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Optimal design of low voltage AC/DC microgrid

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ABSTRACT - This paper challenges the traditional AC distribution network by proposing a new AC/DC microgrid topology in the context of developing countries' electrification. The K-means clustering technique is employed to group DC loads into a predefined number of clusters. Next, the minimum spanning tree (MST) is applied to the clusters in order to get the minimum length of the DC conductor. Hence, by using the shortest path (SP) algorithm, the closest electrical poles connected to the DC load of each cluster at which the AC/DC converter is placed, are found and then, balanced by the means of mixed-integer linear programming (MILP). Finally, the AC lines connecting all the poles and clusters are designed with the MST. The optimal conductor sizing of the complete AC/DC microgrid is determined in order to satisfy voltage and current constraints.

Keywords—*k-means clustering, MST, SP, MILP, optimization, AC/DC microgrid.*

1. INTRODUCTION

Recently, some electrical appliances have become DC loads: USB sockets, chargers, LED lightings, etc. while, the development of distributed energy resources, operated in DC such as solar photovoltaics and battery energy storage is increasing[1]. To deal with these technological trends, AC/DC microgrid could be an alternative option for rural electrification in developing countries, in remote rural areas particularly [2]. In a low voltage AC microgrid, authors have proposed a novel algorithm to optimize the topology and phase balancing to tackle the load demand uncertainty [3], also, the photovoltaics (PVs) and batteries have been optimally sized and located by using a genetic algorithm [4]. That previous study focused only on the AC system. This paper proposes the AC/DC structure which deals with the growth of DC loads. To connect loads to the AC main feeder via the converter, the K-means clustering technique has been applied to pack the DC loads.

The K-means clustering technique has been widely used to study the classification in data mining and machine learning. Moreover, it is recently being applied in the electrical power system. In[5] and [6], authors have used the K-means algorithm for the optimal sitting of distributed generation (DG) in order to minimize the power losses, to improve the voltage profile and power quality. Furthermore, the K-means clustering can classify and recognize the voltage- sag in the power system by calculating the center cluster (centroid). The distance among different sag incidents was determined and then when some distances are nearer, the centroid can be set to represent these voltage-sag incidents [7].

In [4], each consumer has been directly connected to the AC main feeder. However, in our context, AC/DC converters have been installed so that the AC line could supply DC loads. To connect DC loads together in each cluster, the minimum spanning tree has been employed in order to get the shortest length of the DC conductor. This algorithm was introduced to solve the problem of searching the shortest path of a graph without any loops [8]. In the AC network, the power unbalance increases power losses. To tackle the problem, researchers have used the first-fit bin-packing (FFBP) algorithm as well as the mix-integer quadratically constraints programming (MIQCP)[3][4].

However, it can be noted that various researchers have only focused on the AC network with AC consumers. Therefore, this paper proposes a novel algorithm to pack DC loads in such a way that the AC main feeder could supply DC loads by using the AC/DC converter in each cluster. Then, the load allocation of each phase was formulated by using the mixed-integer linear programming (MILP) solver. The MST algorithm also aims at searching for the minimum length to get the optimal topologies of each cluster in order to obtain an optimal topology of the AC/DC microgrid. In that way, the electrification of developing countries could go faster with the development of DC microgrids before being connected to the AC grid when it will be available.

This paper is organized as it follows: Section 2 describes the proposed method subdivided into four stages: the K-means clustering technique for grouping DC loads (consumers) into a given number of clusters (stage 1), the minimum spanning tree to get the minimum total length of conductor in each cluster (stage 2), the shortest path finding the shortest distance of the connection between poles and clusters (stage 3), and the balance of power consumption between the main feeders (stage 4). Section 3 provides the case study in a rural area including the results and discussions. Finally, the conclusions and perspectives are presented in Section 4.

2. METHODOLOGY

The full algorithm implemented to design the AC/DC distribution microgrid, depicted in Fig.1, consists of the following steps:

- 1) Input data of the network: load demand, location of the future MV/LV substation, poles consumers, line parameters, and a number of clusters.
- 2) Grouping DC consumers into a given number of clusters by using the K-means clustering technique evaluated by the Elbow method[9].

