Efficient Placement of Electric Vehicles Charging Stations using Integer Linear Programming

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***Abstract*—This paper presents an efficient optimization approach for the placement of electric vehicles charging stations within the road network. The approach is based on the integer linear programming technique for solving optimization problems. In this paper, the optimization problem is formulated as complex combinatorial problem with goal to find minimum number of strategically selected locations for charging stations which will enable covering of the route between each two nodes of the road network. The necessary input data are the road network configuration with distances and adopted electric vehicle autonomy. The input data are used for creation of the graph representing the road infrastructure with nodes as potential locations for charging stations. The application of proposed approach is demonstrated on example road configuration with emphasis on its scalability, generality and processing cost.**

***Index Terms*—charging stations, electric vehicles, integer linear programming, optimization, path planning.**

I. Introduction

Transport sector is recognized as one of the most energy intensive sectors within the energy balance of most countries. Taking into the account that the main energy carriers in transport sector are fossil fuels, which have a strong negative impact on the climate change [1], it is evident why electric vehicles are viewed as an important measure for increasing of the transport sector sustainability. Electric vehicles cannot alone solve the greenhouse gases emission problem completely since they need electric power, which is one of the main sources of emission [2]. Their positive impact is achieved in the best way if their development is coordinated with renewable energy resources usage.

Plug-in hybrid electric vehicles (PHEV) are introduced as the transient phase while the technology of electric vehicles becomes commercially competitive with respect to the traditional vehicles technology. Testing of PHEVs in controlled conditions shows potential for significant petroleum displacement [3]. In order to realize an environmentally and economically sustainable integration of plug-in hybrid electric vehicles, the optimization techniques that consider the constraints of both the electricity grid and the transport sector are developed [4, 5].

As battery pack costs decrease, electric vehicles will become increasingly cost competitive which will enable their widespread presence in the near future [6, 7]. Therefore, low availability of necessary charging stations infrastructure is becoming the main barrier for further expansion of electric vehicles usage. According to the recent statistical data, electric vehicles outnumber public charging stations by more than six to one [6].

Although the locations of charging stations in the future will be selected depending on the various factors (traffic frequency data, travel patterns, market needs, etc.), for the initial phase of building of charging stations infrastructure, an efficient, economically acceptable, placement of stations is the main goal. Therefore, the goal is to select minimum number of charging stations which will be strategically allocated to enable transport between each two points of the road infrastructure, taking into the account the average electric vehicle autonomy. In this manner, each point of the road infrastructure will be reachable for an electric vehicle, and low availability of the charging stations for electric vehicles will not be the main barrier for expansion of electric vehicle usage. Further development of charging stations network should be guided by the real traffic data referring to the specific case.

Electric vehicle owners charge their vehicles most frequently at home or at work. Fast charging is not used frequently, and it primarily takes the form of planned stops for long-distance trips. Therefore, the number of fast charging public stations is the lowest and they should be strategically located to enable covering of the long-distance intercity trips [6, 8].

Determining optimal locations of electric vehicles charging stations is analyzed within various research papers [9]. A method of locating and sizing of charging station for electric vehicle based on grid partition is presented in [10]. The main constraints taken into account are traffic density and charging station's capacity constraints. Genetic algorithm (GA) is employed as the optimization tool. In [11], a model for optimal placement of charging stations based on the real world vehicle travel patterns is given. Mixed integer linear programming technique is used for the optimization problem solving. An activity-based approach using multiday travel data that employs GA as an optimization technique is presented in [12]. GPS based travel survey data are the basis for the optimization problem solving. The approach that captures the interactions among availability of public charging opportunities, prices of electricity, and destination and route choices while

