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ELECTRIC VEHICLES CHARGING OPTIMIZATION: REDUCING OPERATIONAL COSTS OF SMALL COMPANIES

Ivan ANASTASIJEVIĆ[1]
Aleksandar JANJIĆ[1]

[1] Department of Power Engineering, Faculty of Electronic Engineering, University of Nis, A. Medvedeva 14, Nis, Serbia

Abstract

This paper deals with the reduction of operational costs of small companies using charging optimization of electric vehicles. Firstly, charging/discharging optimization of electric vehicles is done. Furthermore, general operational costs of small companies with optimized charging/discharging electric vehicles and costs of small companies with conventional vehicles are approximately calculated and the results are compared. The main criteria for comparison are vehicle fuel and electricity costs. It is found that charging/discharging optimization of electric vehicles can reduce general operational costs of small companies.

Key words*: Charging optimization, Electric vehicle, Cost minimization, Vehicle-to-grid concept.*

1 INTRODUCTION

One of the most prominent problems in the world is air pollution and producing of greenhouse gases (GHG; such as carbon dioxide, methane, nitrous oxide, etc.) Increased production of GHG causes many problems, but the most important one are greenhouse effect and climate changes. Since transportation is one of the biggest consumers of fossil fuel, it has a major impact on producing and emission of GHG [1]. In order to stop climate change and greenhouse effect on the planet, fossil fuel must be replaced by environmentally clean energy sources (renewable sources of energy). According to the European Union (EU) strategy there is a need of reducing emission of GHG by 20% [2]. One of the possible ways to achieve this goal is to replace internal combustion engines in transport with electric drives. Electric vehicles (EV) are environmentally friendly, given that they do not emit GHG.

There are various problems which can be related to EV; and they are usually related to the influence of EV on the power grid. There is also a problem with the autonomy of vehicles and time needed for recharging batteries. As technology of batteries in EVs is developing, battery capacity rises. It means that autonomy of vehicles also rises and recharging time reduces. Generally, the most common problems caused by EVs in distribution grids are: increase of power losses in transmission lines, voltage deviation, power flow problems (transmission network congestion), varying in power load, etc. [3, 4, 5]. Primarily, if there are numerous EVs connected to the grid it is obvious that power transmission lines can be overloaded. With numerous EVs connected to the distribution grid at the same time, unexpected peaks in power consumption can occur [3]. Voltage deviation problems in distribution grid are also consequence of numerous EVs charging at the same time. Furthermore, the main consequence of voltage fluctuations is deterioration in power quality [3].
The problems mentioned above can be solved using coordination and optimization of the charging of EVs [3,4]. The use of coordinated or optimized charging of EVs is possible only with Vehicle-to-Grid concept (V2G) [4]. V2G concept is based on communication between EVs and power grid for using auxiliary services of EVs (battery storage) to support better functioning of the distribution grid. V2G concept allows bidirectional power flow between EV and distribution grid, so the batteries of EVs can be used as energy storages or energy sources. The capacity of battery in single EV is small, but there is a big number of EVs connected to the grid at the same time, thus overall capacity of batteries and possibility for energy storage is not negligible.

Additional services which can be provided from EVs and V2G concept are: placing the energy in distribution grid, when there is a need for that – peak shaving and load leveling [6], using EVs for voltage and frequency regulation in the grid [7], decreasing of power losses which can be regarded as economic problem as well, etc. Most auxiliary services affect the distribution power grid improvement and distribution company interests.
Using the EVs for V2G concept can lead to the decrease of battery lifetime or capacity. Since EVs will be used for distribution power grid improvement, there must be some privileges or benefits for owners of EVs to permit Electric Distribution Company to use their vehicle for auxiliary services [8]. Owner Benefit can be refund of retrieved energy from EV, or paying fee for using EV for V2G on a monthly basis.

The main subject of this paper is charging optimization of EVs and their usage to reduce operational expenses of small companies. In addition, this paper deals with the comparison of operational costs between small companies using conventional vehicles and small companies using EVs with optimized charging. Initial investment will not be used in the comparison. The main criteria for comparison are electric power costs and vehicle fuel costs. Expense calculation is approximated and some constraints for optimization are also simplified, but it is possible to draw appropriate conclusions according to the acquired results.