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- 3) Searching the minimum connection's length of DC conductors in each cluster by using the MST algorithm. Then the DC conductors have been sized[10].
- 4) A low voltage DC load flow algorithm [11] is used to find the poles from which each cluster will be connected. The criterion used is the minimization of power losses. The single-phase AC/DC converters will be located in the chosen poles.
- 5) Applying the load allocation algorithm to balance the power of each phase. Then, the cross-section of the AC main lines 50 mm², 70 mm², and 95 mm² was investigated [12].
- 6) The AC unbalanced load flow was performed in order to get the optimal topology by respecting electrical constraints.

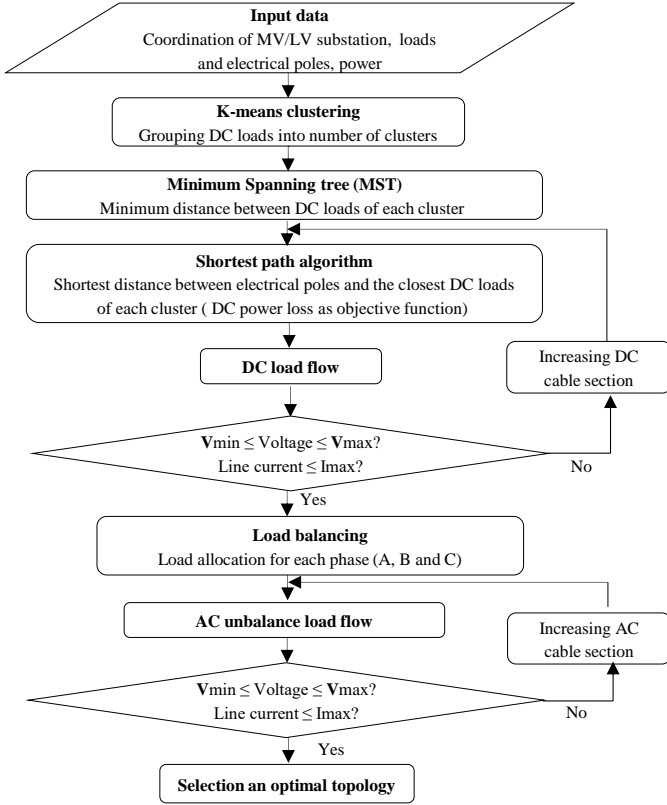


Fig. 1. Flowchart of the proposed method

2.1. K-means clustering

K-means clustering is the algorithm aiming at grouping objects into a set of clusters. This clustering technique minimizes the square error of the distance to cluster centers in order to minimize the total distances of clusters [13]. However, parameters of the K-means algorithm include initial centers and the number of clusters which may affect significantly the final cluster formation. The objective function F is given as it follows [14]:

$$\text{Minimize } F = \sum_{j=1}^K \sum_{i=1}^N \|x_i^j - c_j\|^2 \quad (1)$$

where

i : index of loads

j : index of clusters

N : number of data

K : number of clusters

x_i^j : data point

c_j : cluster center

The procedure of the K-means algorithm is shown in Fig. 2.

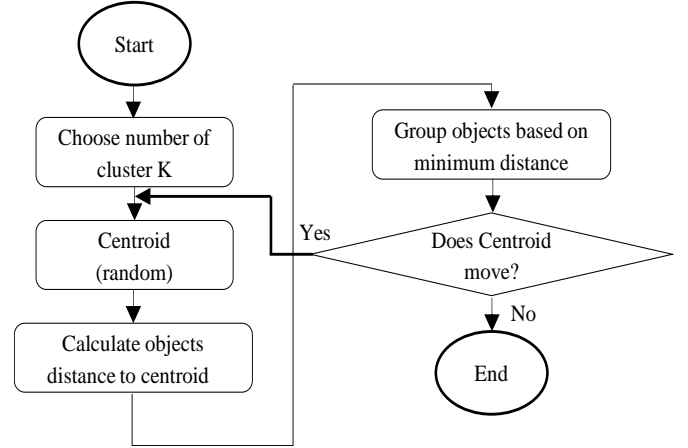


Fig. 2. Flow diagram of K-mean algorithm

Fig.3 shows an example of a case study's data [3] grouped into a number of $K=3$ clusters by the K-means clustering Matlab function. Also, three centroids were illustrated among them.