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searching for the optimal locations for charging stations is presented in [13]. The goal was to take into account the constraints of transportation and power networks. A mathematical program with complementarity constraints is used as the optimization algorithm. An approach for the optimal planning of electric vehicle infrastructure for highway corridors is given in [14]. The goal is to minimize the placement of publicly funded charging infrastructure. The approach is applied to the Texas Triangle. A hybrid particle swarm optimization based approach is presented in [15], where layout of charging-demand districts is the main input needed for the problem solving. The two step optimization algorithm is proposed in [16], which consists of immune algorithm as the basic optimization tool and with employing Voronoi diagram to determine the preliminary zone of coverage. In [17], the problem of optimal placement of the fast charging stations is solved for a typical microgrid basing on the real traffic data. The goal is to minimize the investment and operation costs, as well as the mobility cost corresponding to the electric vehicles. The analyzed problem includes distributed generation, and the proposed algorithm performs search of all possible locations for charging stations prior to the optimum solution selection. A charging station location model with queue is proposed in [18]. It considers capacity, recharging time, and waiting time and it employs a heuristic method for solving the optimization model. In [19], the economic cost and the time consumed for charging are minimized simultaneously using Pareto front concept. The charging demand is divided using rasterization and Voronoi diagram in order to enhance calculation efficiency. A multiobjective charging station planning method which can ensure charging service, i.e. maximization of the traffic flow, while reducing power losses and voltage deviations of distribution systems is proposed in [20]. The cross-entropy method is employed to solve the optimization problem. A two-phase heuristic algorithm is utilized in [21] to find the optimal layout and scale of charging stations for electric vehicles. A flexible mixed integer linear programming model is proposed in [22], taking into account the spatial demand, resource constraint, limited driving range, and relative location of stations to each other. In [23], a simulation based optimization model, which employs integer linear programming is proposed for finding the optimal locations for charging stations. The approach shows that a combination of level one and two chargers maximize the charging energy available when applied to the central-Ohio region. The same optimization technique is used in [24], but with estimation of refueling demand by using regression analysis on real data. The optimization goal is to optimally locate in advance specified number of slow charging stations taking into account their capacity limits and coverage area.

Selection of the optimal route for electric vehicle enables better vehicle autonomy utilization, and therefore can impact the planning of the charging infrastructure. In [25], a GA-based route search algorithm is presented, which finds the best routes dynamically considering road conditions. A review of three algorithms for optimal route search on real road networks and demonstration of the data structures and procedures related to the algorithms is given in [26]. Energy shortest path problem and energy vehicle routing problem are addressed in [27], as well as the problem of charging stations placement, which are solved using integer linear programming technique.

Research work performed so far analyzes performance of various optimization techniques for solving of the optimal placement of electric vehicle charging stations problem. The core of the problem formulation is the same and it relies mostly on the availability of traffic flow data and number of electric vehicles in the observed area. However, there are differences in the constraints that are included within the optimization problem: type of charging stations, coverage, routes, operation and maintenance costs and electrical grid impact. In the case of unavailability of the electric vehicle traffic flow data, which is the case for countries with no or negligible electric vehicle penetration, in order to apply the mentioned optimization approaches, an appropriate estimation of traffic flow should be made. This may be challenging and it can lead to unreliable results, i.e. suboptimal charging stations placement. In order to overcome this problem for emerging markets, an optimization approach that does not need traffic flow data is proposed. It is based on the road network configuration and it has the main goal to propose an initial optimal placement of charging stations, which can, in the future phases of electric vehicle penetration, include traffic flow data that is specific to the analyzed area.

The rest of the paper is organized as follows: Section II presents the optimization problem formulation and describes the proposed approach based on integer linear programming. Section III includes the application of the proposed approach on test road configurations, and the results. Section IV concludes with a summary and discussion of some directions for future research.

II. Optimization Problem Formulation

Although there is a constant improvement achieved by the electric vehicles producers, one of the main limiting factors for higher penetration of electric vehicles is their autonomy. Therefore, an appropriate charging stations infrastructure is needed to ensure further expansion of electric vehicles usage. However, in order to build electric vehicles charging stations, there should be a corresponding business interest for potential investors, which, in the case of low electric vehicles penetration is not high. This problem could be mitigated by investing in the minimum number of necessary charging stations needed to enable covering of the routes between each two nodes within the observed road network, taking into the account the autonomy of electric vehicles. Afterwards, as the penetration of the electric vehicles within the total vehicle fleet grows, the business interest for building charging stations infrastructure will also grow and it will be market driven.

