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A framework for optimal clustering of a greenfield distribution network area into multiple autonomous microgrids

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Abstract

Microgrids (MGs) are recognized as cores and clusters of smart distribution networks. The optimal planning and clustering of smart low-voltage distribution networks into autonomous MGs within a greenfield area is modeled and discussed in this paper. In order to form and determine the electrical boundary of MGs set, some predefined criteria such as power mismatch, supply security and load density are defined. The network includes an external grid as backup and both dispatchable and non-dispatchable Distributed Energy Resources (DERs) as MGs resources. The proposed strategy offers optimum sizing and siting of DERs and MV substations for the autonomous operation of multiple MGs simultaneously. The imperialist competitive algorithm (ICA) is used to optimize the cost function to determine the optimal linked MG clustering boundary. To evaluate the algorithm the proposed method is applied to a greenfield area which is planned to become a mixed residential and commercial town. The MGs' optimal border, DERs location, size and type within each MG and LV feeders route are illustrated in both graphical and tabular form.

Keywords: Distribution Network Clustering, Autonomous Microgrid, Distributed Energy Resources (DERs) Supply-Security, Imperialist Competitive Algorithm (ICA)

1. Introduction

Engineers dealing with electric system planning and operation problems must consider system upgrade deferral, energy and power loss reduction and reliability improvement. In recent years engineers have tended to partition existing distribution networks into multiple small networks, which are called Microgrids (MGs). MG is a distribution system involving a group of loads, DER storage units and may connect to other MGs and upstream distribution grids [15]. The main benefits of MGs are improved reliability, resiliency, power quality, diversification of energy sources and lower cost [6, 12, 21, 28]. Proper design of MGs to achieve technical and economic benefits is important for utilities [30, 10, 25, 11, 17]. Reliability and supply security have a considerable effect on system performance and provide the main focus of interest of power system planners and operators [27, 14]. In the literature evaluating the reliability of active distribution networks has been discussed [8, 13]. However, from the MGs point of view, reliability and supply security issues are relatively new subjects in the fields of planning and operation. They have not been properly addressed in the MG planning stage and they must be factored in for successful operation of MG in islanded mode. Some approaches have been presented on cluster distribution networks in respect of a set of MGs, with multiple scenarios considered [29]. In other papers, algorithms are presented in terms of MG design, taking account of reliability and security criteria. To the author's knowledge and belief, most of the research related to MGs has been conducted on existing networks, in attempts to resolve technical and economic problems such as loss reduction, differing system upgrade, reliability improvement and so on by partitioning the network into MGs in order to use them to enhance the efficiency of conventional grids [5, 24, 9, 18, 7]. The studies in [26, 16] present methods for optimal location and sizing of DER units. Moreover, they developed approaches to determine optimal combination of different types of DERs in MGs based on reliability and economic criteria to maximize benefits and satisfy technical indices. In [20, 31], the authors present methods for MG optimal planning and design for a combined utilization of cooling, heating and power considering economic and emission criteria. The study in [32] explores new applications for generation expansion planning using agent-based simulation in MGs. A multi-agent planning model is pro-

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posed to maximize MG payoffs and to alleviate environmental obligations in energy markets. In [4], the authors present a method for MG planning by investigating the economic rationality of MG deployment and giving the optimal combination of DER units for installation, taking into account multiple uncertainties that affect the optimality of planning. In [19], they studied the planning of MGs, considering their interconnection to improve reliability, and presented an innovative approach by applying a probabilistic minimal cutest based iterative methodology for interconnecting and power sharing between MGs. A clustering-based method is considered for analyzing the variable data related to renewable energy resources. After reviewing previous works on MG planning, it is evident that many of them are limited: they studied existing networks and tried to develop approaches to optimize them by transforming the operating network to an MG, or simply studied its operation problems. In the literature, existing studies overlooked MG-based planning to design the network from the initial step to be based on MGs. But in this paper a method is proposed to design a distribution network based on MGs from the first step of the design phase to meet all energy demands of customers, considering supply security and reliability constraints, and to have most characteristics of modern networks. We developed an approach to design a distribution network which is basically composed of autonomous LV microgrids, and determined their optimal service area. These MGs are parallel and connected to an upstream MV distribution network that acts as a backup for the planned MGs. The optimal combination of different types of DERs for each MG to minimize the investment cost will be presented. In the proposed algorithm, the first step is to evaluate a greenfield site where there is no distribution network operating: only load points are determined and their demand is forecast. Then different kinds of DERs are located there, MGs are formed and service areas are determined; based on the boundary of each MG the total power amount and the capacity of backup source at PCC (MV/LV transformer) is specified, considering certain criteria we designed. The proposed planning and design method will present a set of multi-autonomous MGs, which constructs a distribution network at optimum cost, supply security and adequacy to benefit consumer, utility, environment and satisfy the IEEE1547-2011 standard related to MG structure. We provide a method to minimize all fixed and variable costs, while considering the main technical constraints of a modern distribution network. ICA is used to solve the planning problem in an optimal manner [23, 3]. Finally, to evaluate the presented method, we applied it to a real case with all real and forecast data.