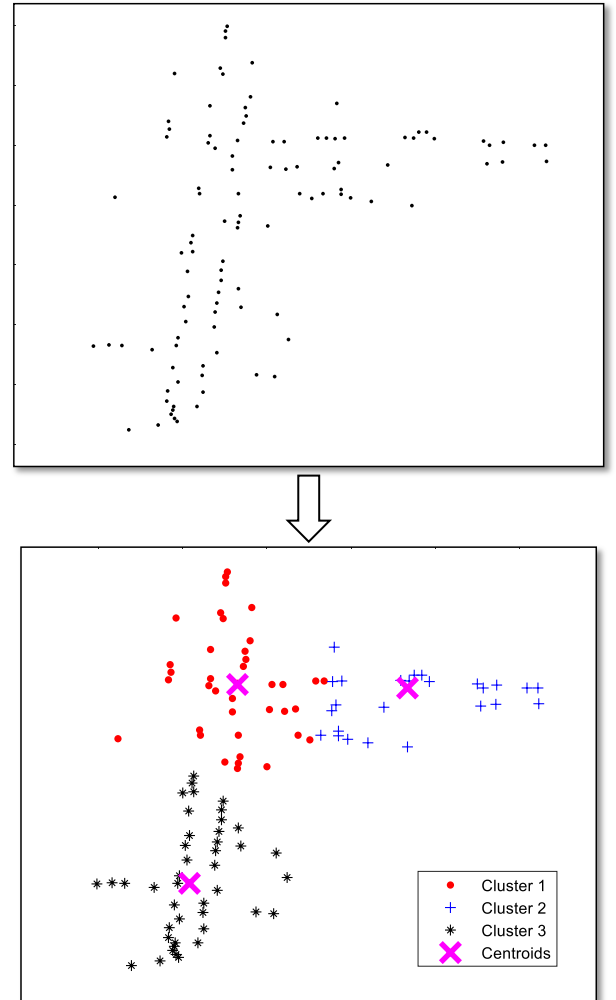


Fig. 3. Application K-means clustering on the study case with $K=3$

The classification of the K-means clustering is a sensitive technique based on the initial centroids. The greater the number of clusters is, the better the objective function is.

However, the number of cluster K should be optimally selected. To choose the optimal number of cluster K , the Elbow method was introduced. The Elbow method or “knee of a curve method” is a method that looks at the percentage of variance as a function of the number of clusters [9].

The idea of the Elbow method is to say that the optimal number of clusters is obtained when the addition of another cluster does not improve the objective function. Fig. 4 shows the percentage of the variance as a function of the number of clusters where it can be seen that the optimal number of clusters is 11.

