A Review of Control Strategies and Metaheuristic Algorithms Used in DC Microgrids

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Abstract- A comprehensive and comparative review of control strategies for power-sharing operation in DC microgrids are presented in the paper. Since a microgrid consists of distributed generation sources and energy storage units, a control layer is required to manage the power-sharing operation between them. For this purpose, the control schemas used in DC microgrids are categorized as centralized, decentralized, distributed and hierarchical. Therefore, a review of these four control structures is presented in the paper firstly. Then, the hierarchical control method is handled in detail because it is widely preferred in DC microgrid control schemas. Among several methods and algorithms used in the hierarchical control layers, methods based on artificial intelligence and metaheuristic algorithms are being gained popularity in up-to-date studies. Hence, a methodological comparison of these methods is presented in order to put forward their advantages and disadvantages. In the last part of the paper, genetic algorithm, particle swarm optimization and the gray wolf algorithm which are the mostly used metaheuristic algorithms are comparatively tested for the optimization of a sample microgrid. Results show that the gray wolf algorithm offers the best performance in terms of the rising time, the overshoot percentage and the settling time.

Keywords- DC microgrid; Power Sharing; Hierarchical Control; Metaheuristic Algorithms

1. Introduction

Recently, the need for efficient, low-cost, eco-friendly and reliable renewable energy sources has increased. Furthermore, the design and implementation of distributed grid solutions by using renewable energy sources which are close to each other as well as to the loads has become important in order to reduce the transmission losses and to obtain more reliable grid infrastructures [1-3]. As a result of these developments, microgrid concept is developed to ensure both the controllability of distributed energy sources and the continuity of energy supply to the critical loads [4]. Microgrid structures also increase the voltage and the frequency stability of the main grid.

Although the microgrids can use both the DC and the AC power systems, the use of DC microgrid structures have some critical benefits [5-9]. For instance; energy sources those have DC output like PV systems and batteries can be directly connected to DC microgrids without using complex power electronics inverters. Similarly, the most energy storage units can be connected to the DC microgrids through DC-DC converters. Furthermore, while the variable frequency energy sources such as wind turbines requires AC-DC-AC inverters to connect to an AC microgrid, only AC-DC converter is used to connect them to a DC microgrid. Thus, the control complexity and the need for additional components are minimized and the cost is reduced in DC microgrids. On the other hand, AC grids are negatively affected by harmonics caused by inverter/converter circuits. Since the reactive power issues and harmonic problems are not faced in DC systems, they are more stable and serve better power quality as compared with AC ones [10].

Considering the advantages briefly described above, it is clear that there will be a significant simplification in the connection operation of DC microgrid structures to the loads fed with DC voltage and energy sources that generate DC voltage at their output. As a result of this simplification, efficiency and reliability of the system will increase while the need for power conversion is reduced. This situation has a positive effect on the operating cost of the grid and the probability of failure. Although the stability in DC systems is mainly based on voltage regulation, the power flow should be kept in control simultaneously too. Another issue to be considered is to keep the maximum power value within the determined limits. Therefore, the energy demand should be distributed appropriately among different sources in microgrids. For this purpose, the power sharing control process should achieve some critical duties such as ensuring power and current sharing operations between converters in order to avoid units from overloading, improving the voltage stability, preventing circulation currents between converters, providing the optimal power flow between the microgrid and the main grid to operate the system in the most economical way [5].

As a result of its considerable advantages as described above, there are so many studies dealing with microgrid control methods and power sharing strategies in recent literature. Although each control technology has its own characteristics, advantages and disadvantages, research on hierarchical control and stability has gained popularity in recent years, leading to a continuous search for new and smarter solutions [11-14].

In the study of Han, Ning,Yang and Xu [15], it is specified that the multi-agent system control and metaheuristic algorithms are better solutions for eliminating the disadvantages of low current sharing accuracy in traditional droop control. In addition, it is emphasized that accuracy can be increased by using energy management systems. In [16], a comprehensive review of the hierarchical control structures used in DC microgrids is presented and several control objectives have been determined for each control level. It is pointed out that when the performance of the control unit in the microgrid is improved, more efficient control can be achieved in local converters, however this requires the use of distributed optimization techniques. The solution to improve the DC microgrid control structure is the integration of optimization, digitalization and smartening.

In a DC microgrid, instantaneous DC bus voltage signals should be adopted for estimation of operating states. Only with the development of artificial intelligent technology, the optimization of DC microgrid operation will be able to achieve better control results. In their study, which provides an overview of hierarchical control strategies, Yao and Ertuğrul [17] review state-of-the-art control strategies for the hierarchical control framework of microgrids. In particular, examining the first and second levels of hierarchical control, it is concluded that using simple PI controllers for the control of converters and power sharing in the microgrid at the first level is the most common method. The need to adjust the PI control parameters in the most accurate way to improve the droop parameters ranked first in identifying gaps in the literature for possible research trends. According to the approach under consideration, the idea of hybrid control methods obtained by mixing different control methods should be included in primary control. On the other hand, it is said that the flexibility of secondary control can be further increased by combining the distributed and centralized structure. It has also been found that the control of multiple microgrids or clusters of microgrids is a new question that needs further study. Connecting multiple DC microgrids together to form a DC microgrid cluster has several advantages and disadvantages in solving power management related problems. Generally considered in the third layer of hierarchical control, power flow management between DC microgrid clusters is implemented with distributed control, which can increase the reliability, fault tolerance and flexibility of DC microgrid clusters. So far, existing distributed tertiary control methods are generally based on traditional linear proportional-integral (PI) algorithms, and thus the performance of such complex and non-linear control of DC microgrid clusters is limited. Therefore, a new proposition including a predictive function for third-level control and a dynamic consensus procedure for neighbour-to-neighbour information exchange is discussed in [18,19].

In another study [20], which deals with a hybrid power management strategy in a system containing 2 clusters for DC microgrid clusters, a fuzzy augmented hierarchical power management strategy based on fuzzy logic control is proposed. This proposed system not only increases the supply reliability and optimum use of resources, but also has been applied for DC bus voltage control and power flow analysis, and its effectiveness has been verified by simulations. In the article, attention was drawn to the use of artificial intelligence methods for such complex controls.

Another paper on the management of the microgrid cluster examines the conflict between the DC bus voltage instability problem of classical droop control and efficient current sharing [21]. A three-layer control strategy is adopted to solve this problem. The first layer provides voltage control with a closed-loop PI controller, while the middle layer includes calibration of the droop parameters. The top layer provides coordination between the sub-microgrids. Unlike other studies in the literature, in this study, more than one parallel boost converter has been used for each source and voltage compensation has been provided between them.

In [22], a DC microgrid cluster consisting of multiple DC sub grids connected to the common DC bus via bidirectional DC/DC converters is discussed. In this way, a decentralized power management strategy is proposed for the coordinated operation of a complex DC microgrid cluster and ensuring system reliability. In this strategy, a new coordinated decentralized power management approach is presented, which takes into account the bus voltage regulation, depending on the capacities of each sub-microgrid and the presence of critical loads, as well as balancing the power flow in the system. In another study, as a different approach, the principle of power flow to the load according to the demands is discussed. Here, optimum power sharing is tried to be achieved depending on the status of the PV unit and EDS according to the demanded power by using the power switching circuit. The converter at the output of each source is momentarily adjusted to share the current load demand [23]. However, in complex and multi-bus systems, this will cause communication delays, making real-time applications difficult.

According to Gao, Kang and Cao [24], these real-time energy management applications are very important to quickly detect potentially threatening elements in the system. It is clear that the future smart grid should include a fast converter communication system and a high-level energy management system in order to be able to effectively control, operate reliably and coordinate the operation of hundreds or thousands of sub-microgrids. For this reason, it has been emphasized that smarter, more technological and complicated systems will be needed.

In terms of the smarter, more technological and complicated systems, artificial intelligence may offer better results. In [25], which stated that artificial intelligence methods are preferable to solve the problems in microgrids, artificial intelligence-based control structures in grid interactive and/or interconnected multi-microgrid environments has been examined. The study reviews more than 200 microgrid control methods, 124 of which are based on hierarchical control and artificial intelligence has been used in 23 of them. In particular, it has been mentioned that metaheuristic algorithms and deep learning studies in hierarchical control structures create a gap in this field in the literature. An overview of existing traditional control methods, their disadvantages, the need for artificial intelligence techniques and their application at different levels is reviewed and future scopes are presented.