2 SMALL COMPANY MODEL

The model of small company which is used in this paper is described in this section. The company has ten vehicles, which are used on a daily base, from 10am to 16pm. During that time, vehicles pass 35 kilometers each. It is considered that the firm also has a main building with offices for employees. Generally, electric consumers in main building are computers, indoor lighting, printers, etc. The loads are not as big as the ones in manufacturing facilities. Daily diagram of electric power consumption of the company main building is presented in Fig. 1. The shape of the diagram is taken from [9].

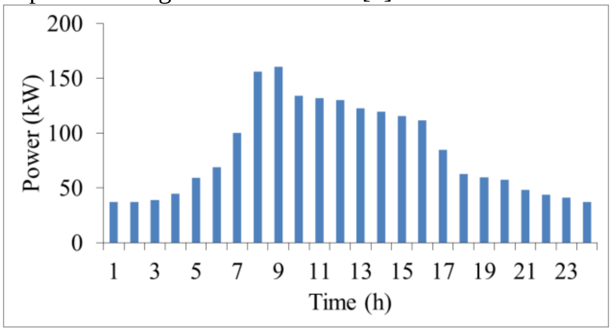

***Fig. 1** Daily electric power consumption diagram of the main building*

Also prices of electrical energy are know for every hour of actual day, or the following day, and they are announced by electricity exchange company. Prices used in this paper are market clearing prices, from “HUPX” (Hungarian Power Exchange) company [10].

2.1. Small company with conventional vehicles

Since EVs which are used in analysis in this paper are Nissan Leaf (according to its dimensions and characteristics it belongs to B – segment cars), conventional vehicles (i.e. vehicles with internal combustion engine) are also from B – segment cars (“small cars”, defined by the European Commission). According to the manufacturers’ data for many vehicles from B – segment cars, average fuel consumption of conventional vehicles is approximately 6 liters/100 km for vehicles with petrol engine and 4 liters/100 km for vehicles with diesel engine, in combined driving.
Since the main criteria for comparison between small companies with conventional and small companies with EVs are electric power costs and vehicle fuel costs, total expenses for companies with conventional vehicles are:

$$C_{total} = C_{fuel} + C_{el.en} \tag{1}$$

where C_{fuel} are fuel costs (depending on fuel price and fuel consumption) and $C_{el.en}$ are electric power energy costs (depending on the diagram from Fig.1 and prices of electrical energy).

3 OPTIMIZATION OF CHARGING

Generally, optimization in engineering is used to minimize operational problems or to maximize welfare of some processes. Charging optimization of EVs is based on scheduling of charging/discharging [3]. There are many papers in literature which usually present a few possible scenarios with or without charging optimization, and according to desired goals, one of them is chosen for implementation in real situations (e.g. [11], [12]).
Subjects which can use optimization of charging of EVs for minimization of problems or welfare maximization are:

- Power plants;
- System operators;
- EVs aggregator
- Owners of EVs [3].

There are economic interactions between these subjects. A review of possible optimization strategies, typical optimization objectives and mathematical optimization methods is given in [3]. Optimization can be observed from different angles: the operator’s, the aggregator’s and the EV owner’s. In this paper EV owner strategy is implemented. Characteristic optimization objectives are cost minimization, maximization of benefits, power loss minimization, battery performance optimization, minimization of consumption fluctuations, etc. The optimization objective used in this paper is cost minimization.

3.1. Small company with Electric Vehicles (EV)

The structure of the company is the same as the one of the company described in subsection 2.1. There are 10 vehicles and a main building. The major difference is that these vehicles have an electric drive (Plug-in electric vehicle) with batteries, instead internal combustion engine. Electrical power demand of the main building of the company is the same as in the case of small company with conventional vehicles (Fig. 1).
EV used in this analysis is Nissan Leaf, because it is one of the best-selling and most common electric vehicles which are regularly serial produced. Nissan Leaf has a battery which can store 30 kWh of energy. Autonomy of this vehicle is tested by many agenices. According to US EPA, autonomy of Nissan Leaf is about 117 km. The results of autonomy, obtained by the Federal Trade Commission (USA) are different and they are 154-177 km. Third-party tests got 100-222 km as result. Official data given by manufacturer is 170 km of autonomy. According to the information stated above, autonomy of this vehicle is considered to be about 150 km (approximate value, used in optimization), and is quite good for purposes that are needed (vehicles pass 35km per day).
The prospect of small companies with EVs is shown in Fig. 2.