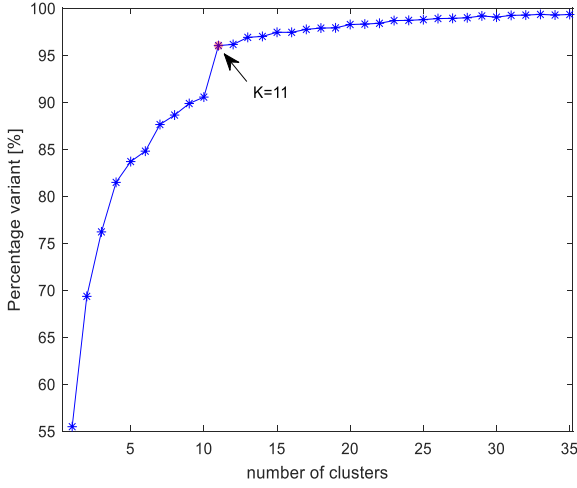


Fig. 4. The optimal number of cluster's selection by the Elbow method

2.2. Minimum Spanning Tree (MST)

The minimum spanning tree (MST) or minimum weight spanning tree is a set of the edges of a graph G that connects all the vertices (nodes) together, with the minimum total edge weight and without any loops (cycles). The sum of the edge weight of the spanning tree is as small as possible. This algorithm was developed by J. B. Kruskal [8] in 1956. If we consider a graph $G = (V, E, W)$ that consists of a vertices, edges, and weighs[15]:

$$\begin{aligned} V &= \{v_1, v_2, \dots, v_n\}; \\ E &= \{e_1, e_2, \dots, e_n\}; \\ W &= \{w_1, w_2, \dots, w_n\}; \end{aligned}$$

Fig. 5 shows the MST algorithm was applied to the graph with 7 vertices and 9 edges.

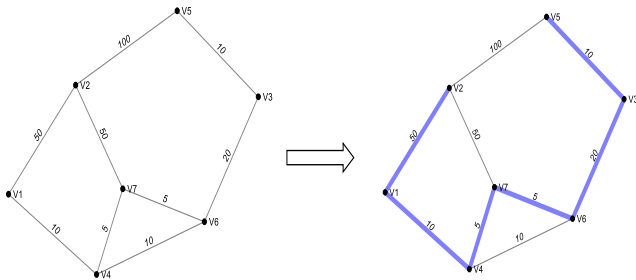


Fig. 5. Application the MST on the graph

The steps for implementing the Kruskal's algorithm are as follows:

1. Sort all edges from the low weight to high
2. Taking edges from the lowest to highest weight and add it to the spanning tree. If it created a cycle, then rejects this edge

3. Keeping adding edge until we reach all vertices

2.3. Shortest Path (SP)

The algorithm is to find the shortest distance from the MV/LV substation to each DC load of the cluster through electrical poles [4]. Fig. 6 shows the pseudocode of the shortest path that finds the index of a load of each cluster and pole. Indeed, it defines the optimal path which connects a pole to its closest DC load regarding the DC power losses.

```

C: number of clusters
N: number of loads in a cluster
P: number of poles
d(a, b): distance between a and b
for i = 1: C
    for j = 1: N
        for k = 1: P
            d_k = d(j, k)
        end
        D_j = min(d_k)
        DC load flow (D_j) ⇒ DC power loss(D_j)
    end
    DC loss_i = min(DC power loss(D_j))
    index = find(DC power loss(D_j) = DC loss_i)
end

```

Fig. 6. Pseudocode of the shortest path regarding DC losses

2.4. Load balancing

The load allocation algorithm has been formulated by using the Mixed Integer Linear Programming (MILP) tool of MATLAB (intlinprog). The objective is to balance the total power of the three AC phases to which clusters were connected. We tried to minimize the error between each phase load. The objective function is:

$$\text{Minimize } f(\varepsilon) = \varepsilon_-^A + \varepsilon_+^A + \varepsilon_-^B + \varepsilon_+^B + \varepsilon_-^C + \varepsilon_+^C$$

Subject to:

- ε : the error of each phase as following:
$$-\varepsilon_-^A \leq \frac{P_{total}}{3} - \sum_{j=1}^K x_j^A P_j \leq \varepsilon_+^A, \quad \text{per phase A}$$

$$-\varepsilon_-^B \leq \frac{P_{total}}{3} - \sum_{j=1}^K x_j^B P_j \leq \varepsilon_+^B, \quad \text{per phase B}$$

$$-\varepsilon_-^C \leq \frac{P_{total}}{3} - \sum_{j=1}^K x_j^C P_j \leq \varepsilon_+^C, \quad \text{per phase C}$$

