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Optimizing Power Balance and Communication links in Microgrids: A Clustering Approach Using Particle Swarm Optimization

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ABSTRACT : Implementation of clustering techniques within electric power networks results in better reliability, self-healing, and controllability. This paper proposes a clustering technique in a microgrid with distributed energy resources to minimize power balance and communication time delays in each cluster. The automatic clustering algorithm is used to put the microgrid into several clusters and the particle swarm optimization (PSO) algorithm is used to obtain the optimal number of clusters. The automatic clustering algorithm employs the assigned objectives, i.e., power balance and communication time delays, to find the optimum clustering within the microgrid. In addition, due to a better convergence, the forward-backward power flow method is used to determine the power balance in each zone. The simulation results are provided with and without employing the proposed algorithm using the Bornholm microgrid in Denmark. Based on the obtained results, communication time delays are improved significantly when employing the proposed algorithm. In addition, clustering a microgrid provides some extra favorable outcomes such as better reliability, self-healing, and fault clearance.

Keywords– Micro-grid, clustering, automatic algorithm, communication system.

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1. INTRODUCTION

Due to the growing demand for renewable energy resources, their integration into the power grid is becoming more complex economically and technically [1]. There are many factors that contribute to these problems, including the uncertain nature of the distributed energy resources (DERs) the fluctuating nature of the weather, power flow analysis, and the high cost of energy storage [2-3]. Recently, clustering has been a widely studied power systems research topic with several critical applications. Here are some of the most crucial applications of clustering in power systems. The clustering technique can be used to group loads with similar patterns together [4]. This can help develop more accurate load forecasting models essential for power system planning and operation. Besides, clustering can be used to identify similar patterns of wind and solar power generation. This can help develop better integration strategies for renewable energy, which is highly variable. In addition, it is possible to identify similar fault patterns in power systems by clustering [5]. It can help develop more accurate fault detection and diagnosis techniques, which are crucial for maintaining power system reliability. Asset management and power quality monitoring are among the other applications of clustering in power systems.

In recent years, there has been an increasing focus on the clustering of DERs with consideration of power systems and communication constraints [6]. The purpose of clustering approaches is to improve the scalability, reliability, and efficiency of the power system by grouping DERs that are able to communicate with one another [7]. A literature review on the clustering of DERs by incorporating power systems and communication constraints is provided in the following [8], which proposes a novel control strategy for coordinating multiple AC microgrids. The proposed strategy consists of cluster formation and cluster-based control. Simulated results indicate that the proposed strategy maintains stable and reliable operation of microgrids regardless of disturbances or operating conditions. A novel clustering-based method is proposed by [9] to assess the reliability of cyber-physical microgrids, taking into account cyber interdependencies. The proposed method uses a K-means clustering algorithm to group the components of the microgrid into clusters based on their electrical and cyber characteristics. Simulation results demonstrate that clustering reduces computational complexity and improves reliability assessment accuracy by reducing computational complexity. An AC/DC hybrid microgrid clustering architecture is proposed in [10], which is scalable, reconfigurable, and able to operate in a coordinated manner through decentralization of control. The proposed architecture consists of multiple AC and DC microgrids that are interconnected through AC/DC converters. The microgrids are organized into clusters based on geographical proximity and electrical characteristics. The clusters are then controlled through a decentralized control system that is based on a consensus algorithm and a model predictive control approach. The scalability and reconfigurability of the architecture are shown to be effective in adapting to changes in the system and enabling the integration of new microgrids.

Although the clustering techniques in power systems are used widely, limited studies are done in the literature that both the power systems and communication constraints are addressed. The purpose of this study is to cluster the DERs in a microgrid while the power systems and communication constraints are considered. The k-means clustering algorithm is used to cluster the DERs into different groups. For the similarity measurement, the DB index that was first introduced by Davies and Bouldin in 1979 is used. Minimizing the power balance and communication time delay in each cluster are introduced as the objective function that must be satisfied by clustering. Finally, particle swarm optimization (PSO) is employed to solve the multi-objective optimization.

The remainder of the paper is outlined as follows. Part II elaborates on the employed methodology; the proposed clustering technique has been shed upon in Section III; the simulation results are discussed in Section IV; finally, Part V, besides recommending the future research scope, concludes this study.