2. Microgrid designing concept

The distribution system is the final stage in the power delivery system, carrying electricity to feed individual consumers. The main function of a secondary (LV) distribution network is to feed all load points with maximum reliability and power quality indices. Accordingly, planning is a difficult problem for a distribution network planner to solve, because the network must satisfy numerous technical, economic and geographical constraints. In recent years, engineers dealing with distribution network planning have been confronted with problems related to increasing penetration of DERs, which has been a game-changer. In conventional network planning, we consider some constraints and candidate locations to find the best location for substation placement, then find the best route for feeders. But when DERs are taken in to account, the topology changes and the network structure will not be radial. Moreover, the costs of network expansion, reinforcement and energy are so high now that they must be considered in the planning stage. One of the solutions to this problem is to construct MGs or to partition off an existing network to MGs to diversify energy resources and postpone the system upgrade so as to achieve technical and economic advantages. In this work, an approach to designing and planning a network from the first step is presented that can meet the cases discussed previously. Our decision variables are DERs, MV/LV substations and MGs service area. The defined cost function involves fixed and variable costs of LV feeders and DERs. Also the optimal capacity of PCC (MV/LV transformer) for each MG will be determined. The proposed cost function is (F_t):

$$F_t = \sum_{\mu=1}^{N_{MG}} \left(F_{DER_{MG(\mu)}} + F_{LVF_{MG(\mu)}} \right) \tag{1}$$

Terms of cost function are defined in the following sections.

3. Proposed planning model

To apply the proposed algorithm to a given area, the first step is to collect the required geographical information and technical data. Precise load forecasting data is important: the data are used to partition the area into square load blocks and the load gravity center of each block is located at the central point of the block. The service area is constructed of several load blocks with different demand levels. Next, DER installation candidate locations must be selected. Assessed by decision variables, some of the candidates may be selected for DER installation, then load blocks must be assigned to each selected DER using the K-Means clustering method and through this algorithm, the area covered by each source will be defined. The algorithm has the following stages:

3.1. Load allocation

The load assignment algorithm using clustering methodology can be explained in steps. First, MD, product of max demand of each block and its distance to each selected DER's location is needed:

$$MD = MaxDemand \times Dist \tag{2}$$

$Dist$ =distance between load point and a selected DER location

Then if MD satisfies the constraints below, then the corresponding DER site will be kept:

$$\begin{array}{c} D \cdot P_k \cdot Dist_{ik} < MD_{max} \\ D \cdot Dist_{ik} < Dist_{max} \end{array} \tag{3}$$

where

$$Dist_{ik} = \sqrt{(x_i - x_k)^2 + (y_i - y_k)^2} \tag{4}$$

$$MD_{max} = \frac{V_{max}}{100} \cdot \frac{1000 \cdot V^2 \cdot \cos\varphi}{R \cdot \cos\varphi + X \cdot \sqrt{\left(1 - (\cos\varphi)^2\right)}} \tag{5}$$

"$D = 1.6$" is correction factor for direct path based on [23] which is used to obtain a real distance between point i (DER$_i$) and k (load$_k$) and V_{max} is max voltage drop (percent) and V is the LV feeder voltage. Resistance R and reactance X are the parameters of the feeder. Now, for each load point, DERs must be sorted by Distance, then loads will be assigned to the nearest DER site considering the following constraints:

$$\left(\sum_{k=1}^{N_{Li}} P_k\right) < P_{max\,DER_i} \cdot LF_{ave\,DER_i} \tag{6}$$

i belongs to a set of selected DER sites. LF_{ave} can be calculated by:

$$LF_{ave} = \frac{total\,annual\,energy}{annual\,peak\,load \times 8760} \tag{7}$$

To ensure that all load points are fed by a certain DER, the following constraint must be satisfied:

$$\sum_{i=1}^{N_{DER}} N_{Li} = N_L \tag{8}$$

To avoid not supplying the load point, a penalty is defined, to be multiplied by the number of loads not served.

3.2. Clustering

K-Means clustering is a method of grouping items into "N" groups. Grouping is done by minimizing Euclidean distances between items and the corresponding centroid. By applying K-Means methodology to cluster load blocks, N_{Li} blocks which are supplied by i-th DER, will be clustered to N_i groups related to i-th DER and N_i is obtained using:

$$N_i = ceil\left\{\sum_{j=1}^{N_{Li}} P_j / \left(\sqrt{3} \cdot V \cdot I_{max} \cdot \cos\varphi_{DER_i}\right)\right\} \tag{9}$$