In various studies on power electronics applications in systems containing renewable energy sources and distributed energy resources, it is considered that artificial intelligence methods would take control of not only microgrids but also a great deal of smart grid management in the future [26-29].

As seen from literature examples given above, the use of DC microgrids is increasing day by day and in accordance with this development their control methods are gaining more and more importance. Therefore, an overview and comparison of the control techniques used in the realization of the power sharing stages in DC microgrids is performed in this paper. Furthermore, metaheuristic optimization algorithms, which have become increasingly popular in recent years, are handled comparatively. The main goal of the paper is to determine the roadmap to be followed in order to popularize the use of metaheuristic methods in power sharing problems in addition to classical optimization methods and to develop a better power sharing strategy by considering the advantages of currently used metaheuristic algorithms. Literature research made within the scope of this paper show that artificial intelligence methods are not commonly used especially in DC microgrid power sharing controls, and the use of metaheuristic algorithms is less than classical methods. Therefore, studies containing both classical and artificial intelligence methods are examined and compared. In order to make a better and realistic comparison between metaheuristic algorithms, a sample DC microgrid test system is designed in Simulink. Then, three metaheuristic algorithms such as particle swarm optimization (PSO), genetic algorithm (GO) and gray wolf algorithm (GWO) are tested comparatively on this system. For this purpose, optimization of the control of droop parameters in the second layer of the hierarchical control is focused in order to eliminate the disadvantages of classical fall control realized in the first layer [28]. Although better results have been obtained from the GWO as compared with others, all algorithms still have improvement requirements. The use of hybrid techniques developed by combining the advantageous aspects of further algorithms can give more efficient results.

2. Control Structures in DC Microgrids

The most important issue for controlling a microgrid is to achieve the power sharing between resources appropriately. The sources are connected to a common bus via converters. The converter topologies used for this purpose can be examined under six main categories such as single bus, multi-bus, multiterminal, ring bus, ladder-bus and zonal. Among them, single bus and ring bus topologies are shown in Figure 1 and Figure 2, respectively. It can be said that the single bus considered as the base for all other complicated topologies [30].

In a multi-bus DC microgrid, each microgrid interacts with its neighbours for power exchange. This is an effective way for isolating the microgrid easily if needed. All nodes are connected to each other by intelligent electronic devices. In this type of microgrids, a secure and fast communication network between distributed energy sources is required to execute the control operation effectively. The main advantage of this structure is that it can contain alternative busbars that will provide power flow in case of any failure and maintenance requirements [30].

As mentioned previously, controlling the converters is important for the stable operation of the microgrid. Although there are different control methods to provide power sharing in DC microgrids, they can be basically classified into three categories in terms of controller type, location, structure and communication connection as seen in Figure 3 [31]. No doubt that each control method has its own advantages and disadvantages. For this reason, they are preferred considering the system requirements. In order to choose the most suitable one, Table 1 presents typical advantages and disadvantages of these methods.

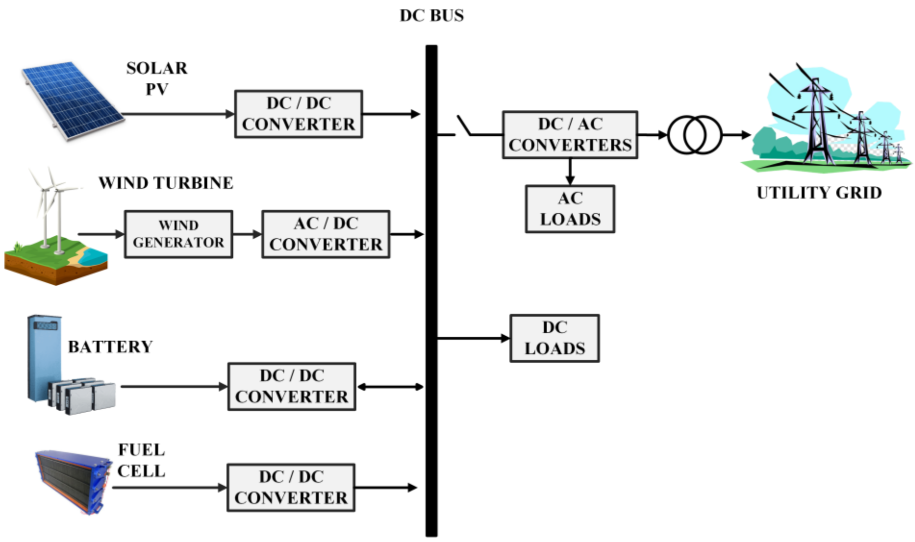

Fig. 1. Single bus DC microgrid [31]

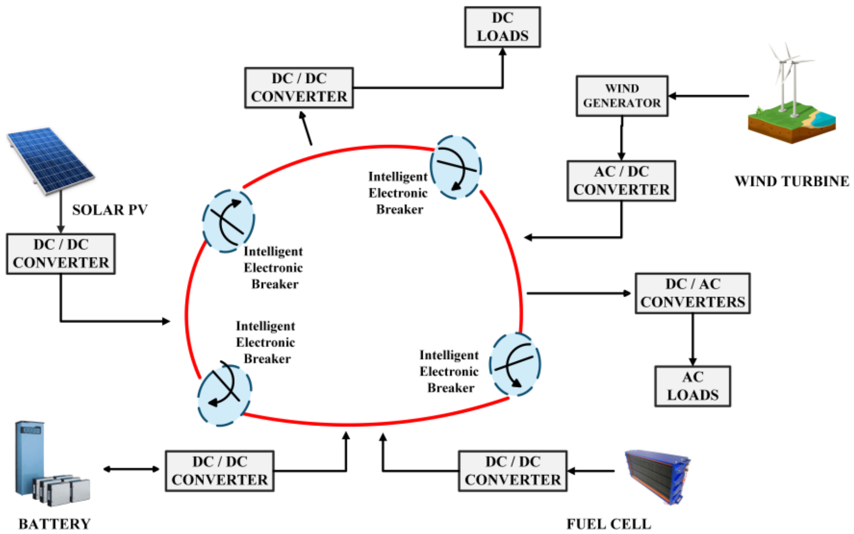

Fig. 2. Ring bus DC microgrid [30]

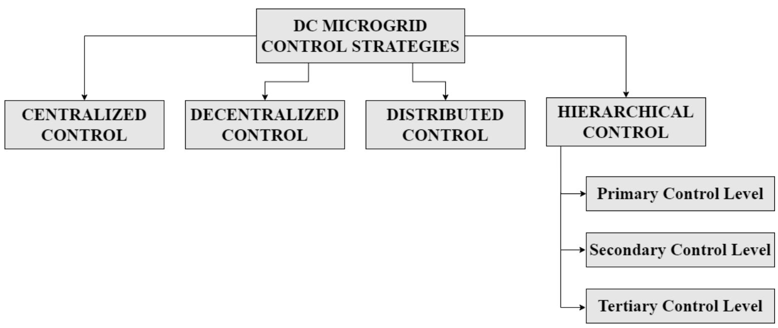

Fig. 3. DC microgrid control strategies [31]

Table 1. Comparison of control structures in DC microgrids

Control Method	Advantages & Disadvantages
Centralized Control	Can be easily synchronized to the main grid. The need for communication between distributed energy sources increases the cost and makes the system as vulnerable to cybersecurity threats. Difficult to coordinate. Operational costs are high. The most important advantages are zero current sharing and small signal stability.
Decentralized Control	As it is not tied to a single central unit, suitable for infrastructure changes if needed. It has a plug-and-play feature. Especially preferred in low-power microgrids. More secure against cyber-attacks as it does not require communication. Disadvantages are high deviations from the nominal voltage level on the main bus, low power sharing accuracy, low efficiency due to transient system response.
Distributed Control	Calculation and coordination costs are low. The main disadvantage is the increased system complexity. Communication network between neighbouring sources minimizes the power fluctuations. It is more secure against cyber-attacks.
Hierarchical Control	It has more reliable and more flexible structure. Includes additional methods for controlling bus voltage and power fluctuations. It is effective in solving the problems experienced in the integration of the micro grid and the main grid. Although it seems more complex and difficult to operate, it is preferred due to its efficiency as compared with other control strategies.

