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ScienceDirect
Heliyon 00 (2018) 1–17
Heliyon
www.elsevier.com/locate/procedia

Optimal Routing an Ungrounded Electrical Distribution System based on Heuristic Method with Micro Grids Integration

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Abstract

This paper proposes a heuristic based model to find the optimal routing of an under grounded electrical distribution system in georeferenced areas. An efficient model was developed by graph search algorithm for network reduction with the minimum expansion tree was geared towards achieving entire users' connectivity. The model proposed compromises of a three layered algorithms. The first handles transformer allocation and routing of medium voltage network, the second algorithm works out the low voltage network routing and transformer sizing and the third presents a method to allocate distributed energy resources in an electric distribution system. In this research an array of rooftop photo-voltaic panels with a specific criteria was allocated. The model was tested in a georeferenced area and a sub-optimal solution was found, which was then tested through an electrical simulation software. The results of the planned system include a connectivity of 100% of end users, satisfied constraints of distance, number of users and voltage drops in the farthest point being less than 2 %. The optimization of power distribution network results in deployment and operational savings by reducing the path feeder, consequently, decreasing the power losses and avoiding the load imbalance in the network.

Keywords: Electrical Distribution System, Graph Theory, Micro grids, Heuristic, Optimization, Planning

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1. Introduction

The unpredictable increase in electricity demand has made challenging the design and planning of any electrical system in transmission or distribution level. Population growth, migration and city planning, lacked in big cities especially in third world countries, principally influence electricity demand. As a result, the conventional electricity planning methods in most of the deployed Electric Distribution Systems (EDS) do not formally consider the increase in the demand and therefore is mainly unplanned. Consequently, the electricity service throughout the network is unsatisfactory, with reliability, and stability problems in the entire system.
Nowadays, it is considered a necessity to integrate conventional EDS necessary with modern technologies, considered as for optimization, security, reliability, and energy efficiency. For instance, Micro Grid (MG)

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is the integration of optimal EDS with Distribute Energy Resources (DER), which are a promising solution for the implementation of Low Carbon (LC) Technologies in a conventional electrical system. Considering that the power generation industry is a considerable source of CO_2, therefore a growing number of EDS has connected to DER in order to follow the LC policies [1].
The LC policies suggest countries adopt clear and measurable objectives to reduce emissions. There are some research, which proposes an acceptable level of reduction. [2] proposed a model to reduce 80% of CO_2 emissions taking as based line 1990, and introduced the implementation of mitigation technologies, including DER in EDS. Figure 1, shows the percentages contributions of each technology in the reduction of emissions. Special attention is focused on the electricity decarbonisation, smart growth and rooftop PV. The first technology is mainly the integration of renewable energy, which is composed of 90% CO_2 free technologies. The second involves the optimal planning of EDS and the transportation systems. The third constitutes of rooftop PV implementation in residential and commercial buildings considering 10% of electricity demand should be reduced by the implementation of rooftop PV.

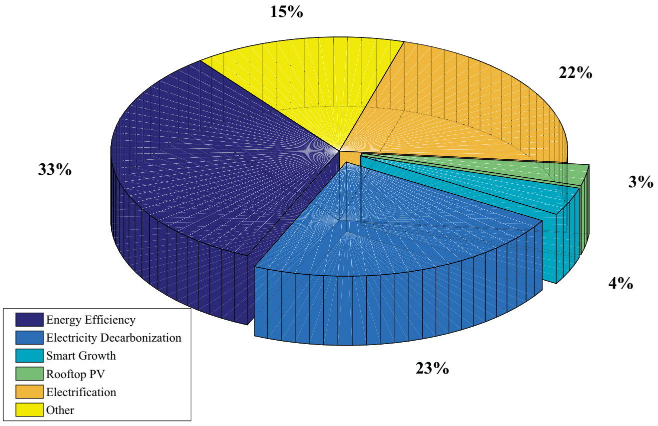

Fig. 1. Percentage of CO_2 reduction contribution of DER implemented in a EDS. Cite: Author