3.3. LV feeder cost modeling

To obtain costs related to LV feeders, the following function is used which contains variable and capital costs (in cost modeling for feeders and DERs, all costs are in USD, then to apply them to main cost function, they are changed to the Iranian Rial Rate "IRR" using currency exchange factor "CE"):

$$\begin{aligned} F_{LVF_{MG(\mu)}} = \Big[\textstyle\sum_{i=1}^{N_{DER}} \sum_{c=1}^{N_i} \Big(D' \cdot C^{Cap}_{LVF,ic} \cdot Dist_{ic} + \\ + \frac{R_{ic} \cdot i_{LOSS,ic} \cdot f_{ELC}}{3000 \cdot V^2 \cdot (\cos\varphi_{ave})^2_{ic}} \cdot 8760 \cdot T + \\ + \textstyle\sum_{k=1}^{N_{L,j,i}} \Big(D' \cdot C^{Cap}_{LVF,kic} \cdot Dist_{ck} + \\ + \frac{R_{jk} \cdot i_{LOSS,ck} \cdot f_{ELC}}{3000 \cdot V^2 \cdot (\cos\varphi)^2_{ick}} \cdot 8760 \cdot T\Big)\Big) \cdot CE \cdot B_{di}\Big] \end{aligned} \tag{10}$$

$$i_{LOSS,ic} = D' \cdot \left(\sum_{k=1}^{N_{L,c,i}} P_k\right)^2 \cdot Dist_{ic} \tag{11}$$

$$i_{LOSS,ck} = D' \cdot P_k^2 \cdot Dist_{ck} \tag{12}$$

$$(\cos\varphi_{ave})_{ic} = \frac{\sum_{k=1}^{N_{L,c,i}} P_k}{\sum_{k=1}^{N_{L,c,i}} \frac{P_k}{(\cos\varphi_{ave})_{ick}}} \tag{13}$$

"$D' = 1.13$" is correction factor for indirect path based on [23] which is used to obtain a real distance between point c (cluster) and k (load block).

3.4. DER cost modeling

To obtain the capacity of each DER unit selected among candidates for installation, it must be at least the sum of the loads which are assigned to it. The load amount served by a DER can be calculated by:

$$L_{DERi} = \sum_{k=1}^{N_{L,i}} P_k / LF_{ave} \tag{14}$$

To model the cost of DER, fixed and variable costs related to each type of DER are considered using the method in [1, 2]. Cost function is:

$$F_{DER_{MG(\mu)}} = \sum_{i=1}^{N_{DER}} \left(\left(C^{Levelized}_{DERi} \cdot P_{DERi} \cdot CE\right) \cdot T \cdot 8760\right) \cdot B_{di} \tag{15}$$

$$\begin{aligned} C^{Levelized}_{DERi} = \frac{C^{Cap}_{DERi} \cdot f^{Cap}_{rec.} \cdot (1 - C_{tax} \cdot C_{Dep.})}{8760 \cdot f_{DERi,cap.} \cdot (1 - C_{tax})} + \\ + \frac{C^{Fixed}_{DERi,O\&M}}{8760 \cdot f_{DERi,cap.}} + \frac{C^{Var.}_{DERi,O\&M}}{1000} + \frac{C_{DERi,fuel} \cdot H_{DERi,rate}}{1000000} \end{aligned} \tag{16}$$

$$f^{Cap}_{rec.} = \frac{D_{rate} \cdot (1 + D_{rate})}{(1 + D_{rate})^{l_t} - 1} \tag{17}$$

3.5. LV network clustering to multiple autonomous MGs

After previous stages, it is time to divide and cluster the whole network as smaller networks. It is considered that all MGs should have a core dispatchable source to supply their critical loads with higher reliability. In this paper, core DERs are assumed to be Combined Heat and Power (CHP) or Fuel Cell (FC) units. DER candidate locations are provided by the taskmaster. In our proposed method, after optimal location of DERs in the given area and load assignment, according to core units, considering the distance between non-dispatchable DERs which are placed in the field and the core DERs, microgrids are constructed by a dispatchable and some non-dispatchable DERs according to predefined criteria. Then all load blocks supplied by these sources, determine the service area of each LV microgrid in distribution network. Next, the load gravity center of each MG is calculated to place the MV/LV transformer as PCC in that location.

4. Imperialist competitive algorithm optmization process steps

In brief, the ICA optimization algorithm used in our proposed method can be listed in the following steps [23, 3]:

Step 1. An initial population called country is needed to start. A country is a set of socio-political characteristics. Each country corresponds to one of the decision variables of the distribution network planning problem.

Step 2. For each country, only DERs with value 1 are kept. Then the connectivity is checked, if it was not connected, a new country must be generated and substituted for it. This process is continued until all the generated countries are connected [22].

Step 3. For each country the cost function is calculated. Then countries are sorted according to obtained costs. Some countries are chosen as imperialist from the set of countries with the lowest cost. Then colonies are allocated among imperialists, mainly under the influence of their power.

Step 4. Every colony will move towards its imperialist, then the value of a colony belonging to an empire can be calculated.

Step 5. A set of colonies related to an empire is randomly selected, revolved, and then new ones are generated. The generation process is like the previous steps.

Step 6. Cost function will calculated for every colony in each empire. The lowest cost is compared to the cost of the imperialist. If it is lower, it will be replaced by the imperialist.