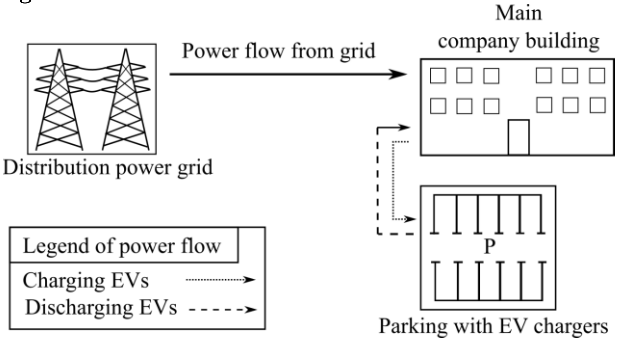

***Fig. 2** Small company with EV*

As it can be seen in Fig. 2, there is a parking lot, which has electric chargers for every parking space. Electric chargers have a special construction and they can provide electric power flow in both directions, from grid to vehicles (charging of EVs), and from vehicles to grid (discharging of EVs). When EVs are parked, they are connected to the electric grid. Thus, battery recharging and auxiliary services from EVs can be achieved through V2G concept, as it is mentioned in section 1. Electrical energy can be stored in batteries of EVs when there are lower prices of electric energy (lower prices matching lower loads in electric grid). Then, when there are higher prices of electric energy (higher prices matching higher loads in electric grid), batteries of EVs can be used as a source of electric power energy. In that way, costs of electric power energy can be reduced, as the demand for electric power from distribution grid is decreased. It is important to mention that the only cost of the company is the cost of electric power energy, while there is no cost of fuel as in the case with conventional vehicles.

As the diagram of the electric power consumption can be planned for the following day, and prices of electric power are also known, using the optimization of charging/discharging of EVs leads to the optimal scheduling of charging/discharging of EVs for the following day.

Total costs for the company with electric vehicles are:

$$C_{total} = C_{el.en.building} + C_{el.en.vehicles} \tag{2}$$

where $C_{el.en.building}$ is the cost of electric power energy consumed in the main building. $C_{el.en.vehicles}$ is the cost of electrical energy consumed by EVs and can be positive or negative, according to the results of optimization. Objective function which is used in optimization is:

$$C_{el.en.vehicles} = \sum_{k=1}^{n} \left(\sum_{i=1}^{m} C_i \cdot P\_auto \cdot X_{k,i} \right) \tag{3}$$

where n=10 is the number of EVs, m=18 is the number of hours when vehicles are connected to the grid through electric chargers. C_i is the price of electrical energy in i^{th} hour, P_auto is electrical power of charging or discharging EV batteries in every hour (constant value, 2.5 kW) and $X_{k,i}$ is variable which describes whether EVs are charging or discharging. $X_{k,i}$ can have three values:

- 1, when EVs are charging,
- -1, when EVs are discharging and
- 0, when electrical power does not flow between EVs and the grid.

The optimization is done in Matlab R2016a. Optimization method used for objective function (equation (3)) is Mixed-Integer Linear Programming (MILP), since variables $X_{k,i}$ can have only integer values. Hour discretization is used in problem solving.

Beside the vector which defines objective function (equation (3)), there is a need of inputting vectors of electrical energy prices, main building load (numerical values from Fig 1.) and additional variables used in optimization.

