Optimization of synchronized frequency and voltage control for a distributed generation system using the Black Widow Optimization algorithm

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Abstract

A distributed generation network could be a hybrid power system that includes wind–diesel power generation based on induction generators (IGs) and synchronous generators (SGs). The main advantage of these systems is the possibility of using renewable energy in their structures. The most important challenge is to design the voltage-control loop with the frequency-control loop to obtain optimal responses for voltage and frequency deviations. In this work, the voltage-control loop is designed by an automatic voltage regulator. A linear model of the hybrid system has also been developed with coordinated voltage and frequency control. Dynamic frequency response and voltage deviations are compared for different load disturbances and different reactive loads. The gains of the SG and the static volt-ampere reactive compensator (SVC) controllers in the IG terminal are calculated using the Black Widow Optimization (BWO) algorithm to insure low frequency and voltage deviations. The BWO optimization algorithm is one of the newest and most powerful optimization methods to have been introduced so far. The results showed that the BWO algorithm has a good speed in solving the proposed objective function. A 22% improvement in time adjustment was observed in the use of an optimal SVC. Also, an 18% improvement was observed in the transitory values.
Graphical Abstract

Keywords: microgrid; voltage and frequency control; Black Widow Optimization algorithm; dynamic response; smart grid
Introduction

The need to reduce CO₂ emissions in the field of electricity generation, recent technological advances in the field of microgrids and the restructuring of the electricity trade are among the factors involved in increasing interest in the use of microgrids. The microgrid can be defined as a low-voltage network, such as in a small urban area, a shopping mall or an industrial area, with loads attached to it. These systems may be able to provide both power and heat to local loads [1, 2]. Some microgrid feeders have sensitive loads. These feeders require local production and production units in the microgrid that are called 'source microgrids'. The source microgrid can include the following: wind turbines, fuel cells, inverter-based internal combustion engines and other renewable units such as photovoltaic systems or hydro units. All types of technologies are not necessary for the formation of a microgrid [3]. When the microgrid operates as part of the utility system, the microgrid sources feed the local loads under a pre-determined procedure. If the generated capacity exceeds the power-demand level in the microgrid, additional energy is delivered to the grid and, if the microgrid cannot feed all its local loads, the required energy flows from the main grid to the microgrid. When there is a problem with the utility (during major events, such as short circuits, voltage breakdowns in the mains and general blackouts or when the power quality of the mains falls below certain standards, such as voltage drops), the 'separation tool' of the microgrid is opened and separates the sensitive loads from the main power network, so that the microgrid can operate in islanded mode and provide uninterrupted power [4].

The microgrid must be able to maintain its stability and continue to operate after being disconnected from the network. In this case, the required criteria for sensitive loads in the microgrid must also be met, which requires the use of measuring tools to control the frequency and voltage in the microgrid. The most important challenge in operating a microgrid is the control of its main parameters. So, the main purpose of control is to maintain the voltage and frequency of the network within the allowable range and to provide the required load power. Other purposes such as power quality, reliability or appropriate power sharing may also be considered. For better control, scattered products are connected to the microgrid network through the inverter and therefore the main purpose is to control the inverters.

As mentioned earlier, the most important challenge in operating microgrids is the control issue. Various methods have been proposed for this challenge in recent decades. The plug-and-play nature of distributed generation (DG) units were used [5]. The operation of microgrids is always associated with challenges mainly caused by the time-varying microgrid structure. In this paper, a plug-and-play decentralized voltage control for DC microgrids was proposed. This control method ensured stable and satisfactory performance of the microgrids under the arbitrary interconnection of DG units.

Due to the widespread use of microgrids, interconnecting these systems to form a microgrid cluster enables a higher utilization of renewable sources [6]. So, a pinning-based multilayer and distributed cooperative control strategy for these systems has been presented [6]. A new robust control method was presented [7] for an islanded microgrid consisting of DG units. As in a conventional structure, each unit was connected to its local load through a voltage-source converter, a series resistive-inductive (RL) filter and a step-up transformer. What was presented was a convex optimization problem that led to a low-order dynamic controller of arbitrary structure in which the microgrid channels were all decoupled at the presence of load changes.