2. METHODOLOGY

Analysis from the power system point of view

Islanding the power grid is one of the suitable methods for improving reliability and achieving easy and fast control. However, if the islanding is performed without considering power system constraints, it may cause reliability deterioration [11]. This paper aims to divide the components of a microgrid into multiple clusters so that each cluster consists of at least one distributed energy resource (DER) and one load. The objective of dividing a microgrid into some clusters is to separate the faulted region from the other regions of the microgrid and keep the other regions safe. Therefore, clustering results in a higher level of reliability because when a fault occurs within the microgrid only the faulted area is disconnected.

In this section, different aspects of clustering are analyzed. The first and most important factor that must be considered is the power balance in each cluster. The power balance in each cluster is important because when a cluster is islanded, it must be able to supply its loads to maintain an acceptable level of reliability. In addition, power flow among clusters must be minimized and this complies with the definition of clustering. Finally, the voltage and frequency must be within an acceptable interval.

Analysis from the communication point of view

With the development of information services, a higher bandwidth in network structures is needed. With an increase in the employment of control and protection devices, the need for bandwidth will increase. In electric power applications, various communication infrastructures are utilized; according to their need for higher bandwidth, fiber optic is a suitable choice for data transfer [12]. Fiber optic has some advantages such as low weakening, high bandwidth, and immunity against electromagnetic interferences and other noises [13]. It is known that communication-related parts that are utilized in power networks are vital components of power networks and provide data transfer between network components. In this paper, communication concepts are used for clustering. Due to power network security, data must be transmitted through a secure environment. So, the Internet and other public communication networks such as the telephone cannot be used in power networks and isolated communication networks must be utilized. In this paper, for data transfer, the fiber optic is used and the time delay in clustering is analyzed. The clustering is performed in a way that the time delay between controllers in each zone is minimized.

Backward-forward power flow

Due to high convergence, accuracy, efficiency, and flexibility the backward-forward power flow is used to do power flow in this study. The algorithm is divided into two stages, backward sweep and forward sweep, which makes the calculation process faster and more efficient. During the backward sweep, the load bus voltages are assumed to be known, and the voltage and phase angle at each bus are calculated using the power flow equations. The backward sweep begins at the load buses and proceeds toward the generator buses. During the forward sweep, the voltage and phase angle at each generator bus are assumed to be known, and the voltage and phase angle at each bus is calculated using the power flow equations. The forward sweep starts at the generator buses and moves towards the load buses. This procedure is done until it has an acceptable accuracy.

Objective functions

1) Objective function from power system point of view

The goal from the power system point of view is to minimize power balance in each zone. This means that the difference between power generation and consumption in each cluster must be minimized. Since the microgrids are similar to distribution networks and their resistance to reactance ratio is high, the results of backward-forward power flow are used [14]. The objective function in this section is defined as follows.

$$f_1 = P_{g,ci} - (P_{laod,ci} + P_{loss,ci}) \tag{1}$$

$$f_2 = Q_{g,ci} - (Q_{laod,ci} + Q_{loss,ci}) \tag{2}$$

Where, $P_{g,ci}$ is the total power generation of cluster *i*, $P_{load,ci}$ is the total power consumption of cluster *i*, $P_{loss,ci}$ is the total active power losses of cluster *I*, $Q_{g,ci}$ is the total reactive power generation of cluster *i*, $Q_{load,ci}$ is the total reactive power consumption of cluster *i*, and $Q_{loss,ci}$ is the total reactive power losses of cluster *i*. Since a microgrid is similar to a distribution network, its losses are considered to be 5 percent of total power consumption [15].

2) Objective function from the communication point of view

Time delay in data transfer is an important communication factor that plays a vital role in the stability and reliability of the communication network [16]. In this paper, a fiber optic system is used for data transfer.

Time delay in communication consists of four parts and the sum of these parts constitutes the total time delay. These four parts are defined as follows. Serial delay (T_s), between packet delay (T_b), Propagation delay (T_p), and Router delay (T_r). Therefore, the total time delay can be calculated as follows;

$$T_t = T_s + T_b + T_p + T_r \tag{3}$$

In Eq. (3), T_s and T_b are constant in most technologies [17]. In this paper, the time delay for each cluster is calculated by summing up the delays of the router.

$$T_{r,c} = \sum_{j \in ci} T_{r,j} \tag{4}$$

where, $T_{r,c}$ is the total delay of a cluster and $T_{r,j}$ is the delay of each local router.

Constraints

As it was discussed earlier, the power balance in each cluster must be minimized. However, another constraint is considered a balance constraint. In this section, it is assumed that the power generation in each cluster must be greater than 60 percent of loads and losses; so, only 40 percent of the load is curtailed when a cluster is islanded. Besides, the voltage and frequency of all buses must be between a lower and upper limit.