In order to implement a Smart Grid (SG), the system requires firstly to satisfy the requirement of security and, reliability via technical planning. For the two main reasons listed below an EDS planning must be optimal and technically adequate, the close proximity to the customer and the investment cost compared to the entire network [3, 4, 5]. Moreover, the planning of hybrid electrical systems with micro-grids integration in a real area implies several variables, including the complexity in computational time to be obtained with linear programming. Due to these particular considerations, the raised problem is not trivial. As result, the problem must be solved by applying heuristic models.
Several researchers have developed models to find the best topology through the optimal planning of EDS. For instance, [6] is one of the first to have presented a detailed overview of expansion planning models, compared the different mathematical techniques describing the objective functions, constraints, the programming technique, and the pros and cons associated with the model.The approach is commonly used in wireless communication, Inga et al. [7], [8], [4], [5] proposed a hybrid wireless mesh network infrastructure considering a multi-hop system which is planned for electric consumption metering in a metropolitan area network, thereby performing an advanced metering infrastructure for use in MG.
[9] proposed a critical analysis to integrate the radially as a constraint in an optimization model of an EDS, and [10] proposed a mathematical procedure for modelling the radially. Both studies recognize that the radially constraint is a heavy burden to implement in any model. Other researches have proposed that the problem can be solved using a combination of algorithms, including heuristics to find a good initial solution and then apply the result to a deterministic mathematical optimization, [10]. In [11, 12], [13], [14], a proposed implementation of Minimal Spanning Tree (MST) to minimize the energy supplied by Medium

voltage (MV) in an EDS. In [11] algorithm allowed graphing compression, leading to savings in computing time. [15] also tackled the active power loss minimizing problem using MST.

Optimizing the feeders' routes for MV is done through simulated annealing algorithm in [16], where is proposed a three stages methodology. Another research [17] describes a heuristic based algorithm with the objective of minimizing the power loss using reconfiguration of EDS. [18] used the complex network analysis and graph theory to explain the properties of a topology that are implemented in the real world. Here, the paper exposed their mathematical representation. In [19] describes the network design problem with the first multilevel cooperative tabu search for the capacitated multicommodity. [20] proposed a model to optimize low voltage distribution transformers, considering size, quantity, and siting. In this research an adapted genetic algorithm is applied. The application of heuristics methods in a Geographic Information System (GIS) is investigated in several technological areas, for instance, the introduction of more flexible technologies in urban areas [21]. Whilst, [22] and [23] study the penetration of DERs in an implemented photo-voltaic systems. This problem in [24] is solved through a modified Particle Swarm Optimization (PSO), which included a new mutation method to improve the global searching thereby avoiding the local optimum. In [25] applied the local search heuristics representing the EDS as a spanning forest problem. The proposed algorithms are based on the research of the shortest spanning sub tree and connection network, originally proposed by [26][27].

A model is required to achieve total users' connectivity. In order to do that a minimum expansion tree is applied to form the radial topology, typical of an EDS in MV and LV. By this methodology, the power balance in the network is achieved automatically, as well as, the scalability requirement is guaranteed, whenever further residential or industrial loads are required to be connected to the system. To test the model, it is applied in a georeferenced area, where all the elements of the network are represented as nodes. Aside from the map information like streets, roads, and natural features of the selected region, this representation includes homes, LV transformers and substations.

The present paper presents a mathematical model that represents a combinatorial problem, which includes the cost minimization as objective function and constraints of capacity, distance and voltage profiles. From the mathematical model, the problem is NP-Complete and as a result, lacks a globally optimal solution. The solution of the mathematical model of an EDS planning is proposed as a routing problem which is approached through a complex network analysis and graph theory. Hence, it is necessary to perform a heuristic model that can reach a near optimal solution or sub-optimal solution [24]. The applied graph theory is multilayer; one of them addresses the problem of routing of Medium Voltage (MV), the second the Low Voltage (LV) network, and the third allocate the DER in the EDS.

The remainder of this article is organized as follows: section 2 presents the EDS Sizing and Planning with MG approaching. The problem formulation and simulation results are presented in section 3 and 4, respectively. Finally, in section 5 the conclusions, recommendations and future works.

2. EDS Sizing and Planning with MG approaching

DER and MG is an alternative to achieve a clean ecosystem by reducing emissions, boosting the local generation, continuous electrical service, decreasing the fossil foils dependence [28]. On the other hand, the electricity transportation is a serious concern due to the long distance from the generator to the end user. Therefore, the DERs are micropower generators that are close to the end user or in the same LV network, which avoids the power transmission, generally carried out in electrical networks [29]. The DERs are diverse such as biomass, solar or wind power, and small hydro generators. Those power sources are normally supervised and coordinated within an SG, growing the control and the subsequent security and reliability in the network. The advantage of introducing DER in MG are the less investment or infrastructure cost compared with the large generator implementation, reducing of the power level in transmission and distribution lines, decreasing the environment emissions, a less final cost in electricity bills [30]. At the same time, some requirement should achieve to integrate DER in a distribution network, for instance, power converters are needed to convert the DC power from DER, typical wind and PV generator, to AC power to deliver the generated energy to the network. The power converter performs the grid synchronization and ensuring the safety in the integration of DER [31]. Other requirements to DER implementation are related to the bidirectional of the network due the power flows to the generator to the end user and vice versa, hence the electrical protection has to replace accomplishing the mention specification.