In recent years, due to the construction of these systems around the world, some papers have explored more practical applications. According to the active policy rules of the government of South Korea to develop eco-friendly microgrids with zero carbon emission, many of the diesel generators in stand-alone microgrids are replaced by clean energy sources. This poses challenges in the operation and control of these systems, as it causes the lack of inertia originally provided from the diesel generators. A novel frequency and voltage controller for this case was proposed, which was able to keep the frequency and voltage magnitude of the system constant [8]. For frequency control, a recovery control loop was added to the conventional droop method and inertia-control loops for the purposes of both effective power sharing and stabilization of the frequency response after the occurrence of disturbances.

Under normal conditions, the voltage and frequency are precisely controlled by active and reactive power. In an independent power system with wind and diesel power-generation units, frequency control seems to be very sensitive because the system has low inertia. Also, wind power-generation units cannot actively participate in compensating for the increase in load demand because active power generation depends on wind speed. Similarly, voltage control is very difficult because in addition to the reactive power demand by the system itself, the system also consumes reactive power. Therefore, the reactive power sharing of the synchronous generator alone cannot be sufficient to meet the need for increased reactive power. So, in such cases, the voltage may fluctuate sharply. A static volt-ampere reactive compensator (SVC) is used to prevent larger voltage fluctuations at the point of common connection. A small imbalance between active power generation and load causes frequency deviation and a small imbalance between reactive power generation and load causes voltage deviations. The excitation system in the synchronous generator operates much faster with a small time constant compared to the governor and the initial excitation control. Hence, the effect of excitation loop control for voltage control is not considered [9, 10].

In the reference paper [11], a structure consisting of renewable energies was considered and the active and reactive power transactions in the system were optimized. In this article, different reactive power-control
devices have been studied and compared. The paper [12] also presented a model-independent approach by the use of an SVC to improve dynamic behaviour. Reference [13] also suggested a method for optimally adjusting SVC parameters in an island microgrid. In this paper, a multi-objective optimization was used and the system control was multilevel. In reference [14], a different AC and DC structure was considered for the microgrid and the advantages of using a hybrid converter in series with an SVC were examined. Focusing on the problem of voltage rise, reference [15] has proposed a way to control the source side to avoid this.

References [16] and [17] have proposed a control method based on reactive power compensation. Reference [17] was based on SVC equipment. In this reference, the parameters of the SVC were optimized.

The methods presented in the articles evaluate or optimize a specific component of the system. In this paper, a newer Black Widow Optimization (BWO) algorithm is used with a similar approach to reference [17], but the frequency-control loop and the voltage loop are optimized simultaneously. The BWO algorithm is one of the novel search algorithms that is used due to its simplicity of implementation due to the lack of parameters that need to be quantified. Reference [18] has used this algorithm for optimal allocation of DG in a distribution system and reference [19] has used this algorithm for the estimation of synchronous generator parameters. This algorithm was not used for controlling SVC equipment and optimizing control loops. In our recent research, we demonstrated optimal load frequency control of island microgrids via a proportional–integral–derivative (PID) controller in the presence of a wind turbine and photovoltaics (PV) [5].

In this work, considering the issues raised, the beneficial effect of the excitation loop for effective frequency control has been identified. The study for the single machine infinite bus system was performed with four large SGs that delivered power to the infinite bus via a long transmission line. The effect of a frequency-control loop and a voltage-control loop on each other for a separate diesel–wind system was investigated. Both the frequency- and voltage-control loops are optimized simultaneously. A linear model of the hybrid system has also been developed. Dynamic frequency response and voltage deviations are compared for different load disturbances and different reactive loads. The gains of the SG and SVC controllers in the IG terminal are calculated using the BWO algorithm with the goal of low frequency and voltage deviations. The results showed that this algorithm has appeared successful in terms of speed and accuracy.

1 Materials and method
1.1 Problem formulation

The schematic of the system under consideration is shown in Fig. 1. As shown in Fig. 1, the load is fed by a stand-alone hybrid system. This system includes a diesel synchronous generator and a wind turbine with a speed squirrel cage induction generator. An SVC is used to control voltage fluctuations. This equipment is located at the point of common coupling.

![Fig. 1: Schematic diagram of a hybrid power system.](https://example.com/schematic.png)
The reason for choosing this equipment is the relationship between reactive power and voltage.

