13 Ω
	R_{load2}	12-20 Ω

Table 2.
Table parameters optimization.

Parameter	Symbol	Unit
Parameter to formula (5)	V_{ref}	48 V
	ω_c	0.6
	ω_v	0.4
	$R_{d\_min,}R_{d\_max}$	0.1, 1.0
	$V_{ref\_min,}V_{ref\_max}$	45.5, 55.5
PSO algorithm	$\omega_{min,}\omega_{max}$	0.4, 0.9
	$\alpha_{min,}\alpha_{max}$	0.2, 0.6
	K_{max}	50
	N_p	40
QHBM algorithm	r_s	1
	g_m	1
	Position queen	$X_{min} + rand * (X_{max} - X_{\min})$
	Iter_{max}	50
	N_p	2000

set at 50 and 2000. While Table 2 provides detailed factors, additional context is essential for a comprehensive understanding of the optimization process. This includes elucidating the interactions among various factors, delineating optimization goals, and discussing the impact of parameters on results to establish a foundation for further enhancement. In the microgrid, maintaining a consistent power delivery and adhering to maximum current ratios are ensured through droop control, with a critical requirement to limit internal voltage drop to within a tolerance of 2.4 V. Table 2 compares the optimization of droop parameters (V_{ref} and r_i) using QHBM and PSO methods. The study, conducted over 50 iterations, revealed that PSO converged after 40 iterations, whereas QHBM achieved convergence after only five iterations. The minimum error value for performance analysis in the microgrid is translated into a droop parameter to incorporate it.

A. Droop control for DC microgrid

The DC microgrid system consists of multiple converter-based sources that are connected in parallel, resulting in voltage differences that induce current circulation between the DC sources [37][38][39]. To facilitate the parallel operation of DC sources with limited current at each start, droop control is necessary. The droop controller sets the output voltage reference, which can be provided as equation (1)

$$V^*{}_{o,i} = V_{ref} - r_{d,i} \cdot I_{0,i} \tag{1}$$

The DC microgrid system defines the following variables: V_{ref} (voltage global reference), $V^*{}_{o,i}$ (output loca voltage), $I_{o,i}$ (current output), and $r_{d,i}$ (resistance virtual) with regard to source i in the microgrid network. To maintain in order to ensure that a DC microgrid system achieves the appropriate global voltage value, output voltage $V^*{}_{o,i}$ does not exceed 5 % of the reference voltage. Additionally, Based on the maximum current, each converter's virtual resistance is created. Dictated by a particular droop control approach equation (2)

$$r_{d,i} = \Delta V_{max} / I_{o,i}^{max} \tag{2}$$

In the context of DC microgrids, that is $r_{d,i}$ (resistance virtual), ΔV_{max} (tolerable voltage change) and $I_{o,i}^{max}$ (Maximum output current of DC microgrid power supply) are relevant. The ΔV_{max} value represents the acceptable range for the global voltage reference. Typically, this range is set to 5 % of the reference voltage [40]. Despite the fact that the virtual resistance is selected using the voltage reference range divided, since the droop controller does not use more current than the source's maximum converter can handle, it cannot guarantee proportional current distribution due to the effects of transmission line impedance [13].

B. Optimum parameter droop for DC microgrid

The purpose of the proposed formula is to optimize static parameters, namely V_{ref} and $r_{i,i}$, for each source $i = 1, 2, .., Ns$ in the microgrid. The optimization aims to minimize the average current division error and voltage drop under various loading conditions within a DC microgrid. While there are countless potential loading conditions, this paper focuses on investigating loading conditions involving different resistive load values.

1) Formula optimization droop control

The optimization problem involves finding the optimal values of $r_{d,i}$ and $V_{ref,i}$ to minimize two distinct error terms: voltage change error (V) and current shunt error (c). The k-th load condition allows for the calculation of these error terms as equation (3) and equation (4)

$$\varepsilon_{c,k} = \sqrt{\sum_{i=2}^{N_s} (i_{o,1,k} - i_{o,i,k})^2} \tag{3}$$

$$\varepsilon_{v,k} = (V_{ref} - \sum_{n=1}^{N} \frac{V_{n,k}}{N})^2 \tag{4}$$

In the given equation, $\varepsilon_{c,k}$ error trem $i_{o,i,k}$ represents output current of the i-th source under the conditions of the k-th load V_{ref} and $V_{n,k}$ is the voltage of the n-th supply under the k-th load condition, or is the target system voltage. The number of nodes and references in the microgrid system is represented by the letters N and N_s.