An adequate EDS planning and sizing has the objective to guarantee the reliability and quality of energy if the demand increase, and assure that final plan has the best technical features with the minimum investment possible. Efficient design approach is imperative considering the growing cost of energy, equipment and materials, that connote the final investment cost in EDS, and it repercussions on the final user charge. Whilst the EDS administrator, handling EDS planning, has to analyze the inherent features of the future network, including the load peak magnitude and its geographic location, it is not an effortless commitment since there is not an instrument that helps in the planning process. Therefore, the constituted elements of a network must be sized and placed to adequately provide energy to fixed loads, minimize final expenditure, decrease the construction cost feeder loses, whiles satisfying the reliability constraints such as capacity, voltage profile and end user number. The solution of a mathematical EDS planning model compromise discrete and continuous variables. Discrete variables correspond to a logical decisions group that represents, for instance, the activation or deactivation of determined connections in the network; whiles continuous variables means the type or length of an electric conductor [32].

In accordance with the EDS features, the constraints can be subject to environmental, topological, regulatory and electric conditions [16]. For instance, the radial nature of the network is a topological constraint that avoids the loop between the nodes; or the resilience characteristic is an environmental constraint, which equips the network with the ability to reconnect after adverse events. In addition, if a system should satisfy conditions such as the underground or overhead implementation, it would be subject to regulatory constraints [33]. For analysis, EDS can be divided into the total or partial load or whether the system must behave as dynamic or static system, and how each affects the final achieved results is studied, thus these different approaches can simplify the model to facilitate the mathematical resolution. In addition, researches specify a portion of the planning instead of tackling the entire EDS and them include an increasing load in a dynamic trend [34][35]. To cope with the rising demand, it is possible to establish a target year to allow the varying of the load demand, taking into account that electricity demand is permanently on the rise.

The implementation of underground electrical network has gained popularity, as compared to overhead implementation, due the lower cost, the environmental concerns, the network security and safety toward eventualities. Besides, if underground facilities are properly planned can be established as a viable alternative for population expansion [36]. In order to analyze the implementation cost of an underground utility, it should be noted that the initial cost can be higher, compared with traditional implementation, however, it is important to carefully examine the cost and benefits in long term view, including efficiency and reliability [37].

The EDS is divided into Medium Voltage (MV) and Low Voltage (LV) networks, implemented in radial topology. The first transmits the energy to distribution transformers from the substation, and the second connects the transformer to the end-user. The MV network originates in the electrical substation, and feeds through branches to the located MV to LV transformers. The designed LV parameters considers the substation loading and rating, location and, area of service. Additionally, it also determines the amount and routing of primary feeders, the number and location of MV to LV transformers. Whilst, the LV network parameters again determines the parameters of each transformer to correspond to the end-user, such as the transformer loading and rating, conductor and size routing.

The EDS operation involves designing from different perspectives; it depends of the aims of the system. For instance, the system can be configured to improve the load balance, the voltage profile or reduce the losses. The EDS reconfiguration is performed through opening or closing switches that connect the branches in the system. In a real EDS system, the number of switches is considerable and therefore is impossible for the operator to determine the optimal configuration to solve the required objective [15]. Thus a procedure is required to develop the EDS optimization, which is not solvable due to the massive computational requirements. For this reason, graph theory is used with a heuristic model that reach a near optimal solution.

3. Problem Formulation

The Optimal Routing of Electrical Distribution Networks is defined as a NP-complete problem, to deal with it in this papers is used a heuristic model. The model is divided into three algorithms, the algorithm 1 solves the problem in MV network, while the algorithm 2 works with the resolution in LV network, and the algorithm 3 determines the allocation of the rooftop PV in the scenario. In the Table 1 the variables used in the model is presented.