The road network is represented by a graph (nodes and branches). Potential locations for charging stations are nodes. Road distances are taken into account as an important factor that affects vehicle autonomy. Graph nodes represent potential starting and ending locations for a route covered by an electric vehicle. The optimization goal is to select minimum number of charging stations located at graph nodes so that, basing on the adopted electric vehicle autonomy, the path between each two nodes of the road infrastructure represented by the graph, can be covered by an electric vehicle. Since the electric vehicle owners are equipped with home based slow charging station, it is assumed that starting position of a vehicle is home, i.e. the electric vehicle is fully charged. Also, the destination node for an electric vehicle is expected to have a privately owned slow charging station.

In order to enable efficient solution of the optimization problem, integer linear programming technique is employed. The problem solving is divided in two stages. In the first stage the determining of the shortest routes between each two nodes that represent start and end node of a route is performed. Depending on the adopted electric vehicle autonomy, and taking into the account the determined shortest route, the covering of the route between each two nodes with a single charging cycle is tested. Basing on this the node connectivity matrix is formed. In the case that the distance of a road section between adjacent nodes is greater than the adopted electric vehicle autonomy, an additional node between the mentioned nodes is inserted. This optimization stage is performed in order to ensure the input data for the minimum placement of charging stations which is the main goal of the second stage.

In the second stage of the optimization approach the search for the optimal locations of charging stations is performed. The goal is to select the minimum number of nodes that represent locations for charging stations so that there is a route between each two nodes that can be covered by an electric vehicle with the adopted autonomy. The algorithm of the proposed optimization approach is given in Fig. 1.

The optimization problem in the first stage of the proposed approach can be modeled as integer linear programing problem defined by the following equations:

$$\min \sum_{\substack{i \neq j \\ i,j \in N}} \left(d_{ij} b_{ij} + d_{ji} b_{ji} \right) \quad (1)$$

subject to:

$$\sum_{\substack{i \in N \\ j \in \alpha_i}} \left(b_{ij} - b_{ji} \right) = \begin{cases} 1, i\text{ - start node} \\ \text{-}1, i\text{ - end node} \\ 0, i\text{ - other nodes} \end{cases} \quad (2)$$

where,

b_{ij} – variable that represents branch from node i to node j, it takes values 1 (branch is selected as a part of the path) or 0 (branch is not selected as a part of the path),

b_{ji} – variable that represents branch from node j to node i, it takes values 1 (branch is selected as a part of the path) or 0 (branch is not selected as a part of the path),

$d_{ij} = d_{ji}$ – distance corresponding to the branch x_{ij} and x_{ij},

N – set of nodes of the corresponding graph and

α_i – set of nodes incident to the node i.

The goal of the optimization represented by (1) is to minimize the total length of the path between the start and end nodes, where path consists of branches (b_{ij}) with the corresponding lengths (d_{ij}). However, in order to ensure the path is connected, the constraint represented by (2) is defined. This procedure is repeated for all node pairs from the road network in order to calculate the corresponding shortest routes and store them in matrix $\boldsymbol{D}$, where D_{ij} represents the corresponding distance between nodes i and j. After that, the node connectivity matrix $\boldsymbol{A}$, needed for the next stage of optimization is created in the following manner:

$$A_{ij} = \begin{cases} 1, R \geq D_{ij} \\ 0, R < D_{ij} \end{cases} \quad (3)$$

where,

i, j – nodes of the graph representing the road network,

R – adopted autonomy (range) of an electric vehicle.

This matrix carries the information whether the nodes i and j are in the range of a single charging cycle of an electric vehicle. These nodes represent the start and end node of a route.