2.1. Centralized Control

Centralized control is a control method in which all generation and load units in DC microgrids exchange data via a communication link as seen in Fig. 4. Different type of energy sources can be utilized to meet the power demand of critical and non-critical loads. The necessity of communication between distributed energy sources (DERs) in central control brings with it cyber security threats and costs arising from failures. However, the cost of communication between sources also stands out as a negative situation [32]. In addition to these disadvantages arising from communication infrastructures, zero current sharing error and small signal stability are important advantages of centralized management. In microgrids with centralized power sharing methods built on the communication infrastructure, the controller parameters are redesigned when a DER is connected or disconnected. This is the main reason why centralized power sharing methods lack plug and play feature [33]. Among the communication-based central control power sharing methods, master-slave power sharing is the most preferred method [34-40]. In this method, one of the DERs (usually the one with the larger production capacity) takes over the main task, while the other DERs take over the dependent mission. The main DER operates in voltage control mode and is responsible for keeping the main busbar voltage in the microgrid within an acceptable range. When the load level in the network increases, the main DER tries to meets the required power in order to prevent the system from the voltage drops.

The power provided by the main DER, which plays an active role in transition stability, is shared between each dependent DER, creating an effective power sharing mechanism. In this case, the reference currents to be supplied from each dependent DERs should be determined by the central control algorithm. If the power capacity to be provided from the dependent DERs is sufficient, the main DER can be restored to its previous level. In this way, the main power in the microgrid is shared equally among the dependent DERs [41-42]. Although the master-slave power sharing method has many advantages in balancing and controlling the bus voltage, communication delays can reduce the system stability [34].

2.2. Decentralized Control

The second major category of power sharing techniques is the Decentralized control method, shown in Figure 5, that used especially in microgrids with low power sharing. Since this method does not need a communication infrastructure, the total system cost is reduced and system reliability is increased. One of the important advantages of the decentralized method is that DERs can be either connected or disconnected to the microgrid without interrupting the operation of system. The converters at the output of the sources are controlled via several local controllers. Signals measured in the local controller are used as input signals to generate a gate pulse for converters where sources are connected to the bus.

Although the drop control technique is the most common decentralized control method, it has some disadvantages such as low dynamic performance, low power sharing accuracy and deviations from the nominal voltage level at the main bus [31, 41]. Consequently, it can be said that the decentralized control method has some important advantages; however, the busbar voltage regulation problem causes some undesired issues like low bus quality and high busbar impedance, efficiency and stability due to the transient system response [43,44].

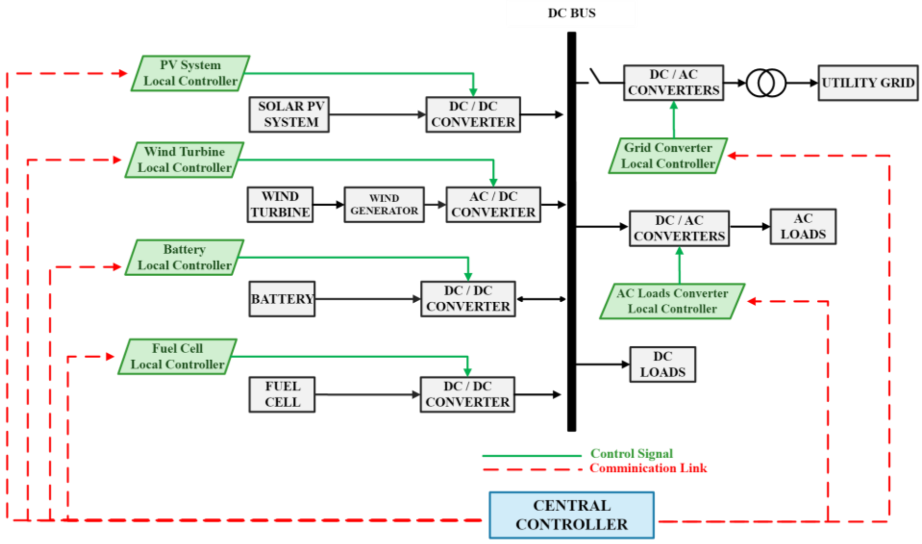

Fig. 4. Centralized control scheme [31]

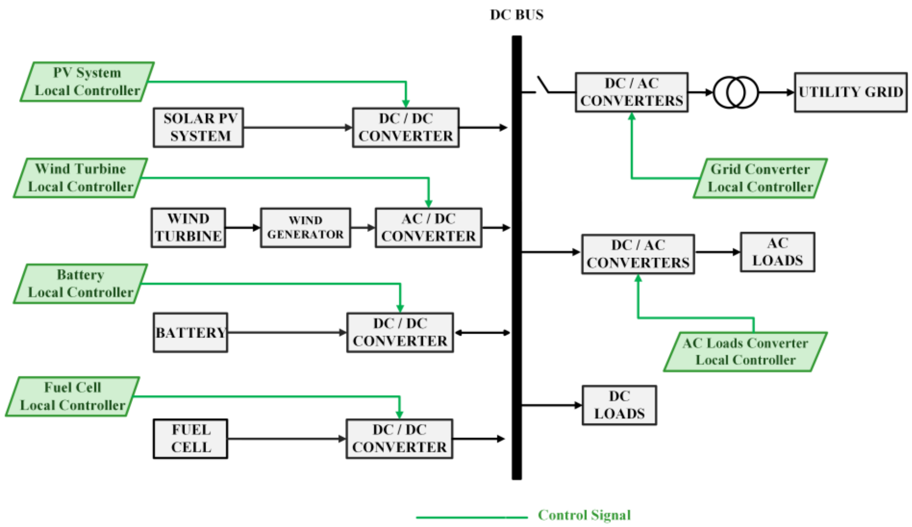

Fig. 5. Decentralized control scheme [31]

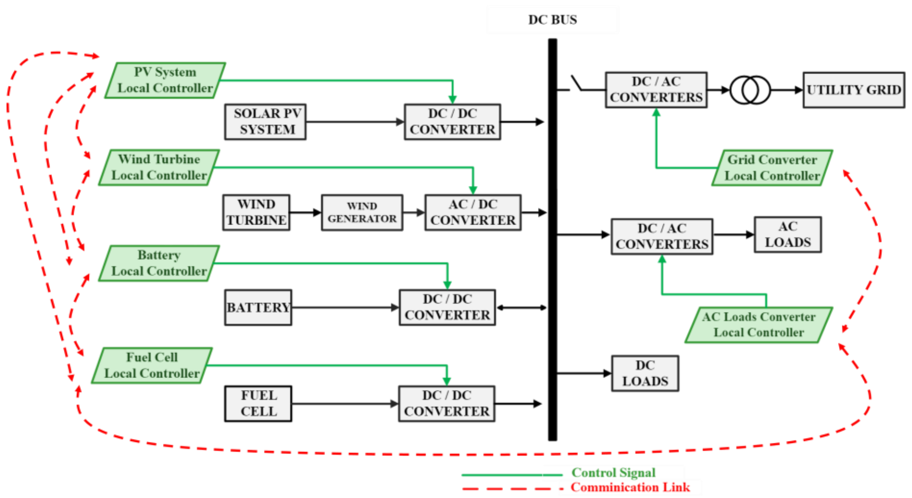

Fig. 6. Distributed control scheme [31]

2.3. Distributed Control

The basic control principle of DC microgrids is connecting the energy sources to the main bus via converters controlled by a local controller. In accordance with this situation, the current and voltage values of the sources are controlled by a local controller in distributed control, as represented in Figure 6. Actually, the distributed control strategy has been improved by combining the advantages of both the centralized and the decentralized control techniques. The local controller of each source needs to communicate with neighbouring sources [31]. In order to reduce the fluctuations during the power sharing process in islanded DC microgrids, the voltage shift technique and the distributed control of some other type of energy sources such as batteries, ultracapacitors and so on is presented in [45, 46]. In distributed control technique, there is not a general power sharing information for whole grid because only the nearest neighbours communicate with each other. Therefore, the concept of consensus algorithm is proposed in [47,48] to get information about the data exchange among several neighbours.

2.4. Hierarchical Control

The hierarchical control technique is especially proposed for overcoming the difficulties during the integration of DERs to the microgrid. In this technique, the control system is divided into multiple layers to make the microgrid management more flexible and efficient. Commonly used three source control architecture is the basic sample of this approach, where the first control layer controls the current and voltage regulation between the power converters used for connecting DERs to the microgrid. Any voltage deviation that might be occurred in this layer is tried to be eliminated in the second control layer. In the third and the last control layer, power flow management, energy optimization and economically utilizing DERs are handled [14]. A general view of hierarchical control structure designed by considering the need for a communication for the coordination and control of the DERs, DC and AC loads in the microgrid is shown in Figure 7, details of which are explained below.