To reduce the error term $\varepsilon_{c,k}$ an appropriate value of r_d must be selected for each source. However, selecting the value of r_i can lead to voltage degradation DC microgrid start-up and load. To ensure that the voltage degradation remains within safe limits (±5 %), the error term $\varepsilon_{v,k}$. Appropriate V_{ref} should be chosen and minimized for all sources in the microgrid system.

Therefore, a microgrid system failure is characterized as $Ek = w_c \varepsilon_{c,k} + w_v \varepsilon_{v,k}$, where w_c and w_v represents the weight assigned to the error term $\varepsilon_{c,k}$ and $\varepsilon_{v,k}$ or thus you get an optimization problem determining the optimal values of $r_i, I,$ and V_{ref} for each source, denoted by $k - i = 1, 2, \ldots, Ns$ .This equation (5) was formulated to minimize total error.

$$E_k = \sum_{k=1}^{N_L} w_c \varepsilon_{c,k} + w_v \varepsilon_{v,k} + \varepsilon_{d,k} \tag{5}$$

Formula E_k depend on equation (6)

$$\varepsilon_{d,k}(\delta v_{0,i,k}, I_{0,i,k}) = \begin{cases} 0, & \delta v_{0,i,k} \leq \delta V_{max} \\ 0, & I_{0,i,k} \leq Io_{i}^{max} \\ \emptyset, & otherwise \end{cases} \tag{6}$$

In the given equation, $\delta v_{0,i,k}$ represents the tolerance for the change in voltage i-th source I under condition K-th of load. It is determined as $\delta v_{0,i,k} = V_{ref-} v_{0,i,k}$. Equation (6) specifies a function that ensures the current and voltage error values remain within the specified range. This function introduces an additional term d, k, which significantly increases the ET value only if the evaluated deflection parameter is set to $\{V_{ref}, r_{d,i}\} = 1, 2, \ldots, Ns$.

The optimization process aims to find values of static parameters that meet operational requirements. It should exhibit high accuracy across all loading scenarios in the DC microgrid. While voltage regulation is important, current-sharing accuracy takes

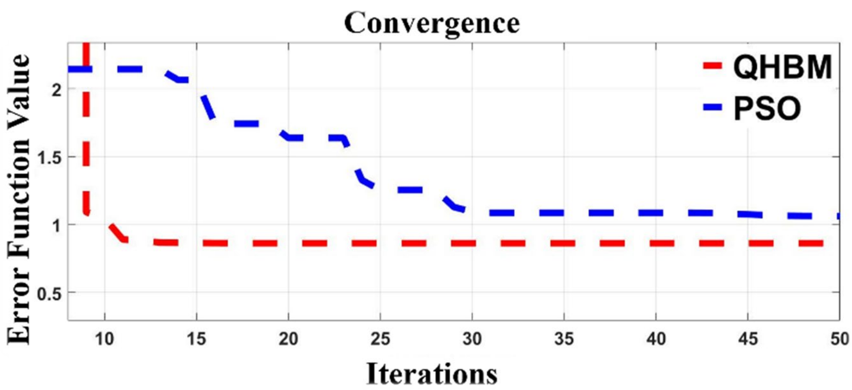

Figure 3. Optimization error function value.

precedence. Hence, the weight constant in equation (5) should be chosen $w_c > w_v$.

Heuristic optimization tools are used because the optimization problem defined in equation (5) is complex and difficult to analytically solve can be employed to reach a satisfactory solution. In this study, QHBM and PSO techniques, which are widely used heuristic optimization methods, are expected to quickly and accurately determine the optimal values for all loading scenarios.