Fig. 2 shows the block diagram of the system shown in Fig. 1. Frequency- and voltage-control structures are combined in this schematic. The constants of the voltage-control loop are taken from [16] and [17]. In transient conditions, the reactive power of the synchronous generator is as follows:

\[
\Delta \lambda = \frac{1}{R_d} + \frac{1}{1 + sT_{d1}} + \frac{1}{1 + sT_{d2}} + \frac{K_p}{1 + sT_p} + \frac{K_R}{1 + sT_R} + \frac{K_a}{1 + sT_a} + \frac{K_v}{1 + sT_v} + \frac{s K_F}{1 + sT_{FF}} + \frac{1}{1 + sT_G} + \frac{1}{1 + sT_{d3}} + \frac{1}{1 + sT_{d4}} + \frac{K_{DP}}{1 + sT_d} + K_9 + K_8 + K_7 + K_6 + K_5 + K_4 + K_3 + K_2 + K_1 + K_0.
\]

From \(\Delta \lambda\):

\[
\Delta P_{M,SG} + \Delta P_e + \Delta P_{M,90} + \Delta P_{M,IG} + \Delta P_{M,IG} + \Delta P_{M,IG} + \Delta P_{M,IG} + \Delta P_{M,IG}.
\]
\[ Q_{SG} = \left( E'_q V \cos \delta - V^2 \right)/X'_d \]  

where \( Q_{SG} \) is the synchronous generator reactive power, \( E'_q \) is the internal armature electromagnetic field (EMF) for the round rotor synchronous machine, \( V \) is the terminal voltage, \( \delta \) is the power angle of the synchronous generator and \( X'_d \) is the reactance of the synchronous machine.

For small deviations, Equation (1) can be written as follows:

\[ \Delta Q_{SG} = \left( \frac{V \cos \delta}{X'_d} \right) \Delta E'_q + \left( \frac{E'_q \cos \delta - 2V}{X'_d} \right) \Delta V - \left( \frac{E'_q \sin \delta}{X'_d} \right) \Delta \delta \]  

where \( \Delta E'_q \) is the deviation in the EMF that is proportional to the change in the direct-axis field flux in transient conditions, \( \Delta V \) is the terminal voltage deviation and \( \Delta \delta \) is the synchronous generator power angle deviation.

Taking the Laplace transform from both sides, Equation (3) is obtained as:

\[ (5) \]

\[ (6) \]

\[ (7) \]

\[ (8) \]

\[ (9) \]

The coupling flux equation for the small disturbance is presented as follows:

\[ \frac{d}{dt}(\Delta E'_q) = \frac{\Delta E_{id} - \Delta E_q}{T'_{d0}} \]  

where \( T'_{d0} \) is the transient temporal constant of the direct axis of the open circuit.

\[ \Delta E'_q = \frac{1}{1 + s T_G} \left[ K_1 \Delta E_{id}(s) + K_2 \Delta V(s) - K_3 \Delta \delta(s) \right] \]  

where

\[ T_G = \frac{X'_d T'_{d0}}{X'_d} \]  

\[ (10) \]

\[ (11) \]

\[ (12) \]

In Equation (12), the \( X \) mode vector is displayed for SVC type 1 and modified for the other two types of SVC. It is shown in Fig. 3. Time domain responses shown in Fig. 2 are obtained using different types of perturbations. The objectives are to control the frequency deviation and voltage of the system after exposure to changes in active and reactive power demand. Optimizing transient responses for deviations of frequency and voltage are achieved by optimizing the proportional–integral (PI) controller coefficients in both the load frequency-control loop and the SVC gains. To minimize the undershoot (US), overshoot (OS) and settling time (ST) in transient responses of frequency and voltage, the objective function is defined as the Demerit (FDM) form in Equation (13). The optimal set of parameters varies according to the type of SVC. For SVC types 1, 2 and 3, they are equal to \( \left[ k_{D1}, k_{D2}, k_{D3}, k_{D4}, k_{D5}, k_{D6}, k_{D7}, k_{D8}, k_{D9}, k_{D10} \right] \), \( \left[ k_{P1}, k_{P2}, k_{P3}, k_{P4}, k_{P5}, k_{P6}, k_{P7}, k_{P8}, k_{P9}, k_{P10} \right] \), \( \left[ k_{F1}, k_{F2}, k_{F3}, k_{F4}, k_{F5}, k_{F6}, k_{F7}, k_{F8}, k_{F9}, k_{F10} \right] \). The minimization of the objective function is defined in different ways by Equation (13):