Every optimization problem has constraints, which can be in form of linear inequality or linear equality. Linear inequality constraints used in optimization process are:

$$SOC_{k,i} \le 100, \tag{4}$$

$$SOC_{k,i} \ge SOC_{MIN}, \tag{5}$$

$$SOC_{k,m} \ge 80, \tag{6}$$

where k has values from 1 to n=10 (k corresponds to EV index) and i has values from 1 to m=18 (i corresponds to hour index). SOC represents State Of Charge of EV battery in percentage. SOC_{min} represents minimal value of battery capacity below which it should not be discharged. It depends on Depth of Discharge (DOD), which is usually 80% of battery capacity. The difference between the battery capacity and DOD gives the value of SOC_{min} (which is 20%) [13]. SOC of the battery must be between the boundaries defined by constraints (4) and (5). Equation (6) determines SOC of the battery which is desired at the end of charging/discharging process. Constraints are simplified and refer to the preservation of EV battery from rapid deterioration of characteristics [14].

4 RESULTS OF OPTIMIZATION AND COMPARISON OF COSTS

The results for small company with EVs are collected after completing the charging optimization of EVs. Time intervals, in which EVs should be charged or discharged, are obtained (Fig. 3)

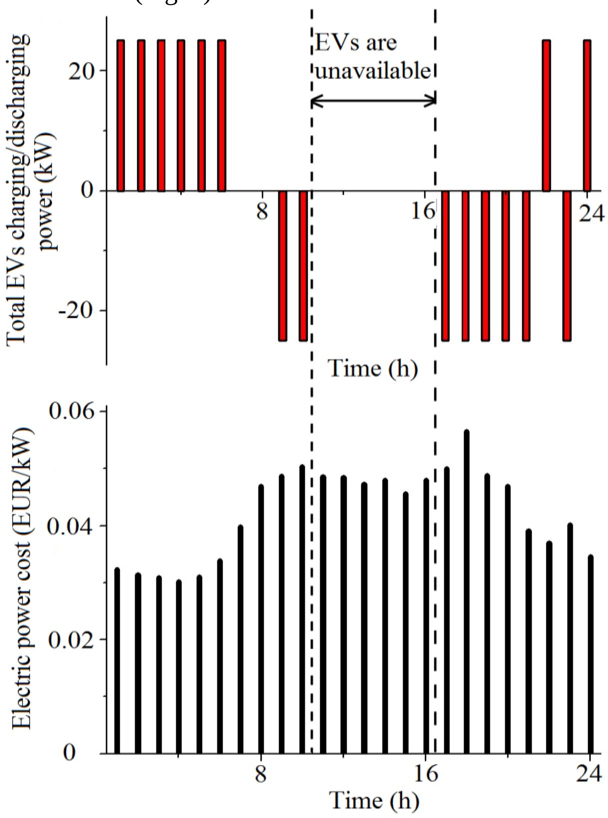

Fig. 3 *Column graph of charging/discharging power of EVs and costs of electrical energy in every hour of a day*

In order to achieve savings, it is important that EVs should be charged in time intervals when the cost of electrical energy is lower. EVs should be used as electric power sources when the cost of electrical energy is higher. Charging and discharging power of EVs as well as the costs of electrical energy are given in Fig. 3. In Fig. 3 it can be seen that EVs are charged in hours when electricity costs are lower (that is usually during the night). EVs are used as energy source when electricity costs are higher. In that way, optimization goal should be accomplished, but the question is the amount of savings.

Electrical power which is used in the main building of the company (blue columns), power of charging/discharging EV batteries (red columns) and total electric power demand from power network (green columns) are presented in Fig 4.

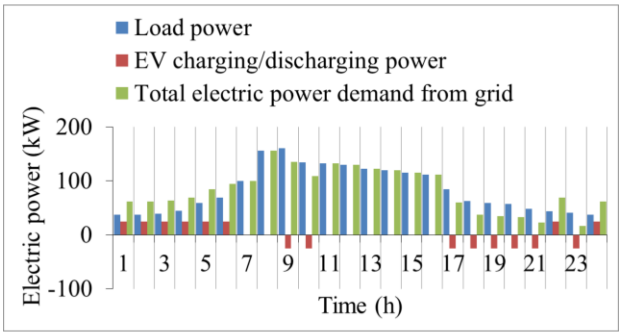

Fig. 4 *Load power of the main building,EVs charging/discharging power and total demand on electric power from power grid*

Negative values of EV power are present in the hours when EVs are discharging (Fig. 4). Then the EVs are sources of energy. Total electric power demand from the grid is increased when the prices of electrical power are lower. Total demand of electric power is decreased when there are higher prices of electrical power.