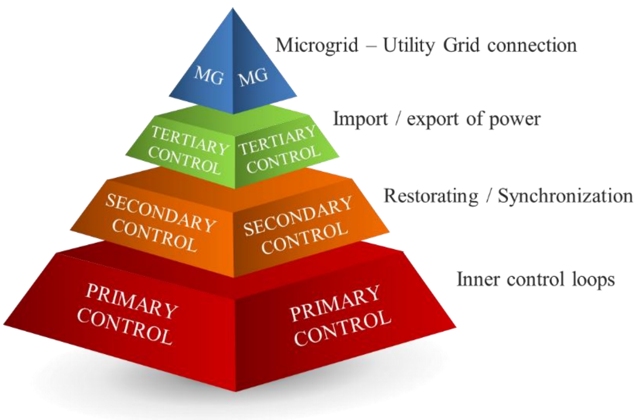

Fig. 7. A general view of hierarchical control structure [50].

2.4.1. Primary control level

The load sharing process between DERs is achieved at this level. The physical realization of this operation is provided by the power converters placed on the output of each DER [51]. The primary controller is also responsible for improving voltage stability and preventing circulating currents between converters. Decentralized power sharing methods are widely implemented in this layer. Master-slave control is a common approach used for active current sharing between multiple converters [49]. Droop control has also been used frequently at this level as presented in [53-57]. Besides droop control, DC is another distributed method used at the primary control level for bus configuration and power management operation between sources and loads [58,59]. Fuzzy logic control (FLC), one of the artificial intelligence methods, is also used at this level [60]. Actually, FLC is quite suitable for non-linear systems and can control different functions such as the balance problems on energy storage systems and voltage drop issue on distribution lines. For example, Nguyen and Lee proposes a FLC based method in which both the power sharing and the voltage regulation are provided by simplifying the second control level with a single fuzzy logic controller depending on the voltage shift principle [56]. In this context, while fuzzy logic is frequently used in MPPT studies, it is seen in the literature that artificial intelligence algorithms such as PSO are also used [63,65].

When more than one source is connected in parallel to a DC bus, to achieve a reliable control operation is being an indispensable requirement due to some critical issues such as the different output impedances of the converters and the line resistances between the converters and the DC bus [67]. To better understand the difference between the power supplied from each parallel source, a simplified DC microgrid with two converters connected in parallel is modelled as in Figure 8 [67,68]. In this model, while V_1 and V_2 represents the output voltages of converter 1 and converter 2, I_1 and I_2 represents their output currents, respectively. R_L is the load resistance, I_L is the load current, V_{DC} is the DC bus voltage, R_1 and R_2 are the line resistances between the load and the converters. To ensure optimum load sharing performance, conventional droop control creates drop resistors R_{d1} and R_{d2} in series with R_1 and R_2. The difference in current supplied by both sources can be calculated as in Equation (1) by using the Thevenin equivalent circuit shown in Figure 9 [69].

Equation (1), shows that the difference in current supplied by each source is inversely proportional to $(R_{d1}+R_{d2})$. Therefore, the higher the droop resistors R_{d1} ve R_{d2} means the better the load sharing. The main idea of droop control is to increase the output resistance to reduce the difference between the currents [67]. However, increasing the output resistance disturbs the bus voltage regulation because the thevenin resistance R_{TH} is increased. When two parallel sources are feeding a constant current load, when the load is increased by α, if the voltage drop experienced in the DC bus is defined as a function of α, this drop can be modeled as in Figure 10. In order to compensate this voltage droop, a secondary control level is needed.

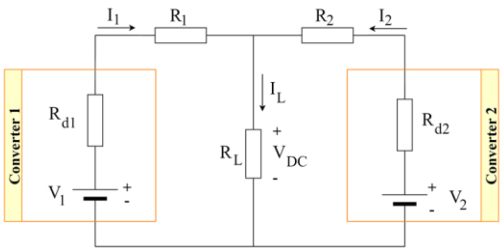

Fig. 8. DC microgrid with two converters [67,68]

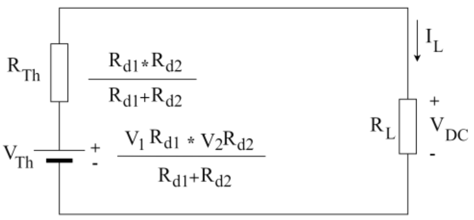

Fig. 9. Thevenin equivalent circuit of Fig. 8 [69].

$$I_1 - I_2 = \frac{2\left(V_1 - V_2\right)}{\left(R_{d1} + R_{d2}\right)} + \frac{\left(R_{d2} - R_{d1}\right)}{\left(R_{d1} + R_{d2}\right)} \cdot I_L \quad (1)$$

The DC bus voltage is expressed by Equation (2).

$$V_{DC} = \frac{\left(V_1 \cdot R_{d2}\right) + \left(V_2 \cdot R_{d1}\right)}{\left(R_{d1} + R_{d2}\right)} - \frac{\left(R_{d1} \cdot R_{d2}\right)}{\left(R_{d1} + R_{d2}\right)} \cdot I_L \quad (2)$$

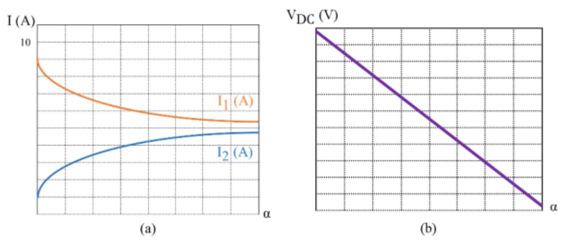

Fig. 10. Load sharing and busbar voltage regulation using droop control [67]
(a) Load sharing as the output resistances of the sources are increased by a factor of α
(b) Change of bus voltage as α increases

2.4.2. Secondary control level

The control structure at this level is responsible for regulating voltage fluctuations. A voltage is usually applied to the system in the secondary control loop to eliminate voltage deviation caused by the droop mechanism. This controller assigns the appropriate voltage setpoint for each converter. Thus, achieving voltage regulation is the main objective of this phase. For this reason, it can also be called Voltage Limit/Replenishment Control [70]. In the most commonly used droop control method at the second control level, the total power is shared between the converters at the outputs of the supplies in proportion to their rated power. Since voltage is a local variable in the microgrid, droop control cannot provide direct current sharing between sources in practical applications where line impedances are not negligible. In other words, line impedances neutralize the sagging mechanism in proportional sharing of the load. Another control loop is used at the secondary control level to improve current sharing accuracy [55, 55]. However, since the line length is short in small-diameter microgrids, the effect of line resistors on current sharing is negligible and therefore a current regulator is not needed. A control block diagram of the voltage and average current regulator (ACR) is shown in Figure 11. The voltage regulator controls the DC bus voltage at the specified reference value (V*). Another controller normalizes the output currents obtained from the converters in the microgrid, according to the reference current. Two different PI controllers with ACR used for current and voltage control and their effects on the system are shown graphically in Figure 12. As the load increases, the DC link voltage drops to VMG. The secondary controller measures the DC bus voltage and calculates the correction time of δV. The ACR locally adjusts the slope of the droop characteristic by calculating the correction term δVc to regulate the output current at a weighted average value [5]. It then sends this term to all converters to increase their output voltage. The voltage regulator can be implemented with a centralized or decentralized control technique [50]. Distributed control is also frequently used to eliminate the communication requirement between converters [70].