2) Particle swarm optimization

The method of Kennedy and Eberhart introduced PSO for the first time in that year [35]. Since its inception, the PSO algorithm has gained significant popularity and witnessed extensive advancements in its applications and methodologies [41]. The PSO method, renowned for its dependability and simplicity, uses swarm intelligence a concept inspired by animal collective behavior to solve optimization issues. All particles in the population independently follow the best routes found by others, helped by iteratively changed velocity and location vectors as equation (7) and equation (8)

$$V_p^{k+1} = \omega^k V_p^k + \alpha_1 r_1 \left[x_{pbest,q} - x_p^{k+1}\right] + \alpha_2 r_2 \left[x_{gbest,q} - x_p^{k+1}\right] \quad (7)$$

$$V_p^{k+1} = x_p^k + V_p^{k+1} \quad (8)$$

The PSO algorithm is given a particle position and velocity of the search space's k-th iteration at that time are represented by the vectors $V_{pk} = [V_{p1}, V_{p2}, ..., V_{pk}]$ and $X_{pk} = [X_{p1}, X_{p2}, ..., X_{pk}]$, respectively. Furthermore, the vector $X_{pbest,q} = [X_{pbestq1}, X_{pbestq2}, ..., X_{pbest,q}]$ denotes the best local particle position, while the vector $X_{gbest,q}$t = $[X_{gbest1}, X_{pbest2}, ..., X_{gbestq,}]$ represents The globally optimal position that each particle in the population should aim for. This global best position is best global fitness function $f(X_{qbest,q})$ discovered by the particle.

The parameters r_1 and r_2 are random variables with values ranging from zero to one. The terms c_1 and c_2 are acceleration constants used to determine the influence of the best local and global positions on the particle's motion. The variables w and k denote the inertia weight and the number of iterations, respectively. Selecting the right value for w is crucial in achieving a balance between local and global search. Typically, w is linearly decreased from the maximum inertia weight ω_{max} to the minimum inertia weight ω_{min} as equation (9)

$$\omega = \omega_{max} - (\omega_{max} - \omega_{min}) \frac{k}{k_{max}} \quad (9)$$

Inertial weight is expressed as: ω and k_{max} representing the maximum number of iterations in the computational process, play crucial roles in PSO Algorithm Performance. Additionally, parameters α_1 and α_2 also have a significant impact on the algorithm's performance.

3) Queen honey bee migration

Bee colony algorithm inspired by bee behaviour, honey bee colonies' finding food sources offers a solution for many optimization problems. In this algorithm, the queen bee guides the colony's search fot a new hive, utilizing the instincts of scout bees. The migration process involves overcoming various obstacles, such as weather conditions, fatigue, and predators. It continues until the queen bee discovers a location with a probability of success [32][42]. QHBM algorithm consists of three stages: initial positioning, selection, and travel.

III. Results and Discussions

A. Simulation and optimization result analysis

The calculation uses the current value of the converter and each power source's voltage of the DC microgrid $\varepsilon(c,k)$ and $\varepsilon(v,k)$ for the optimization problem. Simulations are conducted separately for QHBM, PSO, and conventional droop under various loading conditions. Figure 3. represents the convergence of QHBM and PSO, showing the decrease of the error function value with iterations. With Error

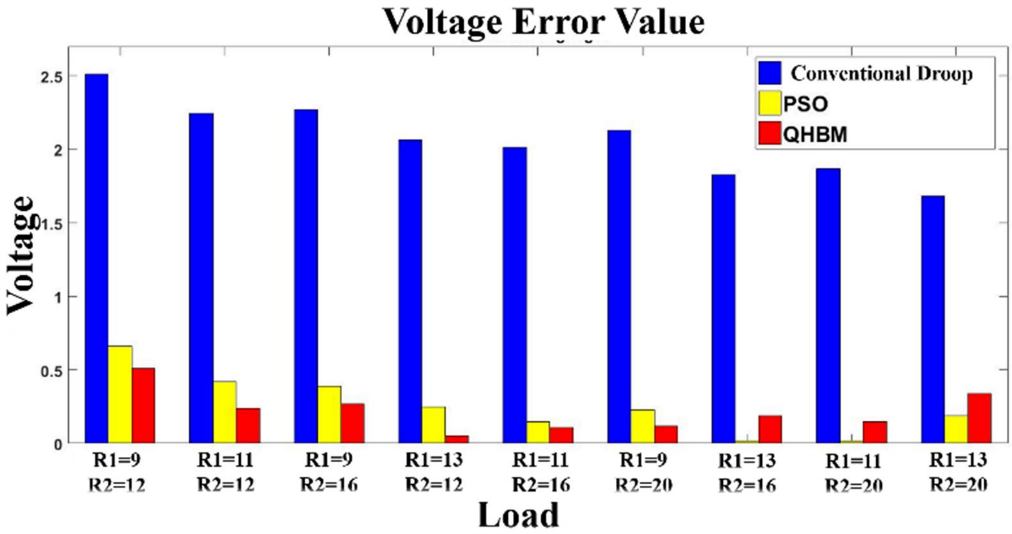

Figure 4. Comparison voltage value of droop conventional, PSO, and QHBM.