\[ \text{FDM} = \sum_{n=0}^{N} \left[ \Delta f(n)^2 + \Delta V(n)^2 \right] \Delta t \]  

where \( \Delta f \) and \( \Delta V \) are defined as the frequency and voltage deviations, \( N \) is the total number of samples for the voltage and frequency responses and \( \Delta t \) is the time interval between samples. In addition to the mentioned objective function above, the constraints on power generation are added as follows:

\[ \delta u_i^2 b_i^{v,\text{min}} \leq Q_i^v \leq \delta u_i^2 b_i^{v,\text{max}} \]  

Therefore, both of the target functions in Equation (14) will be optimized using the BWO algorithm.

1.3 Solution method

The objective function obtained in the previous section is optimized to obtain the appropriate values of voltage and frequency controllers. The purpose of this optimization is to minimize voltage and frequency fluctuations. The simultaneous voltage- and frequency-control block diagram shown in Fig. 2 is also obtained according to the mathematical relations of the previous section. After optimization, appropriate values of controllers are placed in these control loops and the results are analysed.
Nowadays, meta-heuristic algorithms play a vital role in the approximate solution of optimization problems. These methods are based on searching in the sample answer space in order to minimize the objective function. This is done by obtaining the main quantities of the objective function in order to minimize the dependent quantities. Choosing the right algorithm for different problems is important so that an algorithm for one type of problem can be suitable and at the same time unsuitable for other problems.

The Black Widow spider is usually a nightly insect. The female spider stays in the dark away from sight during the daytime and during the night spins the web. Actually, the female spider lives in the same place for most of her life. When the female spider tries to mate, it marks some certain spots of her net to send signals to the male spider. The first male spider that enters the web renders the female’s web less attractive to rivals by web reduction. The female spider consumes the male during or after mating and then transfers eggs to the egg sac. After the eggs hatch, the offspring engage in sibling cannibalism. But they stay on their mother’s web for a short period of time and they may even consume the mother spider. This cycle continues and leads to the survival of the fittest. The best one will be the global optimum of the objective function.

The flowchart of the algorithm used to solve the problem is shown in Fig. 4.

In the BWO algorithm used in this work, there are some parameters that must be quantified and are essential for better results. These parameters are procreating rate, cannibalism rate and mutation rate [20]. The parameters of this algorithm are shown in Table 1.

The Cuckoo algorithm is another method used in this paper. It was inspired by the obligate brood parasitism of some cuckoo species by laying their eggs in the nests of host birds of other species. If a host bird finds out that the eggs are not theirs, it will either throw these eggs away or abandon its nest and build a new one elsewhere. Each egg represents a solution. The goal is to use the better solutions to replace a worse one in the nest. This algorithm has been used in optimizing the SVC parameters in reference [17].

The parameters that must be set in this algorithm are the upper and lower limit of the allowed eggs, the maximum allowable spawning distance, the number of eggs
lost in each iteration, the grouping parameter K-means and the parameters of diversion.

The parameters of this algorithm are shown in Table 1.

Proper adjustment of parameters has a significant impact on the results in both algorithms. Attempts have been made to consider the best of these parameters. Also, the initial population is assumed to be the same for both algorithms.

1.4 Optimized parameters

In the previous section, the system under study was described. The goal is optimal control over frequency and voltage. The system parameters obtained by the BWO algorithm are shown in Table 2. The PI controller is used in the frequency-control loop and the SVC is used to control the voltage loop. The optimization diagram of the BWO algorithm is also shown in Fig. 5.

As can be seen from Fig. 5, the target functions in both algorithms have changed slightly after about the 20th iteration. Therefore, the number of repetitions of 100, after which the change of the cost function becomes <0.1%, is considered as a convergence condition.

As shown in Fig. 5, the optimization diagram leads to a smaller value using the BWO algorithm. Also, the optimization speed has been better in this method.