Step 7. Similar empires are combined. To do this, the Euclidean norm of distance between every two imperialists is calculated and if it is less than a pre-defined value, then the two empires are combined. The imperialist with the lower cost is selected as the new empire's imperialist and the two set of colonies are assigned to the new empire as its colonies.

Step 8. Each empire tries to win a colony; a powerful empire has more chance to win a colony. During the competition process, if any empire remains with no colony it will be collapsed and the imperialist will be assigned to the selected empire as a colony.

Step 9. The process will continue until only one empire remains or the maximum number of iterations is reached. All of these steps are shown as a flow chart in Fig 1.

Table 1: Parameters used in developed software

	Parameters	
1	Planning Period, years	8
2	LV Voltage, kW	0.4
3	Energy loss cost factor, f_{ELC}, IRR/kWh	800
4	Tax rate, C_{TAX}	0.392
5	Discount rate, D_{rate}	0.07
6	Currency Exchange	30,000
7	Number of Countries, N_c	30
8	Assimilation Coefficient	1.1
9	Number of imperialists, N_I	3
10	Revolution Rate, R_{rev}	0.2
11	Colonies cost coefficient, Co_{cost}^{colony}	0.02
12	Life time, l_t, years	30
13	Number of Decades	150

5. Case study

Without loss of generality, the proposed planning method can be used to form autonomous and non–autonomous multiple MGs. In this paper the autonomous case is studied in detail. The boundaries of each MG are determined using some predefined electrical, economic and geographical constraints with minimum cost using ICA. For each MG the supply area of DERs and MV substation (as MG's PCC) is determined. In this paper, we design a distribution system based on autonomous LV microgrids which satisfies the IEEE1547-2011 standard related to MG structure. Our proposed method is applied to a greenfield site which is planned to become a mixed residential and commercial town. All loads are considered as maximum forecast value and DER's output power is assumed to be its expected output power value. After gathering all required data, the area is divided into 50×50 meter load blocks (Fig 2). According to the data prepared by the taskmaster, total forecast load is 3778.72 kW with 0.9 power factor and suitable candidate locations for installing each type of DER units specified (Fig 2). For the given algorithm we used 4 types of DER units, Wind Turbine (WT, type2), Photovoltaic cell (PV, type 3), FuelCell (FC, type 4) and CHP (type 5). According to customers type (critical loads), to increase reliability, the candidate locations for dispatchable DERs are selected to be near these load points and, consequently, all MGs have at least one dispatchable DER as core source. It is assumed that our grid is a smart grid, all required communication infrastructures are prepared, customers will use smart meters and all of them are engaging demand response programs or load control programs to curtail their load at critical times. All parameters used in the developed software are shown in Table 1.

The cost parameters related to levelized cost of energy are the values published in [1]. Assumed average annual load factor is 0.8 for DERs and transformers. Power factor for LV loads is 0.9. LV feeders. Impedance is considered as