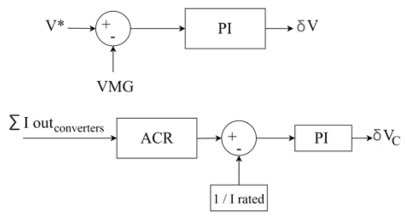

Fig. 11. Secondary controller scheme with ACR [5]

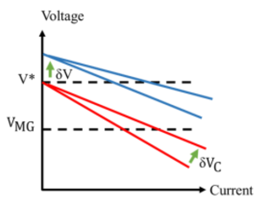

Fig. 12. The secondary controller's effect on the droop characteristics [5]

2.4.3.Tertiary control level

This level usually manages the power flow between the microgrid and the main grid or distributed energy sources. It is also known as the energy management system, and in some cases this control layer also communicates with the distribution system operator. In practice, DC microgrids or DC distribution systems need to be connected to the main grid via a power electronics converter. As shown in Figure 13, this converter acts as a power source or load for the microgrid. Therefore, the tertiary controller can be implemented for the control of this converter [5]. The efficiency curve of the converters is taken into account at the tertiary control level, which is made for the control of the power flow between the distributed energy sources in the microgrid. This layer calculates the aggregate demand, micro-grid voltage and efficiency curves of the converters to optimize the output power of the converters. It has been observed that artificial intelligence optimization algorithms are also used in the control of the specified controller [5]. At the tertiary control level, the classical Newton−Raphson method and its extended versions are still widely used [71, 72]. The power flow between energy sources can also be regulated according to state of charge (SoC) conditions by changing voltage control references or by adaptive droop methods [71-73]. In an application that includes an energy storage system [74], the power sharing between the battery and the supercapacitor (SC) is provided by considering the supply-demand balance. Also, low voltage DC microgrid with hybrid energy storage system (HESS) is used to develop a power sharing to match the demand generation. An artificial neural network-based control strategy has been proposed for the management of this network. In the proposed strategy, voltage imbalances in the DC busbar are taken into account in order to eliminate the power imbalance. However, the control structure with artificial neural network (ANN) for the rapid compensation of these imbalances can reduce the battery charge-discharge time due to the delays in the redirection of the battery currents. The proposed control method only provides power sharing between energy storage systems. The main disadvantages are that it does not include distributed energy resources in this sharing and the possibility of delay due to ANN.

In the study performed by Choi, Ahn and Won [75], power sharing and power flow control between multiple energy storage systems have been performed. A hierarchical control structure and three types of power sharing methods are proposed for this sharing. The basis of the control mechanism is a maximum efficiency optimization based on the piecewise linearized Lagrangian equation. In addition, an energy sharing algorithm based on the EDS energy level has been proposed to proportionally share the power to be provided from the EDSs. After sharing, the output power of all EDSs is equal. Charge and discharge situations are done over other distributed sources in the microgrid in order to achieve this equality. For island mode DC microgrids, a noncommunicative control network based on classical droop control and using only energy storage systems has been proposed by Hou, Lee and Ding [76]. The use of renewable energy sources is not included due to output power fluctuations. Input voltages are controlled by a double active bridge DC-DC converter at the output of the EDS, and these voltages vary according to the load and provide sag control. The fact that renewable energy sources are not taken into account is seen as a disadvantage in terms of clean and reliable energy supply.

The main goal of the control strategy adopted in another study [77] based on energy storage systems is to regulate the DC bus voltage through EDSs in a microgrid structure containing renewable energy sources, EDSs and a diesel generator. Also, it is the secondary purpose to connect the diesel generator to the common DC bus as a backup source in case of emergency to prevent excessive discharge of the EDSs. In this way, both the life of the EDS will be extended and the busbar voltage will be balanced by the diesel generator temporarily connected to the bus. After this voltage stabilization, when the power flow is balanced again, the backup distributed generation source is disconnected. The main task of EDSs is to minimize the fluctuation in the output power of renewable energy sources.

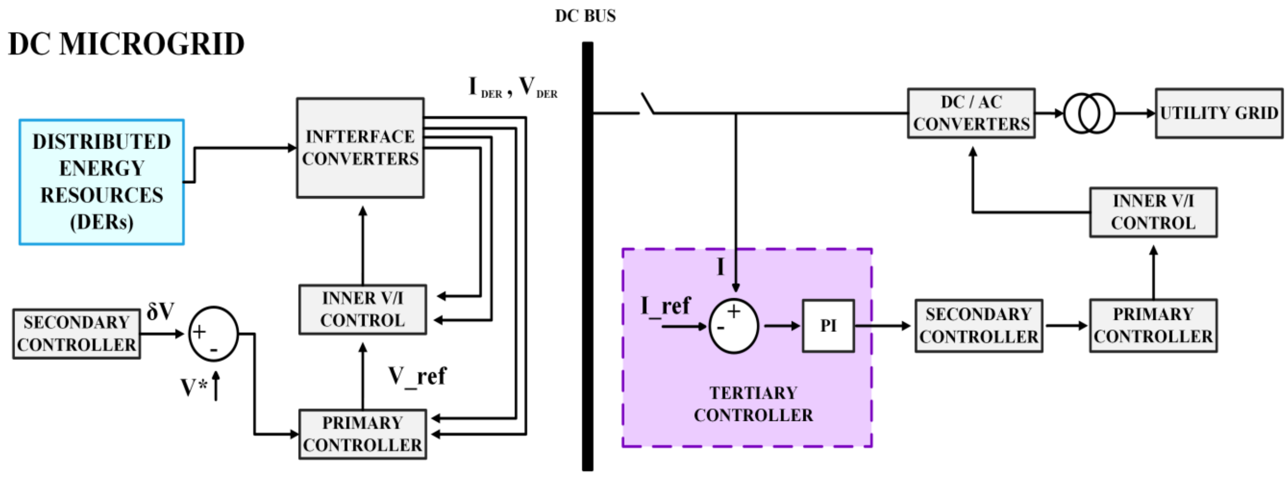

Fig. 13. Tertiary controller between the microgrid and utility grid for power flow [5]

The control structure, which is considered in studies based on the SoC balance, generally plans the charge-discharge times of the EDSs to maintain the droop balance. With DC power sharing based on the SoC level, a power flow directly proportional to the SoC level is provided. Thanks to the power sharing made with this method, the DC bus voltage is kept at the desired level and the stability of the system is verified with the control method. Among EDSs, those with higher SoCs discharge faster than those with lower SoCs. In other words, more power is drawn from the EDS with a higher capacity. The SoC difference between each EDS gradually decreases and the load power begins to be shared equally among the distributed EDSs.

In some applications, SoC-based droop control is provided based on a virtual battery model and virtual impedance [79-81]. Another study presented in literature [82] investigates the multiple distributed energy storage systems in DC microgrid and proposes a hierarchical power sharing control strategy based on discrete consensus algorithm. In this strategy, power sharing between EDSs is achieved in proportion to their SoC levels and capacities.

The application of consensus theory, which is most commonly used at the third level of hierarchical control of microgrids, is of great interest as it facilitates the development of distributed control solutions [71, 82-88]. However, its accuracy has not been determined exactly in terms of convergence to appropriate power values [89]. The consensus algorithm is also used to solve the the most economic way for power sharing among distributed generation resources [90]. Optimal economic distribution is achieved by allowing iterative coordination of local agents (consumers and distributed producers). As the coordination information, the local estimate of the power mismatch is shared between the distributed generators via communication networks.

The most commonly used control methods in layers of hierarchical control are given in Table 2. In addition to the scarcity of artificial intelligence-based methods, it is noteworthy that the use of metaheuristic algorithms is much less common among these methods.

As a general consequence, among the power sharing methods used in microgrids, centralized control, decentralized control and distributed control have their specific advantages and disadvantages. In hierarchical control, which is used to gather all these advantages and eliminate the disadvantages, different methods and algorithms are used at each layer. When the target functions and usage purposes of these methods and algorithms are considered as an optimization problem, it is seen that apart from power sharing, it covers issues such as economic interests and energy management. Therefore, the use of artificial intelligence methods will contribute to the literature in this subject [14].

Table 2. Basic control methods in hierarcihcal control

Control Level	Control Methods	Ref.
Primary Level	Master-Slave Control	[49]
	Droop Control	[53-56]
	Distributed Control	[58-59]
	Fuzzy Logic Control	[60]
	BAT Algorithm	[95]
Secondary Level	Centralized Control	[56]
	DC Bus Signaling Control	[101,102]
	Distributed Control	[70]
	Average Current/Voltage Sharing	[54,72]
	Genetic Algorithm	[72,86]
	Particle Swarm Optimization	[32,96]
Tertiary Level	Newton Raphson	[71,72]
	State of Charge based Control	[73]
	Artificial Neural Network	[74]
	Droop Control	[78-80]
	Consensus Algorithm	[87-90]
	Virtual Impedance	[93]
	Artificial Bee Colony Algorithm	[98]
	The Ant Colony Algorithm	[94]

3. Metaheuristic Optimization

Nowadays, metaheuristic optimization algorithms have become very attractive due to their significant advantages as compared with traditional algorithms. Metaheuristics can be an efficient way to produce acceptable solutions by trial and error to a complex problem in a reasonably practical time. Since there are different metaheuristic optimization algorithms are presented in recent literature, a comparison among them is made in this part of the paper firstly. Then, performance analysis of some well-known metaheuristic optimization algorithms for voltage regulation problems in droop control is realized.