Function Value 0 to more than 2 and Iterations 10 to 50. The QHBM curve (red) stabilizes around the value of 1 after about 15 iterations, while the PSO curve (blue) stabilizes around the value of 1.5 after about 15 iterations. Figure 4 and Figure 5 show voltage errors and current sharing in a microgrid system. Figure 5 QHBM optimized droop parameters reduce average current error below 0.5A, significantly improving on errors above 2.4 A with conventional droop, demonstrating optimization superiority.

In this case study, the droop control system uses three sources and two loads in MATLAB/Simulink, as depicted in Figure 1. Whenever the droop parameters (V_{ref} and r_i) are determined, they are inputted into the system for each DC source. The DC microgrid system is subjected to three different load conditions: low, medium, and high. The parameter values obtained from QHBM, PSO, and conventional droop methods remain unchanged during each test. Details of the buck converter and PI control parameters can be found in Table 1.

B. Analysis of system simulation results with QHBM droop control

Figure 6 illustrates the virtual resistance applied to each converter with a current ratio of 1:1:2. With QHBM droop control. The converters are able to supply different currents, which are affected by V_{ref}, r_i and the impedance of the transmission line. Droop stabilizes at 4s with voltage and current reaching stable values, where currents closely match reference, demonstrating droop stabilization. Furthermore, the converter output voltage remains below V_{max} is 2.4 V.

For the low load test in Figure 6, the microgrid voltage remains close to 48 V, while the current error is 1.3 A. In the medium load test in Figure 7, the current

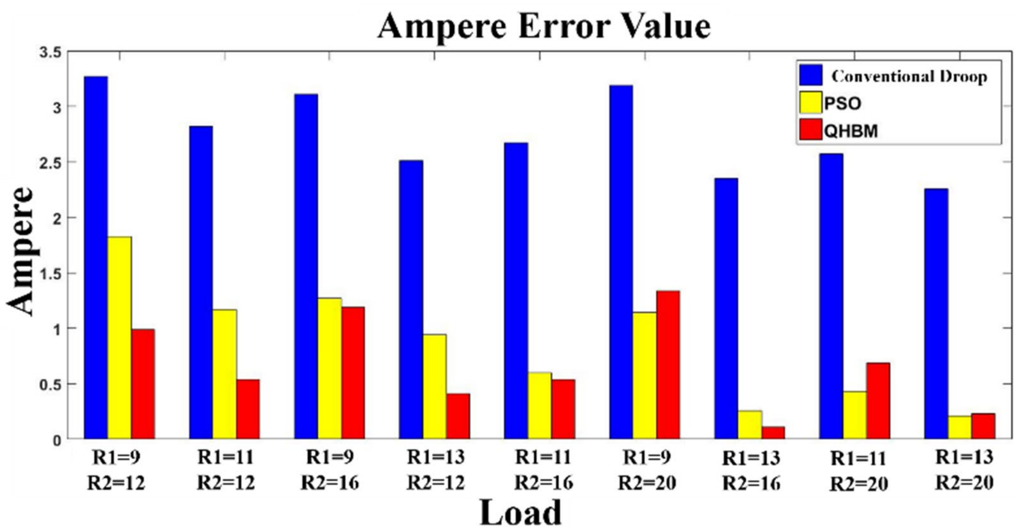

Figure 5. Comparison current value of droop conventional, PSO, and QHBM.

error reduces to 0.4 A. Finally, for the high load test in Figure 8, the resulting current error is 0.9 A. These findings show how well the droop control technique controls the microgrid voltage and achieves proper current sharing among the sources under different load conditions.