Table 2: System parameters

| Gains of PI controller on frequency loop | Gains of SVC in voltage-control loop |
|----------------------------------------|-----------------------------------|
| K_{uu} = 266.34 | K_{uu} = 590 |
| K_{ui} = 12.6 | K_{ii} = 0.04 |
| K_{ui} = 198.56 | T_{s} = 1.12 s |
| K_{ui} = 12.5 | T_{i} = 3.8 s |

Diesel and wind power-generation units produce power commensurate with the average consumption. In this research, an attempt has been made to discover the effect of voltage control by controlling SVC units located in the terminal of wind power-generation units on frequency control. Case studies have been proposed by simulations to determine the usefulness of integrated voltage control for frequency control. To investigate this effect, two control scenarios are considered without and with optimal tuning of the SVC.

2 Results

The simulation results are displayed below. Scenarios are applied to the system according to Table 3.

2.1 Simulation results in the optimal tuning mode of the frequency-control loop without optimal tuning of the SVC

In this case, synchronous frequency and voltage control is not applied. The PI controller used in the frequency-control loop is optimized by the BWO algorithm. As can be seen from the results of Figs 6–8, the system experiences relatively severe voltage and frequency changes. After the short-circuit error, the frequency experiences changes of >0.05. Also, the ST in this case is ~0.3 seconds. The moment the system starts also experiences a long ST.

2.2 Simulation results in the optimal tuning mode of the frequency-control loop and with optimal tuning of the SVC

Upon application of step-load perturbation of the active power load, the terminal voltage also deviates. The deviation in the terminal voltage has been compensated for by
the additional reactive power generation of both the synchronous generator and the SVC. The SVC type 3 leads to less voltage deviation and, as can be seen in Fig. 9, removes the steady-state error deviations with the integral controller actions. The next two types also show better performance than the lack of this equipment but, compared to SVC type 3, they have poorer performance in transient and permanent modes, are left with a small steady-state error in the

| Scenario                                      | Seconds (s) |
|-----------------------------------------------|-------------|
| Starting system                               | 0           |
| 5% increase in active load                   | 0.5         |
| 15% increase in active load and 5% reactive load | 1           |
| 10% load reduction                           | 1.5         |
| Single-phase short-circuit error             | 2           |

Fig. 6: System frequency in the optimal setting mode of the frequency-control loop without optimal SVC adjustment.

Fig. 7: System voltage in the optimal setting mode of the frequency-control loop without optimal SVC adjustment.

Fig. 8: System voltage in the optimal setting mode of the frequency-control loop without optimal SVC adjustment.
voltage deviation and are comparatively slower to suppress the voltage deviation. The same results have been obtained with the use of an SVC in [17]. However, a different solution method has been adopted in the mentioned reference.

The following results have been performed in the case of using a type 3 SVC. For this case, as can be seen from Figs 10–12, the amount of perturbation due to load and error changes has been greatly improved compared to the previous case. For example, in the last scenario in which an error is applied to the system, the ST of the frequency is ~0.1 seconds and the maximum overload is 0.04. System start-up has also been greatly improved. This performance improvement in system voltage is also evident.

As can be seen from the results, in the case of simultaneous frequency control and SVC, the system performs better. This also applies to the relationship between parameters in complex systems such as microgrids. As a result, this synchronized control between voltage and frequency results in better operation from the perspective of overvoltage and subsidence, as well as a better ST in the system, and the system converges more quickly to the nominal value of its parameters.

By comparing Figs 6 and 10 in order to compare the frequency results and Figs 7 and 11 in order to compare the voltage results, an improvement in the results can be seen by using the optimal SVC. At 2nd time when a single-phase short-circuit fault occurs, without optimal SVC, the overshoot rate is up to 50.06 and the undershoot rate is 49.95. The ST is also 0.24 seconds. These values have decreased relatively well in the case of using an SVC optimized using the BWO algorithm. In this case, the amount of overshoot is 50.04 and the amount of undershoot is 49.96. Also, the ST is 0.16 seconds. Overall, a 22% improvement was seen on average in the STs with the use of an optimal SVC. Also, an 18% improvement was observed in the transitory values.
2.3 Comparison of simulation results using the BWO algorithm and Cuckoo search

In this study, the BWO algorithm was used and proposed for the problems. The BWO algorithm is one of the two-stage heuristic algorithms. There are two stages of search and discovery in the operation of these algorithms. Features of this algorithm include easy set-up and implementation. Also, in terms of the results and performance speed, as it turned out, it showed good performance. There are other classes of optimization algorithms in which the search method is
continuous. Among these algorithms, we can mention the Cuckoo algorithm [21]. In conclusion, a comparison is made between these two algorithms with different functions.