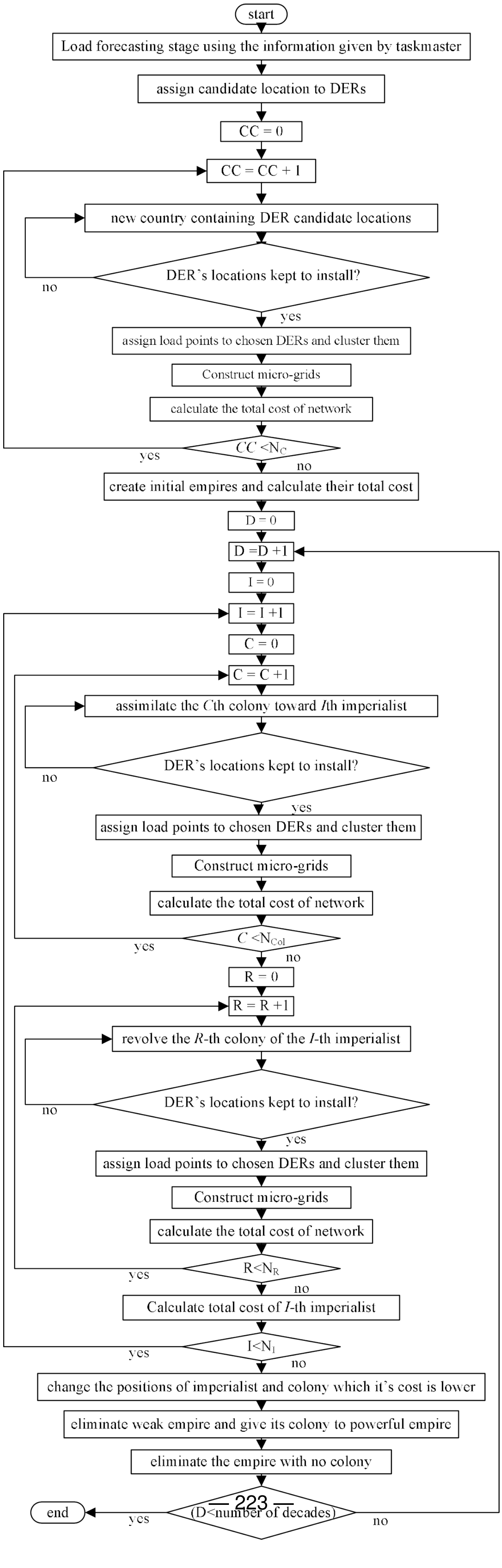

Figure 1: Proposed Method Flowchart

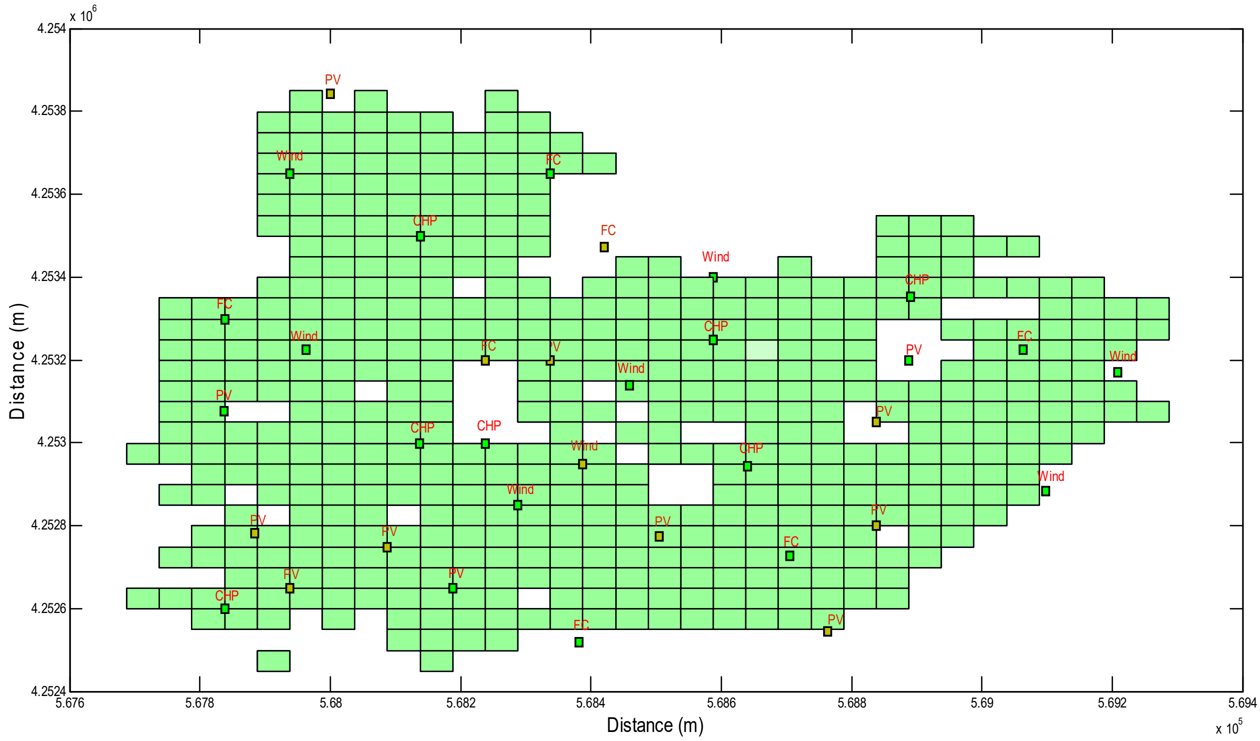

Figure 2: Proposed Method Flowchart

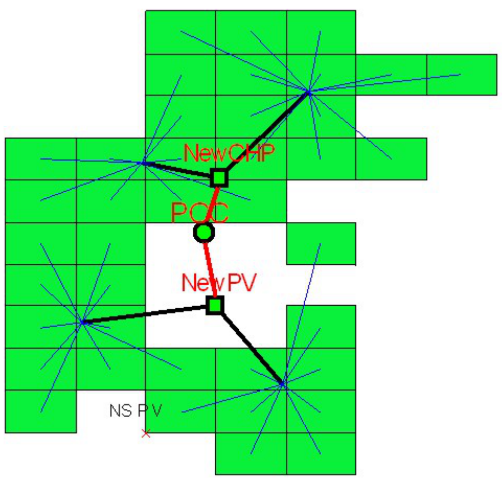

Figure 3: Proposed Method Flowchart

0.2116e-3+j0.08e-3 Ω/m and their maximum current, I_{max} is 200 A. To test the correctness of the proposed method and accuracy of the developed software, two scenarios are evaluated in this paper. First, the planning distribution network based on MGs, considering 100% DER penetration in network, $Dist_{max}$= 400 meter and taking LV network and DER units cost into account (Table 2). In second scenario, $Dist_{max}$ is increased to 800 meters to evaluate the effect of LV feeder length on the number of MGs in the network (Table 3). In the following figures and tables, the results of simulations are shown in detail. Figures 3 and 4 show the given vacant green field which is partitioned into autonomous LV microgrids according to the considered scenarios, and all MG loads, DERs and their capacities are provided in Table 2 and 3. Also, best capacity for MV/LV transformers as backup source for each autonomous MG is determined. Also in Table 4, the locations of PCCs are given (PCC capacity is determined to supply at least critical loads connected to core DERs plus expected loss of load. Expected loss of load is obtained by Binomial Distribution and the probability of a unit failing is assumed to be 0.02). By paying attention to figures, each MG service area is specified with a color, also in every MG, energy resources and load blocks connected to them are indicated, for example in Figure 5, a sample MG is shown (one of the microgrids in the first scenario presented by Figure 3) , its service area has a certain color, its dispatchable (core) DER is CHP (presented by "NewCHP", which means that candidate place is selected to install a new DER unit in the area), MGs' non-dispatchable DER is PV (presented by "NewPV"), all load points are assigned to a DER and "NS PV" in figures, meaning there is a candidate site to install a PV unit but it was not suitable according to the developed software. Bold lines connect the cluster's centroid to related DER and thin lines connect load points to a centroid. PCC indicates the MV/LV transformer optimum installation location and capacity. Also it is connected to DERs located in MGs, to be a back up source for their loads. To explain the results presented in each table, you can consider MG number 2 in Table 2 (second row of the table), in the proposed area we have 34 candidate locations for DER installation, which are num-