Clustering algorithm

In data analysis and machine learning, clustering involves grouping objects or data points based on their similarities or characteristics. In this paper, the automatic clustering method is used. The steps of this method are as follows:

1- Building a vector of the data. These data must be put into groups based on a kind of similarity.

2- Generating a new vector that shows the center of clusters and is determined in such a way that the sum of its distance from all the members of that cluster is minimum. In addition, for calculating the distance between two nodes, the Euclidean method is used.

1) DB index

This index was first introduced by Davies and Bouldin in 1979. First, this index calculates the distance of the members within a cluster and also the distance between clusters. Then, the ratio of the distance between the members of a cluster to the distance between clusters is calculated. The calculated ratio must be minimized. In addition, another operator must be defined to represent the second goal which is to maximize the discrepancy among different clusters. Finally, the continuity and separation conditions must be taken into account. Therefore, the DB index is representative of the ratio of the distance within a cluster to the distance between clusters. As a result, the DB index should be minimum, and its minimum value is obtained using optimization algorithms such as PSO.

3. SIMULATION AND RESULTS

Assumptions

The simulations are carried out using MATLAB programming environment. The minimum and maximum values of voltage are considered to be 0.95 p.u. and 1.05 p.u., respectively. In addition, the minimum and maximum values of frequency are considered to be 49.5 Hz and 50.5 Hz, respectively. The proposed clustering algorithm is tested on a sample microgrid which is located in Bornholm in Denmark (see Fig. 1.) In this study, both the power system and communication network aspects are considered in the optimization problem. The weight factor for the two objective functions is considered to be 0.5 which means that both objective functions have the same level of importance.

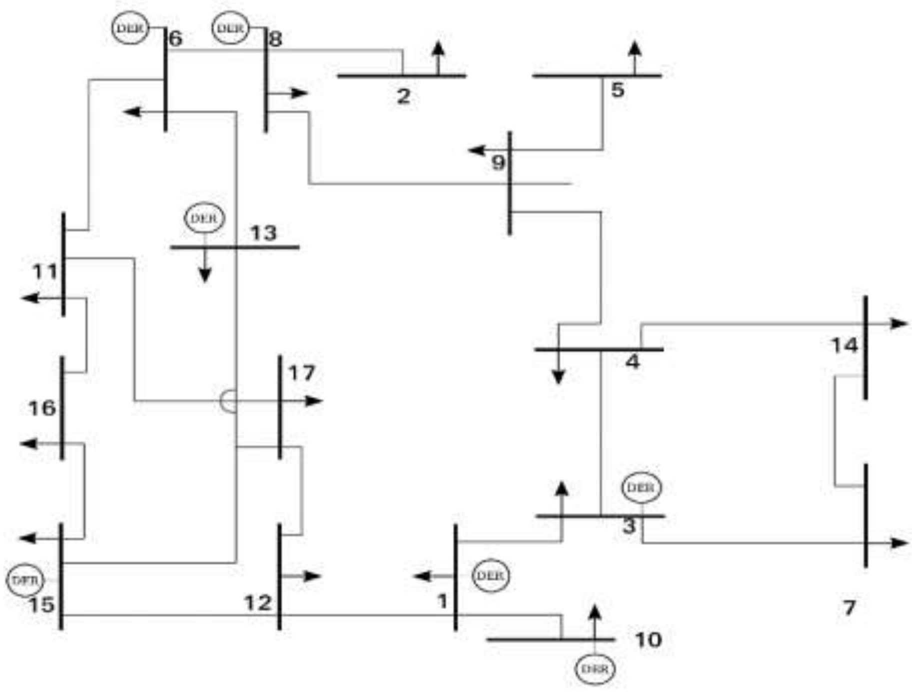

Fig. 1. Network diagram of the micro-grid under study

Results and discussion

The optimization problem to specify the optimal number of clusters is done with the PSO algorithm and the convergence curve is shown in Fig. 2. Besides, the hyperparameters of the developed PSO algorithm are listed in Table I. The results of the clustering are provided in Tables Ⅱ and Ⅲ. The clustering results indicate that the buses have been grouped into three clusters based on their similarity in power balance and time delay communication. Based on the clustering results, cluster 2 contains 13, 15, and 17 buses, cluster 3 contains the 2, 6, 8, 11, and 16 buses, and cluster 1 contains the remaining buses.