Table 1. Parameters and variables

Nomenclature	Description
X	Latitude element coordinate point or points
Y	Longitude element coordinate point or points
ij	Point to point search variables
X_s, Y_s	Residential customer location
X_{np}, Y_{np}	Street nearest point to any customer
X_{se}, Y_{se}	Substation location
X_{be}, Y_{be}	Streets intersection or candidate sites location
X_{tr}, Y_{tr}	MV to LV transformer final location
XL_{st}, YL_{st}	Member Points of L street
SH	End user location
Ind	Optimal transformer index
N	Number of residential customers
M	Number of LV transformers
S	Number of substations
P	Total Number of subscribers N+M+S
$demN_N$	Individual customer demand
$demM_M$	Individual LV transformer demand
G	PxP connectivity matrix
$dist$	PxP distance matrix
$dist_N$	Distance from N customer to corresponding transformer
Cap	Number capacity constraint for all LV transformer
R	Distance constraint (m) for all LV connections
$Path$	Network connectivity route
$Pred$	Association end-user transformer
PVs	PV amount in the network
PVC	PV rooftop location
PVP	PV power assignation
C	Total customer connectivity in percentage
$CostMV$	Total distance (m) cost of designed LV network
$CostLV_M$	Distance (m) cost of M tranformer
$CostLV$	Total distance (m) cost of desgined low voltage network
$Comp_E$	Computational cost (seg) for each experiment
i,j,k	Counter variables for control loops
$flag, used, z$	Temporal variables
$Loc1, Loc2$	Temporal variables

The algorithm 1 has five steps. The first declares the variables, distance R and the capacity number Cap restriction, to zero or receives the georeference information from map, including the latitude and longitude of end-user, candidate sites and substation location. The information was taken from an OpenStreetMap (OSM) file, including the georeferenced information about the houses' shape, main routes, streets, public spaces, and more. The step 2 determines the optimal transformer selection using prim algorithm, which returns the number and transformer index of optimal configuration. The step 3 is responsible to find the nearest street point to customer, it is done tough the distance calculation of each end-user to the each constituted point street, and determining the closest point to each home, this solution has the same number as end existing users. The fourth step searches the optimal routing of MV grid, which used the haversine distance calculation to determine the distance between all elements in the network, after that, the connectivity matrix is calculated with the model restrictions, next the prim minimal spanning tree is applied to find the minimum rout. the fifth step determine the cost, that correspondent to the total distance of the elements of the MV network.

Algorithm 1 Optimal location and routing a MV grid network

```
procedure
Step: 1 Variables
    $P, distN, X, Y, Cap, R$
Step: 2 Optimal transformer selection
    $used \leftarrow prim(X, Y)$;
    $Ind \leftarrow find(sum(used) == 1)$;
    $X_{tr} \leftarrow X_{be}(Ind)$;
    $Y_{tr} \leftarrow Y_{be}(Ind)$;
Step: 3 Find nearest street point to customer
    $Loc1 \leftarrow [X_s Y_s]$;
    $Loc2 \leftarrow [XL_{st} YL_{st}]$;
    for $i \rightarrow 1 : N$ do
        for $j \rightarrow 1 : length(XL_{st})$ do
            $dist_{i,j} \leftarrow haversine(Loc1, Loc2)$;
            $z \leftarrow find(dist_{i,j} == min(min(dist_{i,j})))$;
        $EndFor$
    $EndFor$
    $X_{np} \leftarrow Loc2(z, 1)$;
    $Y_{np} \leftarrow Loc2(z, 2)$;
Step: 4 Optimal Routing MV grid
    $X \leftarrow [X_{np} X_{tr} X_{se}]$;
    $Y \leftarrow [Y_{np} Y_{tr} Y_{se}]$;
    $dist_{i,j} = haversine(X, Y)$;
    $G(dist_{i,j} <= R) \leftarrow 1$;
    $path \leftarrow prim_{mst}(sparse(G))$;
Step: 5 Determine the final cost of MV
    for $i \rightarrow 1 : length(X)$ do
        for $j \rightarrow 1 : length(X)$ do
            $costMV \leftarrow costMV + dist_{i,j}(path)$;
        $EndFor$
    $EndFor$
End procedure
```

The algorithm 2 determines the optimal routing of the LV grid network, which approaches the problem dividing the network in pieces of the transformer that serves to the end user customer. The solution is proposes in 5 steps as follow. Step 1 is similar as the algorithm 1 and aim the initialization or complete the needed information. The step 2 determines the distance between each end user with all solution transformer of algorithm 1. After that, the connectivity matrix is calculated, which considers the connectivity between the transformer and the substation is already done, and the connection from the substation to end-user is non available. Step 3 implement the dijkstra algorithm calculation, which find the optimal LV connections. Step 4 calculates the optimal rout of the corresponded elements to the transformer, the step individually considers the LV connections. Finally, the step 5 calculates the final cost that correspond with the final distance of conductor in LV network.