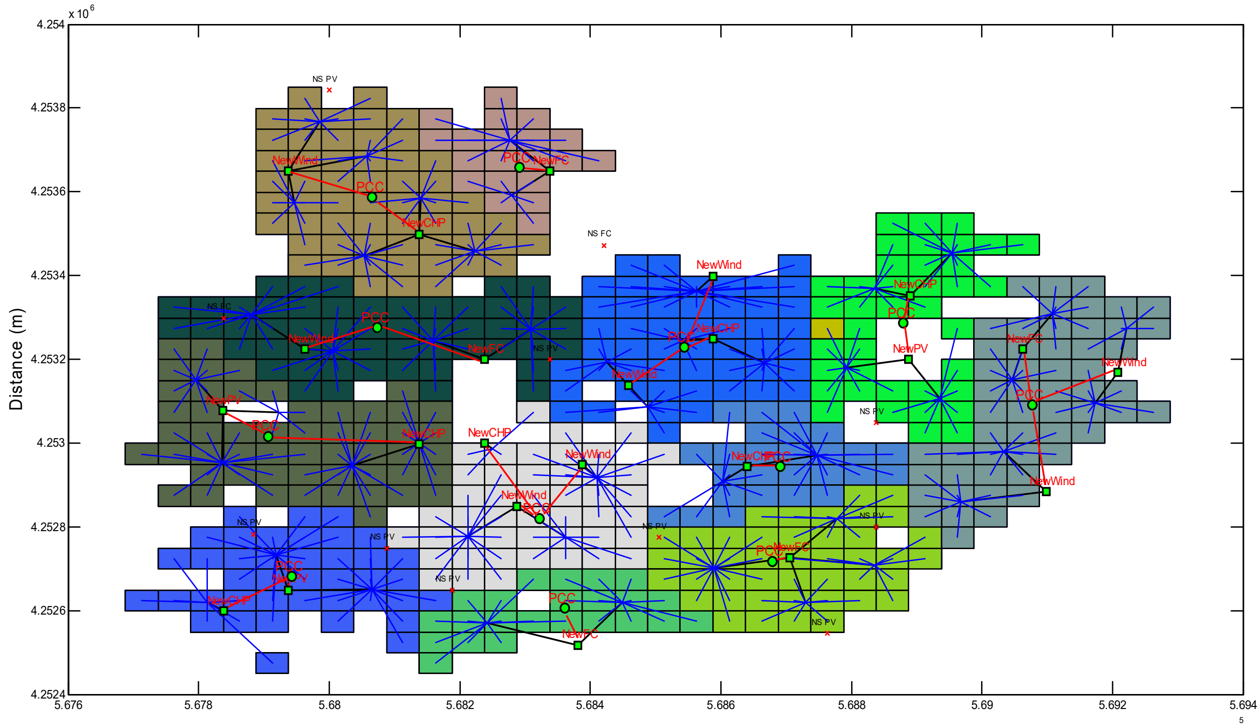

Figure 4: Proposed Method Flowchart

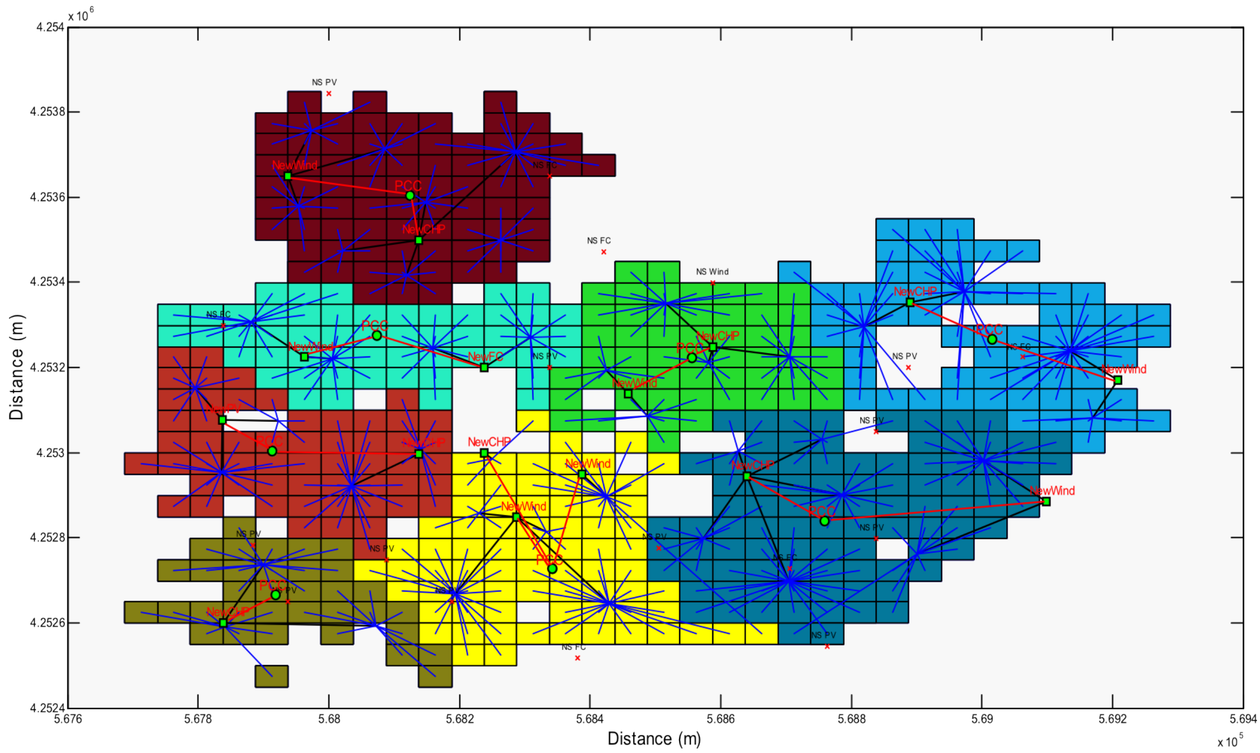

Figure 5: Clustering greenfield distribution network into multiple autonomous MGs (8 MG with specific electrical boundary)

Table 2: Microgrids Specifications

MG	MG's DER	DER Num.	DER Type	DER Real Load kW	DER Cap. kW	Expected Loss of Load kW	MV/LV Trans. Real Load kW	MV/LV Trans. Cap. kVA
1	Non-Disp.	1	2	192.4	250	7.67	144	200
	Core DER	11	4	136.1	175			
2	Non-Disp	4	2	107.2	150	8	128	200
		27	2	133.6	175			
	Core DER	13	5	119.8	150			
3	Non-Disp.	-	-	-	-	3.33	170	250
	Core DER	16	4	166.4	225			
4	Non-Disp.	28	3	280.32	375	11.2	145	200
	Core DER	17	5	133.5	175			
5	Non-Disp	8	2	71.6	100	10.2	23.9	50
		18	2	171.3	225			
	Core DER	21	5	13.7	25			
6	Non-Disp.	-	-	-	-	7.82	398.82	500
	Core DER	24	4	391	500			
7	Non-Disp.	12	3	120.9	175	6.04	157	200
	Core DER	25	5	151.2	200			
8	Non-Disp.	22	2	257.8	325	12	313	400
	Core DER	26	5	301	400			