3.1. Comparison of Metaheuristic Optimization Algorithms

The most important advantage of metaheuristic optimization algorithms is the ability to reach global results without getting stuck at local optimum points [90]. Therefore, many types of metaheuristic algorithms are presented in recent literature. The advantages and disadvantages of each other vary according to the usage areas. In order to determine the most suitable algorithm for the problem under consideration, they should be compared according to application area. The commonly used algorithms for power sharing in microgrids are compared in Table 3 [91].

Table 3. Comparison of metaheuristic algorithms

Algorithm	Advantages	Disadvantages
Genetic Algorithm (GA) [72, 92]	Easy to apply. Has arbitrary type of target and constraint handling. It can be used to solve a given problem. It is not dependent on other devices or apps. It can be used for resources that do not have constraints and goal strategies or are discontinuous. Simple operators can be used for planning and solving high computational complexity.	GA does not have a standard method for having a good structure. In the best solutions, one should be appropriate according to its function and this improvement function should be very accurate. GA has no standard termination and there is not a commonly accepted way for this aim. Optimization with GA can take a long time for some problems which have higher selectivity.
Ant Colony Optimization (ACO) Algorithm [94]	Since it is able to comply with new situations and variables, it can be appropriate for dynamic problems. Feedback calculations are rapid in the discovery of optimal solutions. Since ant creates independent and concurrent solutions, it has natural data parallelism similar to object-oriented programming techniques.	The probability distribution changes distinctly with the number of iterations. Although the optimum convergence is ensured, the convergence duration is undefined. The behavior of this algorithm is difficult to analyze theoretically because it is based on random decision sequences of different independent artificial ants.
Bat Algorithm (BA) [95]	BA utilizes frequency tuning to expand population variety. It offers automatic zoom exploration fields with the best results. Auto-zoom supports to stabilize exploration time while searching. It is easy, adaptable, simple to apply, and able to tackle lots of problems.	Although BA is used in an easy way in nonlinear global optimizations, it does not offer the efficient results in discrete optimization problems. It is difficult to design because it involves the determination of random parameters as in PSO.
Particle Swarm Optimization (PSO) [32, 96]	Computation is easy. There are many sources that can be referenced in the determination of parameters.	Whole resolutions may converge too early, thereby population variety might be lost. Another issue is getting stuck in local optima. As the population size increases, the risk of not reaching the solution in the optimum iteration increases.
Artificial Bee Colony Algoritm (ABC) [97]	It has quite powerful algorithm, convergence time is very short, needs less parameters, and easiy adaptable. It can be applied simply and is able to explore not only locally but also globally.	It may converge during the earlier steps of its exploration; therefore, the classification precision of the acquired solution may be insufficient for satisfying desired necessities. It is difficult to design because it involves the determination of random parameters as in PSO and ABC.

As seen in Table 3, in terms of applicability, while GA, PSO and ABC algorithms provide similar conveniences, ABC algorithm has better dynamic response because it produces fast solutions. Determining random parameters in PSO, BA and ABC algorithms is seen as the common and most important disadvantage. There is no random parameters in the ACO. However, it is quite difficult to analyze the behavior of this algorithm theoretically compared to all other algorithms because the decision sequences of the ants are random. Although metaheuristic algorithms are frequently preferred in optimization studies, their use in power sharing control has not yet become widespread. The fact that the success rate in the performance of metaheuristic algorithms is worth trying. However, following disadvantages of the most widely used algorithms given in Table 3 should be considered:

- Increasing the number of iterations and prolonging the solution time in finding the global optimum
- The problem of getting stuck at local optimum points
- The problem of setting arbitrary parameters
- Probabilistic accuracy may vary depending on population size

When the power sharing problem in DC microgrids is examined, it is seen that metaheuristic algorithms still need to improve. Genetic algorithm, which is one of the most frequently used methods, has been used as SoC-based in [72] and virtual impedance-based in [93] in order to prevent voltage regulation caused by droop control. A regulated virtual resistor has been added for the control of the droop parameters with the PI controller and the voltage regulation has been tried to be adjusted by changing the value of this resistor. The PSO algorithm is used in [32] to regulate the bus voltage regulation by determining the PWM rate of converters and is used in [96] for voltage control together with the SoC-based PI controller. ABC algorithm is used to solve the economic power sharing problem based on controlling the loss in output power of the sources [98]. The ACO is used as a power sharing control algorithm according to the power demand of the loads and according to the economic benefit [94]. BA algorithm based master-slave control method is used for power sharing in [95].

As seen, although some studies have been presented in literature, the use of artificial intelligence in the field of power sharing in microgrids is not yet reached at a considerable level. Therefore, a sample comparative study is achieved in this part of the paper in order to make it clear how metaheuristic algorithms can be used especially for voltage regulation problems in microgrids.

3.2. Performance Analysis of Metaheuristic Algorithms for Voltage Regulation Problems in Droop Control

In recent literature, several control methods have been tried in the second layer of hierarchical control in order to eliminate the voltage regulation problem caused by droop control. Among them, the most widely used ones are GA, and PSO algorithms. As a newer technique than others, the Gray Wolf Algorithm (GWO) is not tried before in the literature for the optimization of droop parameters. Therefore, this paper handles two widely used algorithms (GA and PSO) and a newer algorithm (GWO). These three algorithms are tested in MATLAB/Simulink environment in order to analyze their performances. For this purpose, a sample microgrid system has been designed consisting 4 different energy units as PV, energy storage system, wind turbine and fuel cell. Block diagram and Simulink diagram of the system designed is given in Figure 14 and Figure 15, respectively. The power flow of the PV and the wind systems is managed by DC-DC boost converters, control of which is provided by the maximum power point tracking (MPPT) algorithm. Bidirectional DC-DC converter is used at the output of the energy storage system including Lead-Acid batteries considering both the charge and discharge conditions.