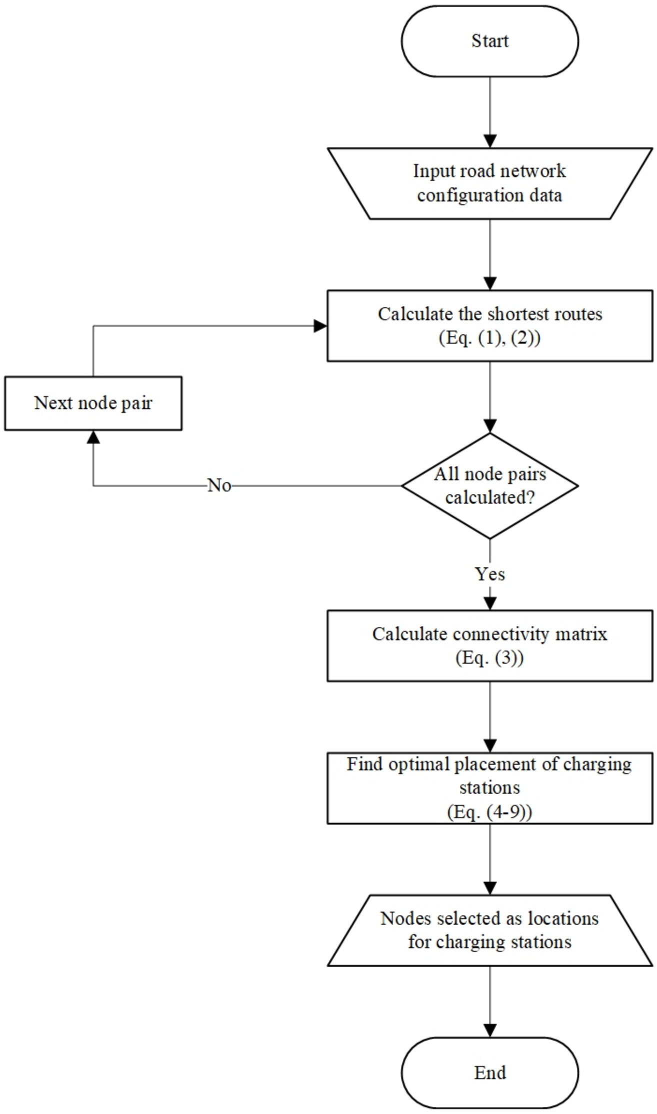

Figure 1. Algorithm for optimal placement of charging stations

The optimization problem of the main optimization stage is formulated as follows:

$$\min \sum_{i \in N} x_i \quad (4)$$

subject to:

$$\boldsymbol{A} \cdot \boldsymbol{X} \geq 1 \quad (5)$$

$$\boldsymbol{B} \cdot \boldsymbol{X} \geq 2 \cdot \boldsymbol{Y} \quad (6)$$

$$t_{ij} + t_{ji} = y_j \quad (7)$$

$$\sum_{\substack{i\in N\\ j\in\alpha_i}}\left(f_{ij}-f_{ji}\right)=\begin{cases}x_i, i\neq N+1\\ -\sum_{i\in N}x_i, i=N+1\end{cases} \tag{8}$$

$$f_{ij}\leq t_{ij}\cdot N \tag{9}$$

$$f_{ji}\leq t_{ji}\cdot N \tag{10}$$

where,

x_i – variable that represents the installation of electric vehicle charging station at node i, it takes values 1 (node is selected as a location for charging station) or 0 (node is not selected as a location for charging station),

$\boldsymbol{X}$ – vector of x_i, $i\in N$

$\boldsymbol{Y}$ – vector of y_j, $j\in V$

$\boldsymbol{A}$ – node connectivity matrix (A_{pq} = 1 when nodes are connected by a branch, otherwise A_{pq} = 0, p, $q\in N$),

$\boldsymbol{B}$ – branch-node incidence matrix (B_{pq} = 1 when branch p is incident to node q, otherwise B_{pq} = 0, $i\in N$, $j\in V$),

V – set of branches of the corresponding graph,

N – set of nodes of the corresponding graph (number of nodes),

y_j – variable that represents the branch connecting the nodes where electric vehicle charging stations are installed, it takes values 1 (the branch is connecting the mentioned nodes) or 0 (the branch is not connecting the mentioned nodes),

f_{ij}, f_{ij} – integer branch flow variable depending on the flow direction and

t_{ij}, t_{ij} – binary branch variable depending on the branch direction.