Algorithm 2 Optimal routing a LV grid network

```
procedure
Step: 1 Variables
    $P, distN, X, Y, Cap, R$
Step: 2 Determine the distance end user, transformer
    $dist_{i,j} = haversine(X, Y)$;
    $G(dist_{i,j} <= R) \leftarrow 1$;
    $G(1 : N, N + M + 1 : N + M + S) \leftarrow inf$;
    $G(N + M + 1 : N + M + S, 1 : N) \leftarrow inf$;
    $G(N + 1 : N + M + S, N + 1 : N + M + S) \leftarrow inf$;
Step: 3 Applying Dijkstra
    $Pred \leftarrow dijkstra(G, P)$;
Step: 4 Optimal Routing LV grid
    for $Trans \rightarrow 1 : N$ do
        $X \leftarrow [X_{np}(Pred)X_{Trans}]$;
        $Y \leftarrow [Y_{np}(Pred)Y_{Trans}]$;
        $dist_{i,j} = haversine(X, Y)$;
        $G(dist_{i,j} <= R) \leftarrow 1$;
        $path \leftarrow prim_{mst}(sparse(G))$;
    EndFor
Step: 5 Determine the final cost of LV
    for $i \rightarrow 1 : length(X)$ do
        for $j \rightarrow 1 : length(X)$ do
            $costLV \leftarrow costLV + dist_{i,j}(path)$;
        EndFor
    EndFor
End procedure
```

Finally, the algorithm 3 allows to determine allocation of the rooftop photo-voltaic panels in the houses, the houses percentage chosen is 10 %, based in the contribution of PV in MG. The algorithm gather, in the step 1, the end user coordinates in one array, after the PV amount is determining with the researched criteria and is stored in PVs, in the step 2. In the step 3 the center of mass is calculated though kmedoids algorithm, the scenario is divided into PVs variable clusters. In the step 4, the electrical power is assigned for each end user, the power for each rooftop is 10KV, the same for all the scenario.

Algorithm 3 Allocation of DER PV generator

```
procedure
Step: 1 Inizialization
    $X \leftarrow [X_s]$;
    $Y \leftarrow [Y_s]$;
    $SH \leftarrow [XY]$;
Step: 2 Determining PV amount
    $PVs \leftarrow floor(length(SH) * 0.1)$;
Step: 3 Determining the center of mass
    $PVC \leftarrow kmedoids(SH, PVs)$;
Step: 4 Power assignation
    $PVP \leftarrow 10KV$;
End procedure
```

4. Analysis of Results

The case study is part of the EDS of the area of Tytherington in the north of Macclesfield in Cheshire, England. The limits in longitude in the present study are -2.1360 to -2.1270, meanwhile, the latitude starts from 53.2730 to 53.2810, the total area is 1.15 Km^2. In the scenario, there are 813 loads with a total power of 5.4 MW. The presented model deploys the EDS, including the network planning expansion. Therefore, the model designs an efficient and reliable EDS, with the lowest investment cost. The network planning expansion allows to use the initial configuration and expanding the EDS with a short and medium time period. The model was developed with the algorithms one and two presented below, which was implemented in Matlab.

In the Table 2 are presented the simulation parameters used in the implementation. The selected area has a density of 700 end users per kilometer square, which is considered lower in comparison with the average density in the cities in Europe. The deployment requires a maximum distance of 100 meters from an end user to transformer, with a coverage of 100 % in the entire network. The installation type in both networks is under grounded and the configuration is radial in order to accomplish with the EDS requirements. The number of main feeders from the substation is one. Whilst, the voltage in the MV installation, between the substation and the transformers, is 11 KV, and the LV network voltage is 400V. Finally, the concentrated load is balanced in all the experimental procedure.