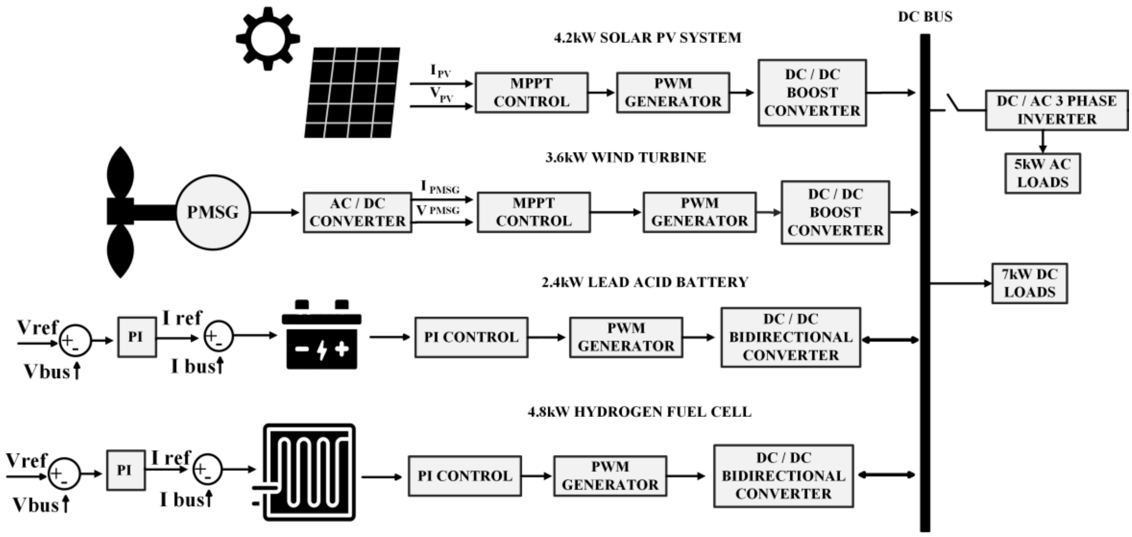

Fig. 14. Block diagram of the designed control system

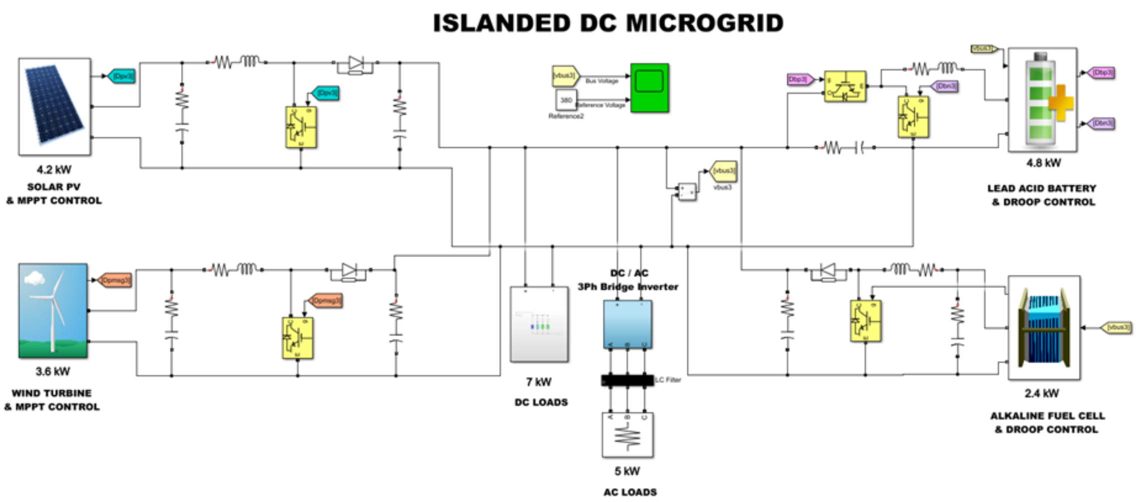

Fig. 15. Simulink diagram of the designed microgrid

Since the PV system and the wind turbine use MPPT control, they are considered as uncontrollable. The droop control with the PI controller is carried out only for the energy storage unit and for the fuel cell. The reference voltage and the reference current are controlled by a PI controller in order to provide the voltage regulation in the DC bus. PSO, GA and GWO algorithms are tried to calculate the coefficients of the PI controller. It should be noted that the MATLAB Simulink model given in Figure 15 is based on the previously studied and succesfully tested microgrid examples in [99] and [100]. The system parameters are given in Table 4.

Table 4. Parameters of the sample test system

Unit	Parameter
PV System	Power at Maximum Power Point = 4.2 kW *(4 parallel x 7 series, 25 cells)* Voltage at Maximum Power Point = 34.63 V Current at Maximum Power Point = 4.35 A Open Circuit Voltage = 43.6 V Short Circuit Current = 4.86 A DC / DC Boost Converter's Parameters; L = 21.36mH C=120 μF
Wind Turbine (PMSG)	Power at Maximum Power Point = 3.6 kW Wind speed = 12 m/s Rotor Speed = 1650 rpm Torque = 1.678 $kg.m^2$ DC / DC Boost Converter's Parameters; L = 5.16mH C=450 μF
Lead-Acid Battery	Power = 4.8 kW Voltage = 96 V Capacity = 50 Ah Bidirectional Converter's parameters; L = 1.795 mH C = 343 μF
Alkaline Fuel Cell	Power = 2.4 kW Nominal Voltage = 48 V Nominal Current = 50 A Number of Cells = 68 Bidirectional Converter's parameters; L = 15 μH C = 330 μF
DC Bus	V_{ref} = 380V Load = 7kW DC, 5kW AC

3.3. Simulation Results

For the simulation, three different scenarios are created by using three different algorithms as PSO, GA and GWO, flowchart of each is shown in Figures 16, 17 and 18, respectively. In all three algorithms, the objective function minimizes the sum of the values from the error signal of the PI loop. According to results obtained from the PSO-PI simulation, the bus voltage is fixed to the reference value in 0.2 seconds as seen in Figure 19. However, 7,89% overshoot is occured. When the number of iterations is reduced to improve the fixation time, settling time is reached to 1.22 seconds and 3.67% overshoot is observed in 100 iterations. Although this change reduces the maximum overshoot, it increases the time to fix. Since the voltage fluctuation rate is taken as 10% while calculating the parameters of the converters at the outputs of the sources in the simulation, a maximum overshoot below 10% is considered acceptable. For this reason, the number of iterations have been chosen as 150, since it is considered more important in terms of optimization to bring the stabilization time of the system earlier. Results for the GA-PI simulation is given in Figure 20 where the bus voltage is fixed to the reference in 1,2 seconds. However, the overshoot is about 7%. That means, PSO offers better performance than GA according to the fixation time to the reference value and GA is better than PSO according to overshoot percentage. It has been observed that the settling time increases when arbitrary values such as population width and mutation rate are changed in order to reduce the exceedance percentage in GA, which has the highest percentage of exceedance compared to the other two algorithms. On the other hand, GWO gives better performance than the other two algorithms considering its settling time to the reference value of 0.06 seconds and its overshoot of 4,21%.

Considering the time to reach the reference voltage value, the overshoot rate and the iteration times of the algorithms, the most appropriate values determined for all three algorithms are shown in Table 5.

Table 5. Performance scores of algorithms

Optimization Technique	Number of Iterations	Rising Time	Settling Time	Over-shoot
Genetic Algorithm	150	0,07 s	1,2 s	6.57%
Particle Swarm Optimization Algorithm	150	0,04 s	0,2 s	7,89%
Gray Wolf Optimization Algorithm	100	0,02 s	0,06 s	4,21%