Where P_j is the power of cluster j :

$$P_j = \sum_{i \in j} P_i$$

- State of the cluster's connection to pole
$$x_j^A, x_j^B, x_j^C \in \{0, 1\}$$

0: disconnected
1: connected
- a cluster can only be connected to one phase
$$x_j^A + x_j^B + x_j^C = 1, \forall j \in K$$
- the value of ε

$$\begin{aligned} \varepsilon_-^A &\geq 0 \\ \varepsilon_+^A &\geq 0 \\ \varepsilon_-^B &\geq 0 \\ \varepsilon_+^B &\geq 0 \\ \varepsilon_-^C &\geq 0 \\ \varepsilon_+^C &\geq 0 \end{aligned}$$

3. CASE STUDY

3.1. Description of the network

Data set from the previous study of the thesis [3] has been used in this paper: the Sandek village in a rural area, located in Batheay district, Kampong Cham, Cambodia is considered as a non-electrified area. The 107 households (DC loads) are single-phase loads with the total power of 43kW and 22 electrical poles. Fig. 7 shows the DC households and electrical poles located along the road, which is supplied by an MV/LV distribution transformer (22kV/0.4kV) via AC/DC converters. The 50V DC voltage level was selected regarding the consumers in a rural area with various low power appliances and the possibility of PV integration in the future [16]. Moreover, detailed information on load was provided in [12].

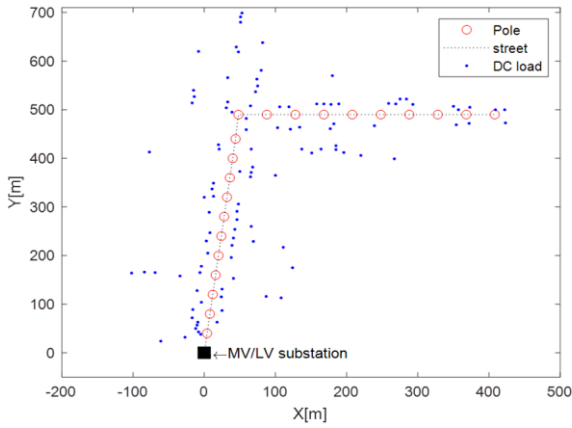


Fig. 7. Study case: low voltage distribution network

3.2. Simulation results and discussion

By applying the K-means clustering technique, all DC loads are grouped into an optimal number cluster $K=11$ as shown in Fig. 8. This number K had a significant effect on the final result. The more the number of cluster K is, the less the length of clusters is. Fig. 9 shows the MST ensures the minimum DC cable's length of each cluster and its total length of clusters is 4717m added by 854m of total DC connection's length from clusters to poles. As a result of $K=11$ clusters, 11 AC/DC converters have been mounted on the poles as well. The connection between clusters and poles were shown in table 1.

Table 1. The connection between clusters and poles

Clusters number	23	24	25	26	27	28	29	30	31	32	33
Poles number	2	4	5	7	10	17	13	16	13	18	21

Fig. 10 shows the complete AC/DC radial distribution system. The three-phase 4 wire feeder supplied DC loads via AC/DC converters. As a result, after the AC load flow, we checked the voltages for the cross-section of the mainline starting from 50mm². The voltages of the cross-section 50mm² did not respect to the voltage constraint. Then, the cross-section was increased to 70mm² and the voltages were improved. All voltages were satisfied with the constraint ($V_{min}=0.9pu$), hence, the cross-section of the AC main line of 70mm² was selected with a total length of 2809m.