TABLE Ⅱ. Communication time delay clustering results

Cluster number	Sum of time delays
1	115 μs
2	113.2 μs
3	257.3 μs

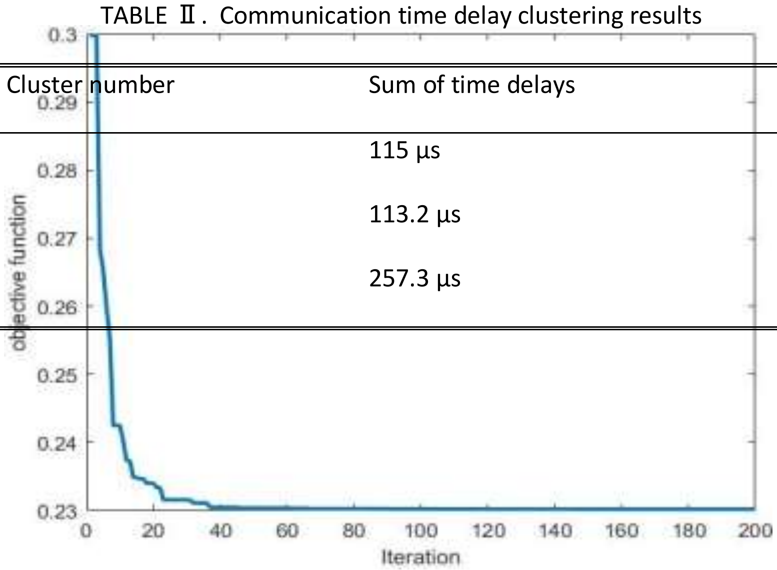

Fig. 2. Convergence curve of the optimization function based on PSO

Based on Table Ⅱ, the time delays associated with each cluster represent the total communication time required to transfer information in each cluster. The total delay time without clustering was 1185 milliseconds, while the total delay time associated with each cluster is 115.098, 113.21, and 257.34 milliseconds, respectively. This represents a reduction in total delay time of approximately 60%, indicating that the clustering algorithm was effective in reducing communication delays within the microgrid. According to Table Ⅲ, the results show that cluster one is consuming more power than it is generating, leading to a deficit in the power balance. This shortage is 19% of the load consumption while the threshold is 60%. If a cluster generation is less than its

TABLE I. Tuned hyperparameters for the PSO

Hyperparameter	Tuned Value
Number of Particles	50
Cognitive Coefficient 1	0.1
Social Coefficient	0.1
Inertia Weight	0.8
Maximum Velocity	0.2
Maximum Iterations	1000

consumption, critical loads such as hospitals would be supplied with power while the remaining loads would be disconnected. Cluster two seems to be in a balanced state, with the power generation almost equal to the power consumption and loss. Cluster 3 has the highest power generation of 15.32 MW, and its power consumption and loss are 14.327 MW, resulting in a power balance of 1.993 MW. This cluster seems to be generating more power than it is consuming and losing, resulting in a positive power balance. As a result, Since the microgrid has a decentralized control system (each cluster has its own control system), the other clusters may continue to operate normally, with power being rerouted around the affected cluster. In this case, the reliability of the microgrid may be improved by the clustering, as the other clusters can compensate for the loss of power from the affected cluster. Fig. 3 presents the voltage and frequency profiles of different buses in the microgrid. Importantly, all voltage readings fall within the accepted range of ± 0.05 p.u., and the frequency values are consistently within the limits of ± 0.5 Hz. These stable outcomes highlight the effectiveness of the clustering algorithm used in this study.

4. Conclusion

This paper proposes a clustering technique for microgrids with distributed energy resources to minimize power balance and communication time delays in each cluster. The proposed automatic clustering algorithm employs the objectives of power balance and communication time delays to find the optimum clustering within the microgrid. Additionally, the particle swarm optimization algorithm is used to obtain the optimal number of clusters. The simulation results demonstrate that communication time delays are improved significantly when employing the proposed algorithm. Besides, clustering a microgrid provides some extra favorable outcomes such as better reliability, self-healing, and fault clearance. In future research, investigate the impact of clustering on other microgrid components, incorporate real-time data, evaluate this study on a larger-scale microgrid, consider different objectives, such as cost optimization or environmental impact to achieve more comprehensive clustering results, and integrate more complex clustering algorithms can be done.

TABLE Ⅲ. Power system clustering results

Cluster number	Generation (MW)	Loss and consumption (MW)	Power balance (MW)
1	3.65	4.526	-0.876
2	9.93	10.04	0.89
3	15.32	14.327	1.993

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