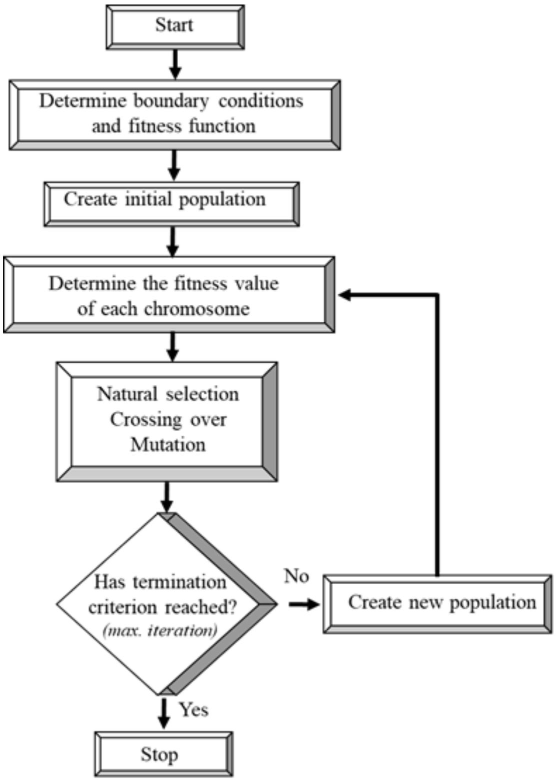

Fig. 16. GA algorithm flowchart

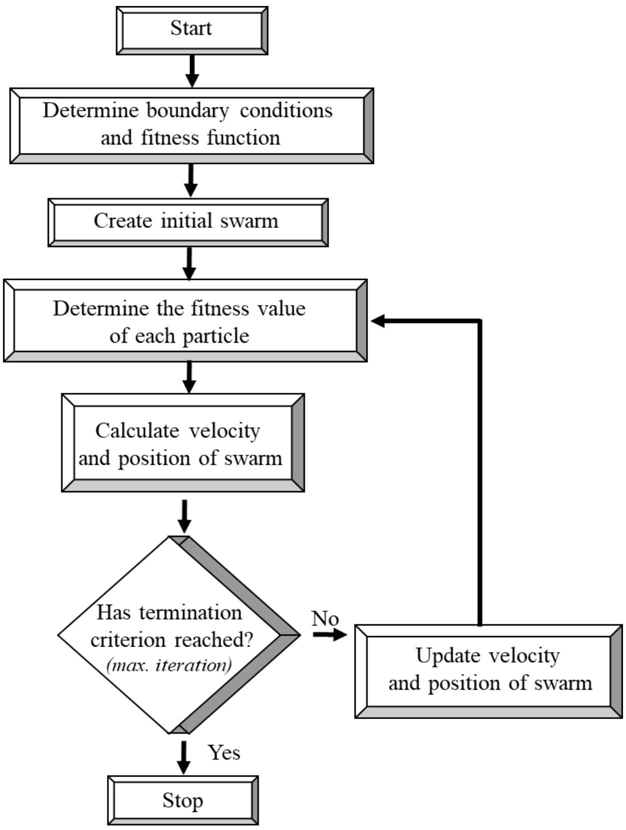

Fig. 17. PSO algorithm flowchart

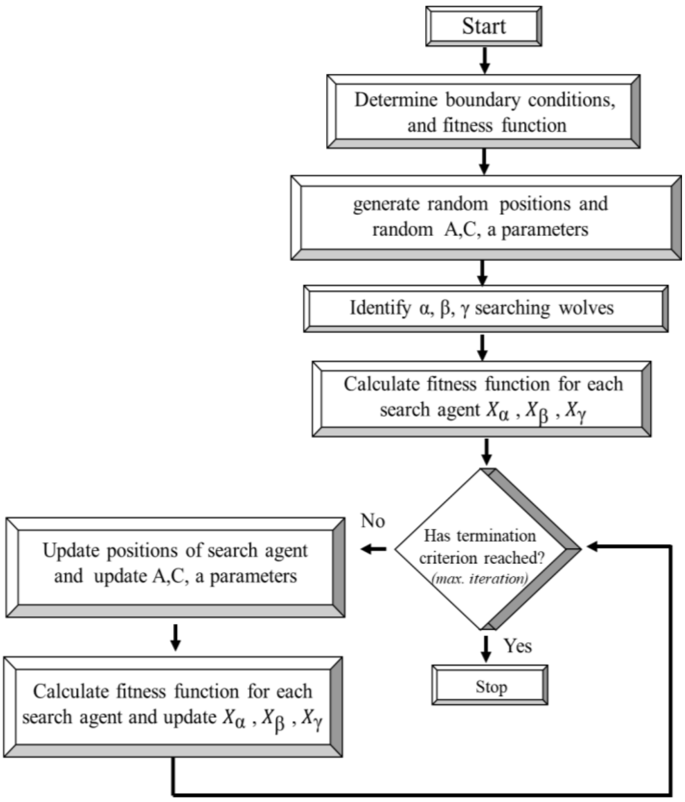

Fig. 18. GWO algorithm flowchart

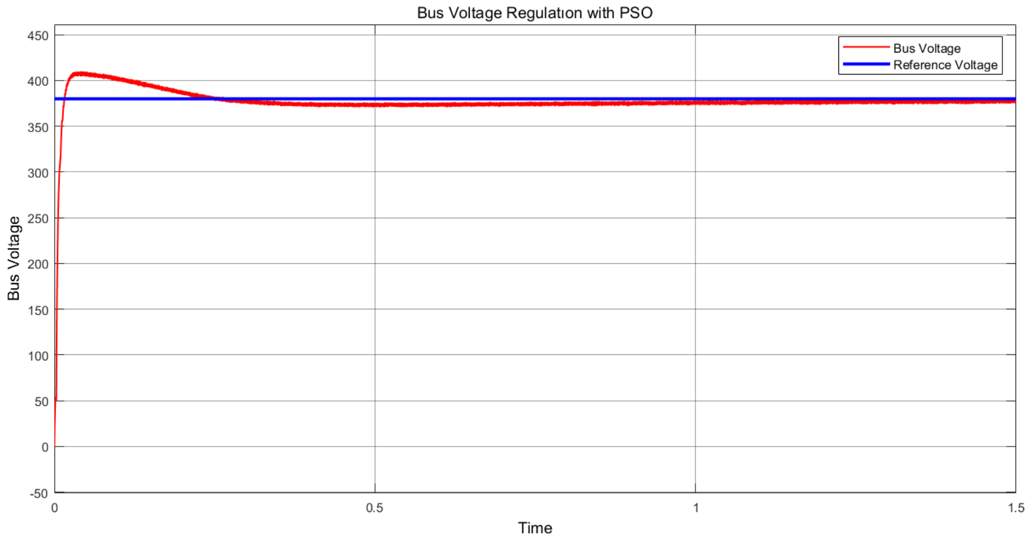

Fig. 19. Simulation results for PSO

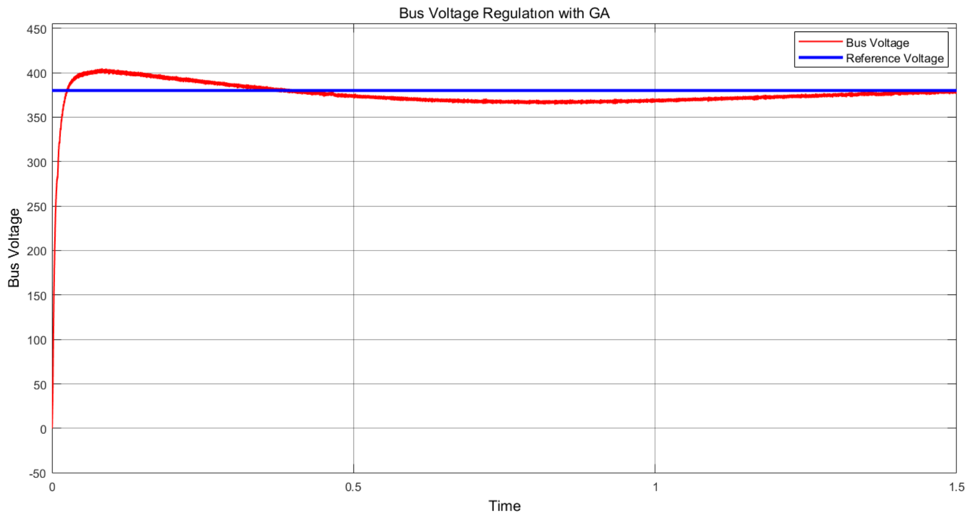

Fig. 20. Simulation results for GA

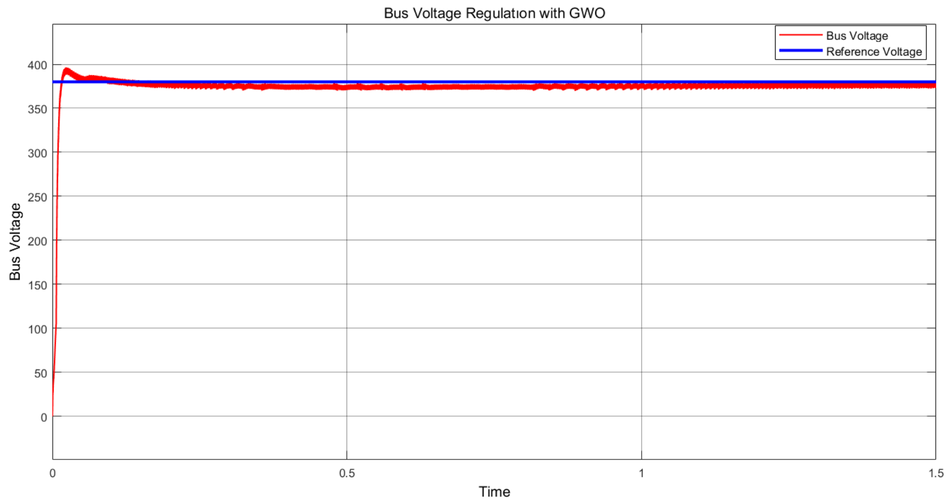

Fig. 21. Simulation results for GWO

4. Conclusion

An overview of the control approaches used in DC microgrids and the use of metaheuristic algorithms in this subject are presented in the paper. The advantages and disadvantages of centralized, decentralized and hierarchical control methods are emphasized. Although various methods have been tried for power sharing in DC microgrids, it has been seen that hierarchical control is the most commonly preferred. Considering the advantages and disadvantages of communicating and non-communicating systems, it has been observed that classical droop control algorithms and master-slave algorithms are insufficient in terms of the ensure a stable and reliable microgrid. As a solution, metaheuristic algorithms have been tried especially at the second and the tertiary level of hierarchical control. This has played an active role in the inclusion of metaheuristic algorithms in power systems. Therefore, a methodological comparison of the most preferred metaheuristic algorithms in the control of microgrids taking into account the up-to-date studies in recent literature is achieved and it has been observed that only basic metaheuristic algorithms are used in hierarchical control.

In order to make a better and realistic comparison between metaheuristic algorithms, a sample DC microgrid test system is designed in Simulink. Then, three metaheuristic algorithms such as particle swarm optimization (PSO), genetic algorithm (GO) and gray wolf algorithm (GWO) are tested comparatively on this system. Results show that the system stability mainly varies depending on the number of iterations. Actually, metaheuristic algorithms are difficult to test and design because there is no specific rule in determining randomly selected parameters. Especially, it has been observed that the population members in the GA constantly repeat each other, and if the number of populations is increased, the solution is getting harder. Although the optimum results are obtained from GWA in terms of the settling time, the instant changes on the speed of the wolves adversely affect the stability of the algorithm. For the PSO, overlapping of the members of the swarm with each other is a remarkable negative effect; particularly, frequently repeating values increase the collision probability of individuals in the swarm. The fact that there is no restriction for this situation in the velocity equations causes these algorithms to droop into repetition at local optimum points. As an overall conclusion, it can be suggested to use hybrid algorithms in order to eliminate the above problems arisen in metaheuristic algorithms.

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