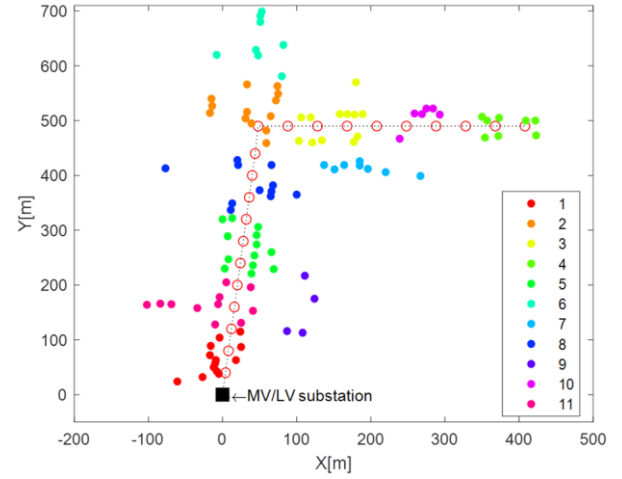


Fig. 8. Households grouped by K-means clustering technique

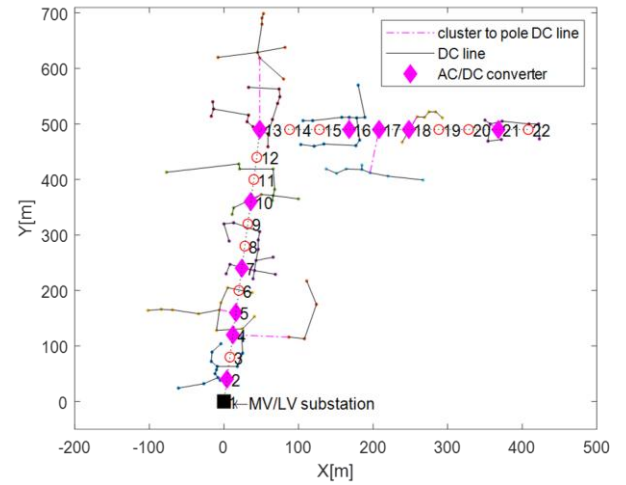


Fig. 9. Application the MST to each cluster and connection to poles

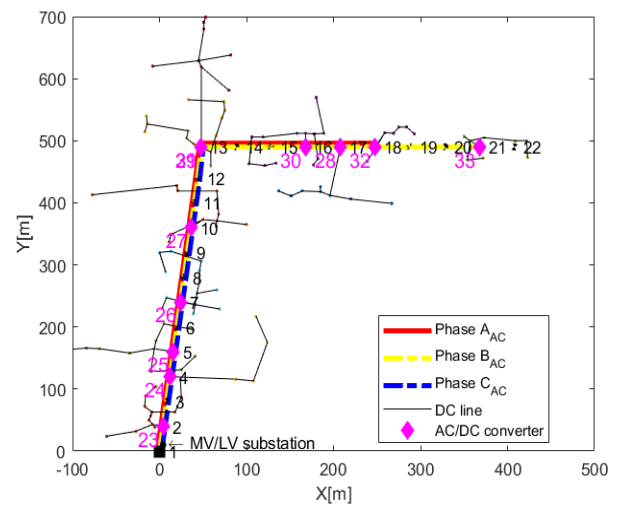


Fig. 10. Radial AC/DC low voltage distribution system

The summary result of the simulation is shown in Table 2. Due to the MILP algorithm, the power of each phase is almost balanced.

Table 2. Summary of simulation results.

Items	value
Number of clusters	11
Total length of AC main feeder Cross-section of AC main feeder	2809m 70mm ²
Total length of DC conductor used in the clusters	4717m
Total length of DC line connection to poles	854m
Total power loss	5.39kW
Power on phase A, B, and C including DC losses	15.79kW, 15.78kW, 15.78kW

In addition, Fig. 11 shows the AC voltage profile of poles as well as clusters. On the pole 21 which is connected to the cluster 33, the lowest voltage was 0.92pu respecting the standards on the LV system in Cambodia which is [0.90pu, 1.06pu].

Furthermore, Fig. 12 shows the percentage of deviations on each cluster. The voltage of all DC loads was classified by clusters. The central red mark indicates the median while the bottom and the top edges of the box indicate the 25th and 75th percentiles of the cluster. The lowest and highest voltages are also indicated. For the example of cluster 5, the median was 0.958pu and the bottom and top edges are 0.94pu and 0.975pu. Also, the lowest and highest voltages are 0.901pu and 0.988pu respectively. However, we noticed that the lowest voltage is in cluster 5 that respects the voltage constraint ($V_{min}=0.9pu$).