9	Non-Disp.	3	3	220.1	300	8.74	75.2	100
	Core DER	29	5	66.5	100			
10	Non-Disp	5	2	134.9	175	8.07	127	200
		32	2	115.6	150			
	Core DER	30	4	118.8	150			
11	Non-Disp.	-	-	-	-	3.55	181	250
	Core DER	31	5	177.6	225			
12	Non-Disp.	-	-	-	-	3.95	201	315
	Core DER	34	4	197.4	250			

Table 3: Microgrids Specifications

MG	MG's DER	DER Num.	DER Type	DER Real Load, kW	DER Cap., kW	Expected Loss, of Load, kW	MV/LV Trans. Real Load, kW	MV/LV Trans. Cap., kVA
1	Non-Disp.	1	2	192.4	250	7.67	144	200
	Core DER	11	4	136.1	175			
2	Non-Disp.	27	2	133.6	175	9.92	259	400
	Core DER	13	5	249.2	325			
3	Non-Disp.	28	3	280.32	375	11.2	197	250
	Core DER	17	5	158.6	200			
4	Non-Disp	8	2	78.4	100	22.8	36.5	50
		18	2	385.5	500			
	Core DER	21	5	13.7	25			
5	Non-Disp.	32	2	217.8	275	8.75	227	315
	Core DER	25	5	218.7	275			
6	Non-Disp.	22	2	261.2	350	19.7	515	800
	Core DER	26	5	495	625			
7	Non-Disp.	-	-	-	-	4.76	243	315
	Core DER	29	5	238.2	300			
8	Non-Disp.	5	2	209.0	275	20.3	530	800
	Core DER	31	5	177.6	225			