The results of the two algorithms are compared with each other in terms of coordinated voltage and frequency control. The results are shown in Figs 13 and 14. As the figures show, the BWO algorithm has been able to achieve better results in voltage and frequency control.

As shown in Figs 13 and 14, in the scenarios applied to the system, the BWO algorithm was able to perform better than the Cuckoo algorithm. The effect of this improvement is better reflected in the ST. This performance is manifested in better control of the transient state created in perturbations. The BWO algorithm has improved the ST by ~12% in different scenarios. It has also improved the overshoot and undershoot of the system by ~12%, except at the moment of start-up. In this way, the ST and overshoots of the system are better controlled and the settling time is shorter. Also, as shown in Fig. 5, the optimization diagram has a good speed. What is certain is that the BWO algorithm was able to optimize the target function well if it reaches close to 95% of the optimal target function after the 20th iteration. Comparative results between these two methods according to the applied scenarios can be seen in Table 4.

Table 4: Comparative results between algorithms

|                           | Cuckoo search algorithm | BWO algorithm |
|---------------------------|-------------------------|---------------|
| Maximum overshoot in     | 50.07                   | 50.04         |
| frequency (Hz)            |                         |               |
| Minimum undershoot in     | 49.91                   | 49.96         |
| frequency (Hz)            |                         |               |
| Maximum overshoot in      | 412                     | 405           |
| voltage (V)               |                         |               |
| Minimum undershoot in     | 349                     | 364           |
| voltage (V)               |                         |               |
| Maximum settling time (s) | 0.3                     | 0.16          |
| Speed up to 90% of the    | 79                      | 43            |
| final answer (s)          |                         |               |

Fig. 13: System frequency in using the BWO algorithm and Cuckoo search.

Fig. 14: System voltage using the BWO algorithm and Cuckoo search.
3 Conclusion

The BWO optimization algorithm is one of the newest and most powerful optimization methods ever introduced. The DG system is a hybrid power one that includes wind–diesel power generation based on induction and SGs. In this research, the dynamic frequency response and voltage deviation for active load disturbances and different reactive loads were compared. The gain of the SG and SVC controllers in the IG terminal was optimized using the BWO algorithm to cause low frequency and voltage deviation. The results were compared with the Cuckoo algorithm. These results indicated the optimal performance of the BWO algorithm. Also, due to the possibility of using the methods in online terms, the simulation time was considered as an important factor that the BWO algorithm had an acceptable simulation time in this research.

The results showed that the BWO algorithm reached 95% of its final value after ~20 iterations and therefore has good speed in finding the optimal answer. Also, in different scenarios, a 12% improvement in the ST and overshoots and undershoots was observed compared to the older Cuckoo algorithm. Therefore, the dynamic behaviour of the system was improved by the proposed method.

Conflict of interest statement

The authors declare that there is no conflict of interest.

Data availability

All data used to support the findings of this study are included within the article.

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Appendix 1

Ratings and data of the typical system studied

| Generation | Capacity (kW) | Load (kW) |
|------------|---------------|-----------|
| Wind       | 150           | 150       |
| Diesel     | 150           | 100       |
| Total      | 300           | 250       |

| System parameters | |
|-------------------|-------------------|
| $K_i = 0.15$      | $T_i = 0.715$ s   |
| $T_{ot} = 5.0$ s  | $X_i = 1.0$ perunit (p.u.) |
| $T_f = 0.02/12$ s | $X_f = 0.15$ p.u. |
| $R_i = 0.06415$ p.u. | $K_i = 0.5$      |
| $T_{ot} = 0.05$ s | $K_{ot} = 40.0$ s |
| $X_f = 1.0/0$ p.u. | $X_i = 337.0$ p.u. |
| $E_{f} = 0.9603$ p.u. | $E_{f} = 1.1136$ p.u. |
| $Q_i = 0.75$ p.u. | $\alpha = 2.443985$ |
| $\delta = 21.05$ | $T_{f} = 0.02/4$ s |
| $\theta = 120.05$ | $Q_{f} = 0.75$ p.u. |

References

[1] Shafaghatian N, Kiani A, Taheri N, et al. Damping controller design based on FO-PID-EMA in VSC HVDc system to improve stability of hybrid power system. Journal of Central South University, 2020, 27:409–417.