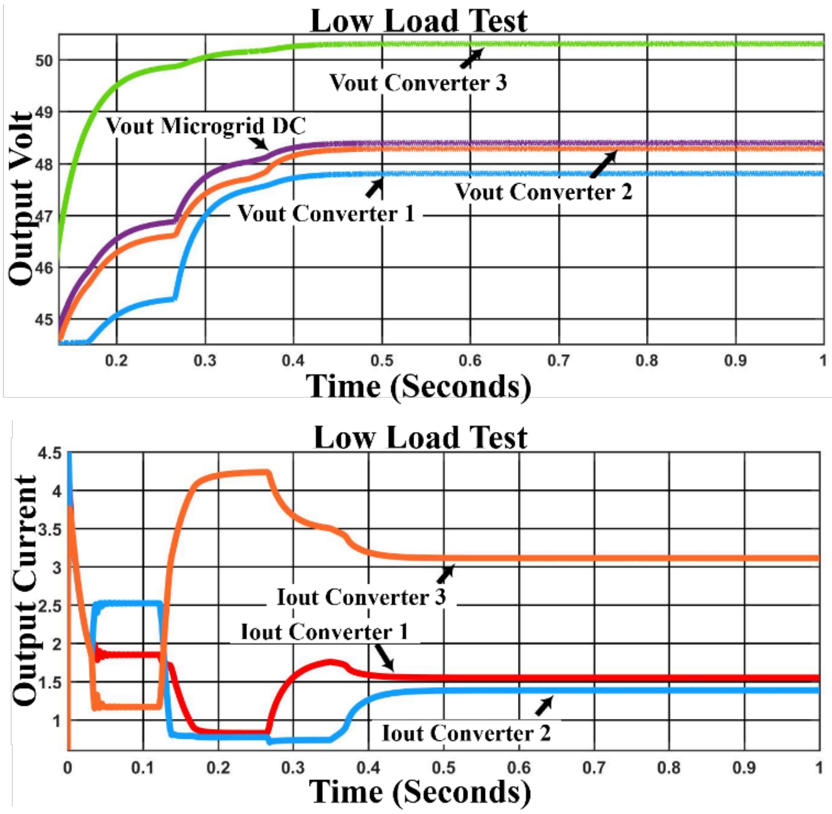

Figure 6. The results pertaining to the voltage and current output characteristics when utilizing the droop control optimization are active at 0.4 seconds for low (R_{load1}=13, R_{load2} =20).

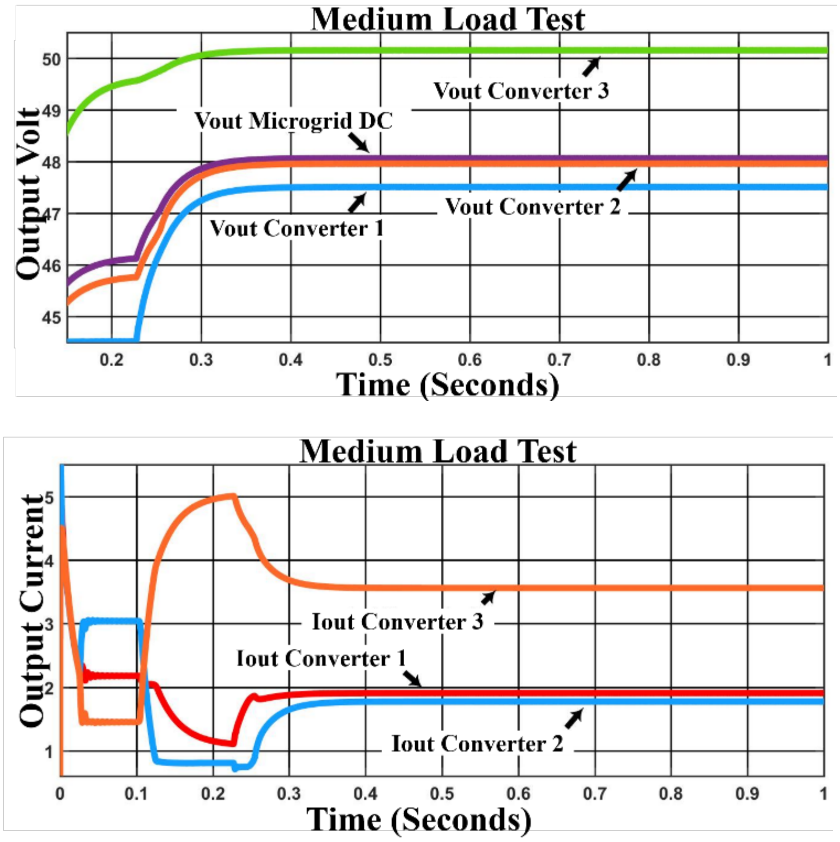

Figure 7. The results pertaining to the voltage and current output characteristics when utilizing the droop control optimization are active at 0.4 seconds for medium (R_{load1} = 11, R_{load2} = 16).