The proposed optimization model (4) aims to minimize the cost for electric vehicles charging station installation. The weights corresponding to the different installation costs of charging station depending on the node can be simply included in (4) as coefficients multiplying the variable x_i without affecting the optimization performance. In this manner some locations may be fixed within the optimal placement solution or eliminated from it depending on the adopted coefficients. Also, other practical circumstances may be included in the same manner (existing stations, power grid availability etc.).

In order to ensure the minimum placement of charging stations certain constraints should be included. The first, represented by (5), ensures that all nodes of the road network are in the range of at least one charging station that is the object of the optimization. The range of a charging station includes all nodes that can be reached from the observed node (where the station is located) by an electrical vehicle with a single charging cycle. The rest of constraints, (6)-(10) ensure that all charging stations are in the range of at least one charging station. It should be taken into account that in order to employ constraints (7)-(10) it is necessary to include an additional node (N+1) within the graph that would serve as a source node. This node acts as a flow generator which, along with the flow conservation constraint (8), limits the search space only to solutions (placement of electric vehicle charging stations) that correspond to the connected graph. This node is connected with an additional branch to a node of the graph. It can be any node but in terms of processing time, the best practice is to select a node with a radial branch or a node with the most incident branches. In that way, the connectivity of electric vehicles charging stations within the road configuration will be ensured. The constraints (7)-(10) eliminate potential loops that may cause suboptimal results. These constraints ensure that there are no islands in coverage of the nodes of the road network. All nodes that are selected as the optimal locations for charging stations with the corresponding graph branches form a connected path. In this manner it is prevented that the optimization procedure results with suboptimal solutions, i.e. the solutions that do not fulfill the basic optimization goal to enable coverage of a route between each two nodes.

The implementation of the optimization problem is simple and CPLEX or Matlab can be used as the optimization tool. In the following section the application of the proposed approach is demonstrated on two different road network configurations. The selected test configurations are of a different size in order to analyze the performance of the approach in terms of scalability.

III. Case Study

An example road network presented in Fig. 2 is analyzed in order to demonstrate the application of the proposed optimization approach. For the simplicity sake, and without loss of generality, it can be assumed that all graph branches are of the unitary length which is the same as the adopted autonomy of an electric vehicle. Taking this into account, all of the graph nodes are potential locations for charging stations. Including real distances and real vehicle autonomy further simplifies the optimization problem since the range of a vehicle often surpasses the distance that corresponds to a graph branch (road part) between two adjacent nodes. This directly affects the connectivity matrix defined by (3), and, as a result, smaller number of charging stations is needed to enable coverage of the whole network.

After applying the proposed approach on the example road network (Fig. 2) according to the presented algorithm (Fig. 1), the optimal locations for electric vehicle charging stations are derived and they are presented in Table I. It can be seen from Table I that minimum number of charging stations that are needed to enable total coverage of routes between each two nodes of the road network is 5.

TABLE I. OPTIMAL LOCATIONS OF CHARGING STATIONS FOR CASE 1

Total number	**Nodes selected as optimal locations**
5	4, 5, 6, 7, 9

It is important to notice that all nodes selected as locations for charging stations are part of a connected path within the graph representing the road network. This ensures that an electric vehicle with an autonomy equal to the distance between two adjacent nodes can cover the route between each two nodes of the road network with charging at the nodes selected as optimal locations for charging stations. As mentioned earlier, it is assumed that an electric vehicle starts a journey fully charged and that it can be fully charged at the destination node by home or work based slow chargers.

Also, for radial nodes like the node 8, it was expected that the adjacent node 7 would be selected as the optimal location for charging station. Therefore, the placement of charging stations at nodes that are the end of radial road branches would lead to suboptimal solutions. As for other nodes, the general conclusion is that the nodes with more adjacent nodes are often part of the optimal solution since they enable coverage of more routes for electric vehicles.