[2] Alayi R, Mohkam M, Seyednouri SR, et al. Energy/economic analysis and optimization of on-grid photovoltaic system using CPPO algorithm. Sustainable, 2021, 13:12420.

[3] Alayi R, Zishan F, Mohkam M, et al. A sustainable energy distribution configuration for microgrids integrated to the national grid using back-to-back converters in a renewable power system. Electronics, 2021, 10:1826.

[4] Sadabadi MS. Line-independent plug-and-play voltage stabilization and L, gain performance of DC microgrids. IEEE Control Systems Letters, 2020, 5:1609–1614.

[5] Alayi R, Zishan F, Seyednouri SR, et al. Optimal load frequency control of island microgrids via a PID controller in the presence of wind turbine and PV. Sustainability, 2021, 13:10728.

[6] Alayi R, Harasli H, Pourderogar H. Modeling and optimization of photovoltaic cells with GA algorithm. Journal of Robotics and Control, 2021, 2:35–41.

[7] Joung KW, Kim T, Park JW. Decoupled frequency and voltage control for stand-alone microgrid with high renewable penetration. IEEE Transactions on Industry Applications, 2018, 55:122–133.

[8] Liu B, Wu T, Liu Z, et al. A small-AC-signal injection-based decentralized secondary frequency control for droop-controlled islanded microgrids. IEEE Transactions on Power Electronics, 2020, 35:11634–11651.

[9] Ghosh S, Chattopadhyay S. Three-loop-based universal control architecture for decentralized operation of multiple inverters in an autonomous grid-interactive microgrid. IEEE Transactions on Industry Applications, 2020, 56:1966–1979.

[10] Shafaghatian N, Heidary A, Radmanesh H, et al. Microgrids interconnection to upstream AC grid using a dual-function fault current limiter and power flow controller: principle and test results. IET Energy Systems Integration, 2019, 1:269–275.

[11] Qi J, Zhao W, Bian X. Comparative study of SVC and STATCOM for low voltage DC microgrids. IEEE Transactions on Industry Applications, 2020, 8:209878–209885.

[12] Ma Z, Wang Z, Guo Y, et al. Nonlinear multiple models adaptive secondary voltage control of microgrids. IEEE Transactions on Smart Grid, 2020, 12:227–238.

[13] Yang X, Du Y, Su J, et al. An optimal secondary voltage control strategy for an islanded multibus microgrid. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2016, 4:1236–1246.

[14] Wang L, Fu X, Wong MC. Operation and control of a hybrid coupled interlinking converter for hybrid AC/low voltage DC microgrids. IEEE Transactions on Industrial Electronics, 2020, 68:7104–7114.

[15] Carvalho PM, Correia PF, Ferreira LA. Distributed reactive power generation control for voltage rise mitigation in distribution networks. IEEE Transactions on Power Systems, 2008, 23:766–772.

[16] dos Santos Neto PJ, dos Santos Barros TA, Silveira JP, et al. Power management strategy based on virtual inertia for DC microgrids. IEEE Transactions on Power Electronics, 2020, 35:12472–12485.

[17] Mehta P, Bhatt P, Pandya V. Optimized coordinated control of frequency and voltage for distributed generating system using Cuckoo Search Algorithm. Ain Shams Engineering Journal, 2018, 9:1855–1864.

[18] Samal P, Mohanty S, Patel R, et al. Optimal allocation of distributed generation in distribution system by using black widow
optimization algorithm. In: 2021 2nd International Conference for Emerging Technology (INCET), Belagavi, India, 21–23 May 2021, 1–5.

[19] Micev M, Čalasan M, Petrović DS, et al. Field current waveform-based method for estimation of synchronous generator parameters using adaptive black widow optimization algorithm. IEEE Access, 2020, 8:207537–207550.

[20] Hayyolalam V, Kazem AA. Black widow optimization algorithm: a novel meta-heuristic approach for solving engineering optimization problems. Engineering Applications of Artificial Intelligence, 2020, 87:103249.

[21] Yang XS, Deb S. Cuckoo search via Lévy flights. In: 2009 World Congress on Nature & Biologically Inspired Computing (NaBIC), Coimbatore, India, 9–11 December 2009, 210–214.