Table 4: PCC (MV/LV Transformers) Location Coordination

	Scenario 1		Scenario 2	
MG Number	$X\cdot10^5$	$Y\cdot10^6$	$X\cdot10^5$	$Y\cdot10^6$
1	5.68	4.25	5.68	4.25
2	5.68	4.25	5.69	4.25
3	5.68	4.25	5.68	4.25
4	5.68	4.25	5.68	4.25
5	5.68	4.25	5.69	4.25
6	5.69	4.25	5.68	4.25
7	5.69	4.25	5.68	4.25
8	5.68	4.25	5.69	4.25
9	5.68	4.25		
10	5.69	4.25		
11	5.69	4.25		
12	5.68	4.25		

bered from 1 to 34 – for this MG, selected places are 4, 27 and 13. Results indicate that the constructed microgrid in its service area has two type 2 (wind) and one type 5 (CHP) DER. Connected loads to WTs are 107.2 and 133.6 kW and related capacities for these turbines must be 150 and 175 kW respectively (considering power factor). Also for core DER, total connected load is 119.8 kW and its capacity must be 150 kW. Expected loss of load for this MG is 7.999 kW. Then the best capacity for the back up transformer (PCC) is 200 kVA.

6. Conclusions

In this paper a framework for optimal clustering of smart LV distribution networks to multiple-MGs is proposed. Without loss of generality, planning can be applied to autonomous and non–autonomous multiple-MGs clustering. The boundaries of each MG are determined using some predetermined electrical, economic and geographical constraints, with optimal manner and minimum cost. For each MG the supply area of DERs and MV substation (as MGs PCC) is determined. This paper designs a distribution system based on autonomous LV MGs, taking into account supply security and economic parameters in the objective function to have an optimal network and satisfy the IEEE1547-2011 standard related to the MG structure. The proposed method is applied to a greenfield area (test case) and some scenarios are considered to test the developed proposed method and software accuracy. Based on the results, for each MG, the boundaries of MGs, the capacity of dispatchable, non-dispatchable DER, main grid and the capacity and supply area of each DER in each MG are determined. From the results it is shown that the number of MGs is changed by the maximum distance of

LV feeders. The number of MGs is increased when the maximum distance of LV feeder is decreased and, vice versa, the number of MGs is decreased when the maximum distance of LV feeder is increased. The planning method can help us to design and cluster a reliable and efficient distribution network into multiple MGs.

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Nomenclature

$(cos\varphi)_{ick}$ Power factor of k-th load of c-th cluster supplied by i-th DER

$(cos\varphi_{ave})_{ic}$ Average power factor of c-th cluster connected to i-th DER

μ MG's number

B_{di} Decision variable

$C_{Dep.}$ Depreciation value

$C_{DERi,fuel}$ Fuel price for DER unit (USD)

$C_{DERi,O\&M}^{Fixed}$ O&M fixed cost (USD)

$C_{DERi,O\&M}^{Var.}$ O&M Variable cost (USD)

C_{DERi}^{Cap} Capital cost for DG unit (USD)

$C_{DERi}^{Levelized}$ Levelized cost of energy (USD)

$C_{LVF,ic}^{Cap}$ LV feeder capital cost from i-th DER

$C_{LVF,kic}^{Cap}$ LV feeder capital cost for k-th load of c-th cluster connected to i-th DER (USD)

C_{tax}	Tax rate
CE	Currency exchange (US Dollar to IRR)
D_{rate}	Discount rate
$Dist_{ck}$	Distance between k-th load and c-th cluster (m)
$Dist_{ic}$	Distance between i-th DER and c-th Cluster (m)
$Dist_{max}$	Max distance or max feeder length (m)
F	Cost function
$f_{DERi,cap.}$	Capacity factor
f_{ELC}	Energy loss cost factor (USD/kWh)
$f_{rec.}^{Cap}$	Capital recovery factor
$F_{DER_{MG}}$	Cost of DER in MG (IRR)
$F_{LVF_{MG}}$	Cost of LV feeder in MG (IRR)
$H_{DGi,rate}$	Heat rate
$i_{LOSS,ck}$	Loss index for feeder from c-th cluster to k-th load point
$i_{LOSS,ic}$	Loss index for feeder from i-th DER to c-th cluster
L_{DERi}	Connected load to DG (kW)
LF_{ave}	Average annual load factor
N_{DER}	Number od DER units
N_i	Number of cluster
N_{Li}	Number of load blocks supplied by i-th DER
N_L	Total number of loads
P_{DERi}	DER rated capacity (kW)
P_k	Block demand (kW)
R	Line resistance (Ω)
T	Time period (years)
V	LV line voltage (kV)
V_{max}	Max voltage drop percent
X	Line reactance (Ω)
x	x coordinate of certain load or source point
y	y coordinate of certain load or source point