In order to test its scalability, the proposed approach is applied on the network configuration presented in Fig. 3.

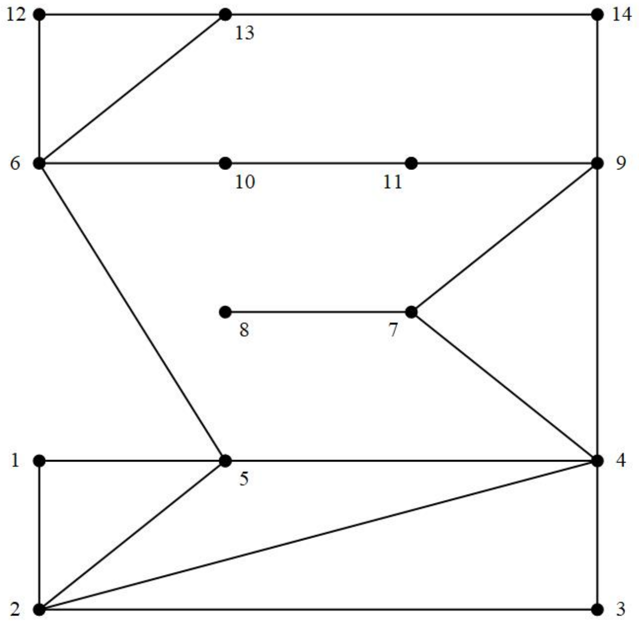

Figure 2. Example road network configuration

The road network is significantly more complex than in the previous case, and as a consequence, more demanding for solving in terms of the processing time. The derived optimal placement of electric vehicle charging stations is presented in Table II. It is needed 43 stations to enable covering of routes between each two nodes. The same conclusions regarding the radial nodes and the nodes with the most of incident branches as the strategically good locations for stations stand here as well as for the previous case.

TABLE II. OPTIMAL LOCATIONS OF CHARGING STATIONS FOR CASE 2

Total number	Nodes selected as optimal locations
43	3, 5, 8, 9, 12, 15, 17, 19, 20, 23, 24, 27, 30, 31, 32, 34, 37, 40, 42, 45, 49, 53, 54, 56, 59, 65, 66, 68, 70, 71, 75, 77, 80, 85, 86, 89, 92, 94, 96, 100, 103, 105, 110

Considering the results of the optimization approach for the analyzed cases it can be concluded that slightly above one third of the total number of nodes should be selected as the locations for electric vehicles charging stations in order to ensure total coverage of the road network. The share of the nodes selected as the locations for electric vehicle charging stations within the total number of nodes strongly depends on the node connectivity, as well as the adopted electric vehicle autonomy.