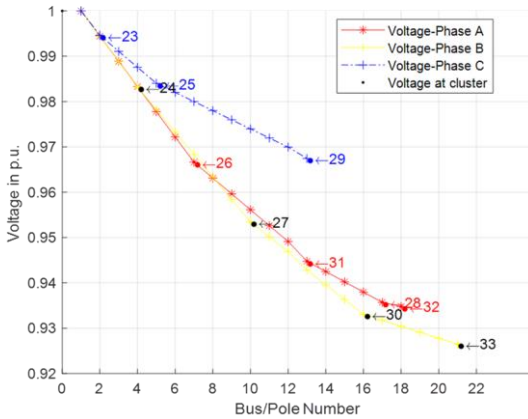


Fig. 11. AC voltage profile of poles and clusters

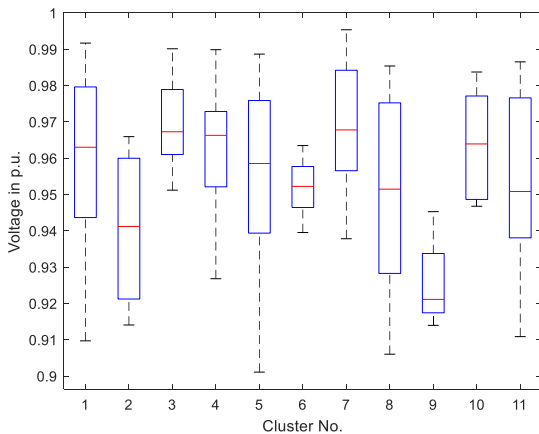


Fig. 12. Summary of DC voltage of each cluster with a box plot

Fig. 13 shows the total power over the day where the peak load was at 19h. Indeed, the total power losses were 5.39kW (about 12.5% of the total power) that include the AC and DC power losses. The power losses on the AC side depend on the balanced powers between phases and the cross-section of main lines while, DC power losses depend on the DC structure of clusters as well as, on how many DC loads are connected. Additionally, the connection between clusters and poles was another factor affecting losses. The voltage level of the DC system was a significant factor in losses as well.

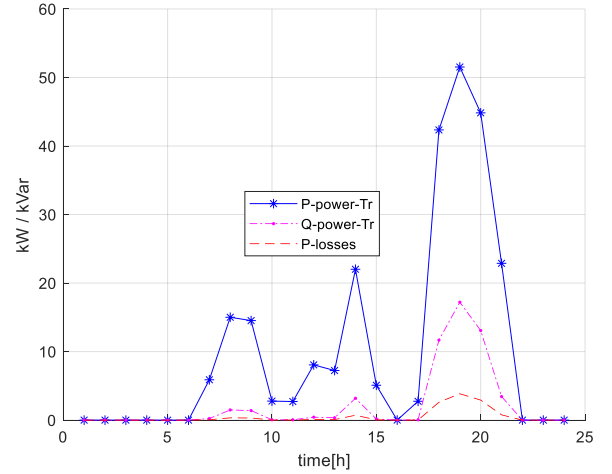


Fig. 13. Total power over a day

4. CONCLUSIONS AND PERSPECTIVES

This paper addresses a novel algorithm to deal with the growth of DC loads and the traditional AC distribution network by proposing a novel architecture of AC/DC microgrid. The K-means clustering has been used to pack DC loads into the optimal number of the cluster. The MST ensured the minimum length of all clusters. Moreover, the allocated power of each phase was almost balanced by using the MILP solver. Lastly, the algorithm has found the topology of AC/DC microgrid. Though some indicators; length of AC and DC conductor, number of clusters, and total power losses, were found, the cost of the system would be computed for a planning duration of 20 years to evaluate the benefit of using the DC structure instead of a complete AC structure. In future work, the total cost of the AC/DC microgrid will be investigated as well as other clustering techniques. Likewise, the sitting and sizing of PV and storage in the cluster of the AC/DC microgrids will be determined.

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