The studied georeferenced scenario is shown in figure 2. First, in order to analyze the designed network performance, the scenario was divided into six different clusters, the homes in the same cluster were outlining with the same colors. The division by clusters was made with the K-medoids algorithm. The clusters are numbered from 1 to 6 in clockwise, starting with the left upper with the number 1 and the located in the middle left is the 6. The power consumption of each home depends on the cluster membership, in the cluster 1 the average consumption is 300 KVA, whilst the average power in the cluster 2 is 400 KVA and the houses of cluster 6 the consumption is 800 KVA, correspondingly. The power assignment is random normally distributed, depending on the cluster membership.

The substation location is aleatory, where must exist enough space for the implementation of this building. It can be changed, and the optimum substation allocation is proposed for future work. The transformer candidate sites are shown in the graph as well. These sites are called manhole or checkup points. To find these points are considered all the corners or bifurcation points in any street, in total there are 314 checkup points. These points are the input of the prim algorithm with the desired maximum distance, therefore the prim algorithm output is the final transformer allocation.

A constraint in the model is the maximum distance between the end user and their corresponding LV transformer. The distance restriction is an input parameter in the prim algorithm, that decided the final transformer allocation. Thus, based on this distance parameter two scenarios are proposed, the first scene takes the restriction of 80 meters and the second 100 meters, and are called A and B scenario, correspondingly.

Table 2. Parameter of Model Simulation Model

Item	**Parameter**	**Value**
End user information	Density	700 per square kilometer
	Amount in study	813 in all study
	Location	Georeference
Deployment	Max transformer distance	100 meters
	MV Network transformer coverage	100 %
	LV Network end users coverage	100 %
MV network parameters	Installation type	Undergrounded
	Network configuration	Radial
	Number of primary feeders number	1
	Voltage level	11 KV
	Total power demand	5.4 MVA
LV network parameters	Installation type	Undergrounded
	Network configuration	Radial
	Voltage level	400 V
	Concentrated load	balanced

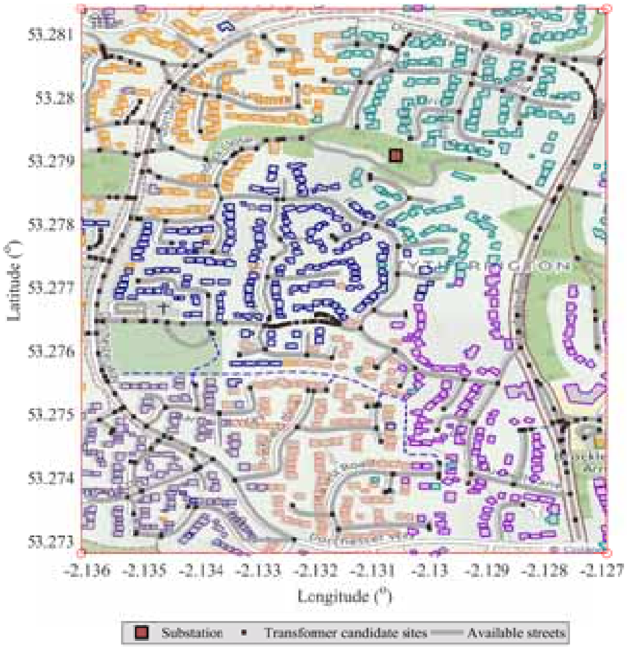

Fig. 2. Studied scenario with the transformer candidate cites and substation localization. The end user power consumption is represent with different colors depending on the cluster. Cite: Author

The optimization applying graph theory is based on the connectivity matrix. The connectivity matrix of the presented **A** scenario is shown in figure 3, where is seen a symmetrical square matrix of **N+M+S** elements. Where **N** is the number of end users, **M** is the number of activated transformers and **S** is the substations number. In order to find the connectivity matrix, the distance matrix is calculated, which shows in the graph represents the distance between homes to homes, homes to transformers, homes to the substation and finally transformers to the substation. The color in the matrix represents the distance, for instance, a dark color means a closer distance compared with a light color. Moreover, the white dots illustrates the possible connections between nodes, the white dots are located whether the restriction distance is accomplished. The number nz in the bottom of the figure is 8426, that represents the number of total connections in the studied scenario. There are two extreme fringes in the figure, the right and the bottom one, those fringes represent the connection between transformers and end users, notice that the form of the fringes changed respect from rest of the figure, mainly there are more white dots that means the higher connection possibility between transformers and end users, it is due the optimal transformer allocation. Besides, the principal diagonal consideration must be considered, because it represents the distance between the same node, and it must be changed for a greater distance in order to do not obtain erroneous model results.