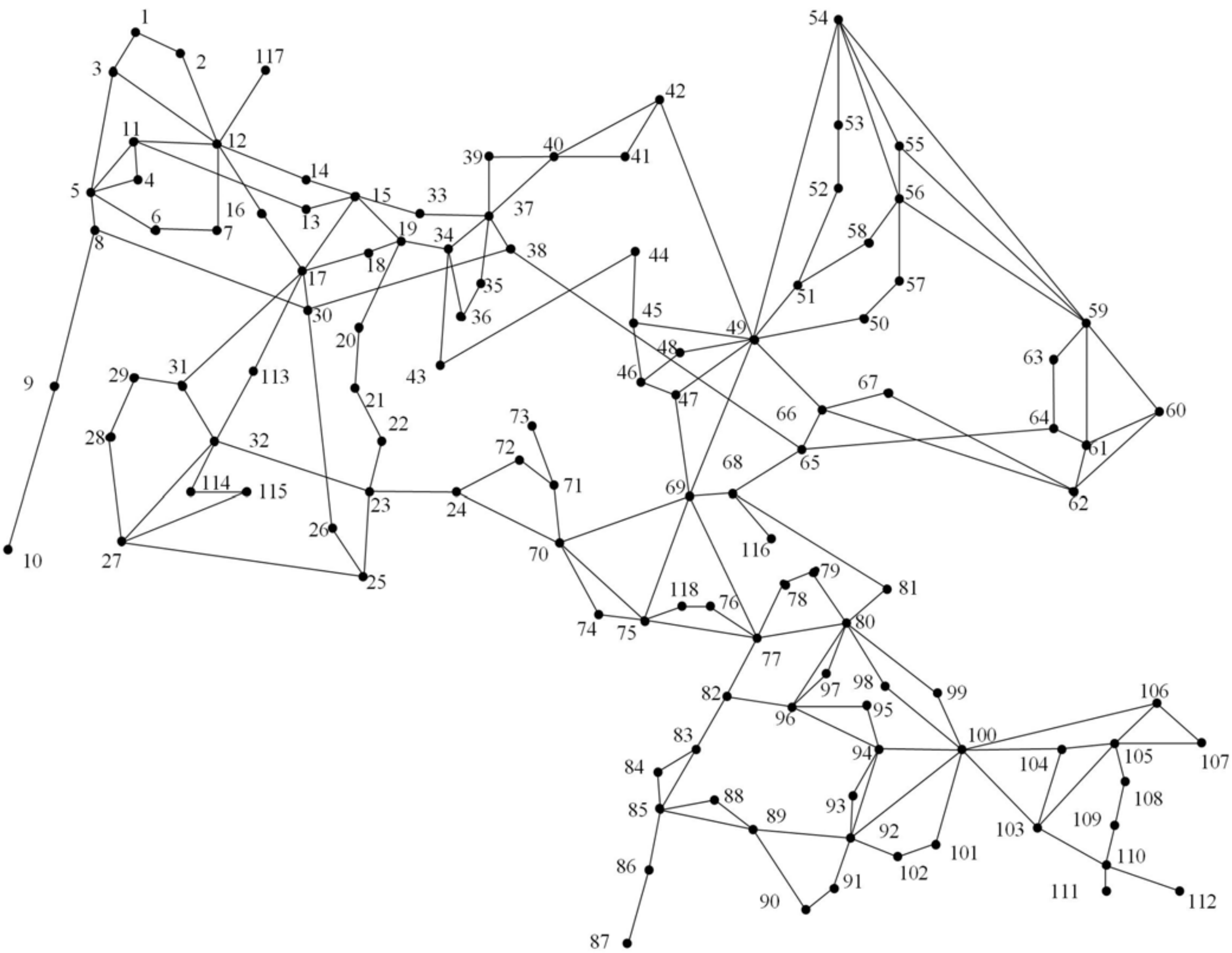

Figure 3. Road network configuration with 118 nodes

In terms of processing demand, the proposed approach is not demanding even when there is a need for fast output for multiple comparative analyses, although its main purpose is planning of the charging stations infrastructure where the processing time is not the main issue. The processing times of the approach for the presented case studies 1 and 2 are 0,02 and 1,54 s, respectively. The calculation is performed on a PC with i7 3,4 GHz processor and 8 GB RAM. The algorithm of the approach is realized in MATLAB. Due to the nature of the optimization problem, the first stage of the proposed optimization approach is more time demanding than the second stage. The main reason is the need for finding the shortest routes between all node pairs.

Since the proposed approach is based on integer linear programming optimization technique, the results derived correspond to the global optimal solution of the formulated optimization problem. The presented processing times with respect to the size of the analyzed road network configurations proves good scalability characteristics of the proposed optimization approach, i.e. it can be efficiently applied to more complex real road network configurations and real electric vehicle autonomy.

IV. CONCLUSION

This paper presents a simple and efficient approach for optimal placement of public electric vehicle charging stations for fast charging. It is based on the integer linear programming optimization technique. The approach does not need large amount of input data and it is intended for the initial optimal allocation of charging stations. Its scalability characteristics show that it can be easily used for various road configurations without any adjustments in the optimization problem formulation. The execution of the approach is not time demanding process. The approach can include additional constraints depending on the traffic and other data availability by simply adjusting the objective function, which makes it flexible for various specific practical needs.

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