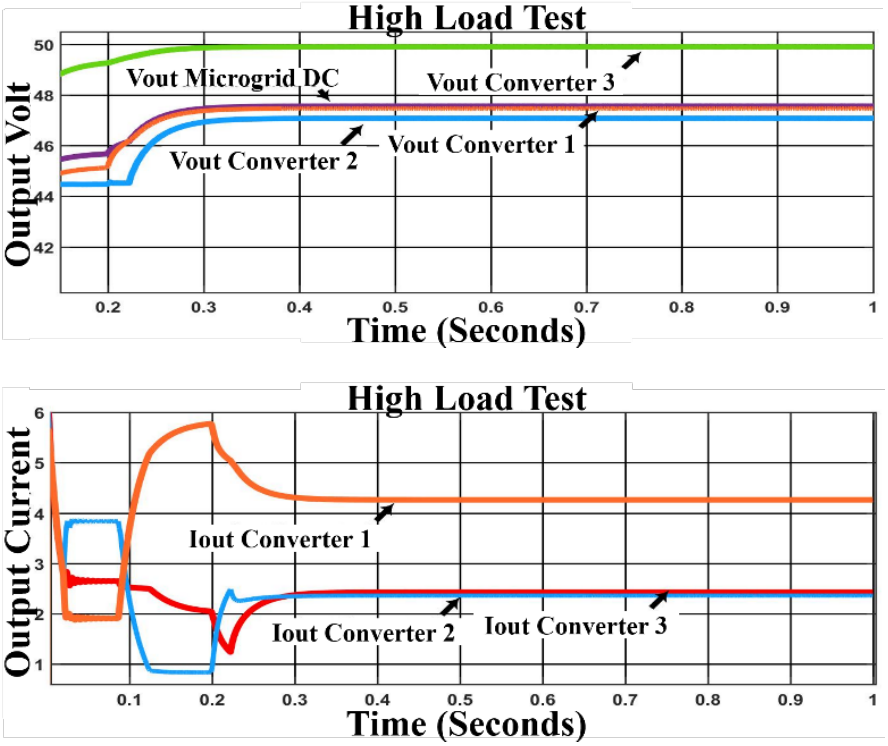

Figure 8. The results pertaining to the voltage and current output characteristics when utilizing the droop control optimization are active at 0.4 seconds for high (R_{load1} = 9, R_{load2} = 12).

IV. Conclusion

In this study, droop control optimization using the QHBM algorithm proved successful in achieving low error values in determining the optimal value of droop parameters. The droop control method incorporates current error and voltage error values to achieve an optimized DC microgrid system. The droop control parameters, V_{ref} and r_i, represent the reference voltage for each DC source and the virtual resistance value, respectively. This droop control approach improves the accuracy and stability limitations of the traditional adaptive droop method which has communication limitations in its control mechanism. By selecting the QHBM and PSO algorithms, the impact of various load conditions on the DC microgrid system is taken into account. Simulation results show that QHBM converges at the 5th iteration with an error value of 0.8737, while PSO converges at the 40th iteration with an error value of 0.9. In addition, the current deviation using QHBM remains below 1.5 A, and the voltage error for each load is below 0.5 V. Simulations were performed using MATLAB/Simulink, and the results highlight significant improvements compared to the conventional droop control method when combining droop optimization with the QHBM algorithm. This study demonstrates how the QHBM algorithm may be used to optimize the droop control parameters, hence increasing the accuracy and efficiency of microgrid DC systems. Future distributed energy system designs will be impacted by this discovery. Control parameters can be improved in real-time by utilizing sophisticated heuristic optimization techniques like QHBM to handle load variability and system uncertainty. This will enhance future smart power networks' dependability and quality of power. Furthermore, QHBM, which has been shown to be superior to PSO, can be used for control and optimization applications in other domains. Therefore, the findings of this study advance science, particularly in the area of distributed renewable power system optimization.

Declarations

Funding statement

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Competing interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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