General operational costs of small companies with conventional vehicles are calculated according to equation (1), while general operational expenses of small companies with EVs with optimized charging/discharging are computed according to equation (2). The results are compared and presented in Fig. 5.

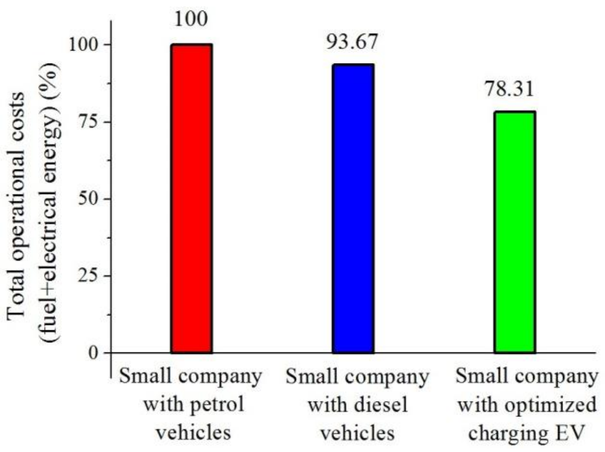

Fig. 5 *Comparison of general operational costs of small companies with conventional vehicles and small companies with charging/discharging optimized EVs*

In Fig. 5 general operational costs of small companies with conventional petrol vehicles, general operational expenses of small companies with conventional diesel vehicles and general operational costs of small companies with EVs with optimized charging are shown. Values are given in percentage, where 100% of costs correspond to costs of small company with petrol vehicles. Costs of other type of small companies are related to this value. According to Fig. 5, savings achieved by using EVs with optimized charging is slightly higher than 21% in comparison with small company with conventional petrol engine vehicle, and slightly higher than 15% in comparison with company with conventional diesel engine vehicle. These savings are related to the case which is compared here. Another benefit of using optimized charging EVs is reduction of air pollution and emission of GHG, although it is not evaluated in this analysis. Changing of initial conditions (number of vehicles, value of passed kilometers by vehicles for a day, time interval when vehicles are used, etc.) can give different results. It is important to mention that bigger number of EVs participating in charging optimization provide greater savings. Higher savings can also be provided by increasing the time intervals when EVs are available for optimized charging.

It is worth mentioning that this analysis and comparison include only operational costs of electricity and vehicle fuel of small commercial companies. Costs of buying vehicles are not included. EVs are more expensive than conventional vehicles, but savings are achieved with smaller costs of "fuel" (i.e. electricity) and less expensive maintenance. Another important part of savings is optimization of charging/discharging. EVs are continuously charged when they are connected to the grid without it and that causes increased electrical power expenses and deterioration of characteristics of the EV batteries, which raises the price of maintenance.

5 CONCLUSION

Charging/discharging optimization of EV batteries is applied for small companies with EVs. Total operational costs in case of small companies with EVs (with optimized charging/discharging) are calculated. The results are analyzed and compared with operational costs of small companies with conventional internal combustion engines. The company with optimized charging of EVs has less operational costs when compared to the companies using conventional vehicles. In the cases compared here, using the EVs with optimized charging reduces general operational costs of small company by more than 21% in comparison with small company with petrol engine vehicles. If general costs are compared with costs of small company with diesel engine vehicles reduction of costs is little less (15%). Results unambiguously show that the use of charging/discharging optimization of EVs can reduce general operational costs of small companies. Additional benefit of using EVs with optimized charging is reduction of GHG emission and air pollution. It should be noted that starting conditions of analysis (electric power consumption diagram of the main company building, passed route by vehicles, time interval when vehicles are on the road, etc.)

can cause different results for operational costs and savings, depending on the case.

In addition, it should be noted that optimization of charging requires electric chargers, which can allow electric power flow in both directions (from the grid to the vehicles and vice versa), and control units which will actuate charging or discharging of vehicles according to the "day ahead schedule". This means that initial investments for the case of small companies with charging optimized EVs are higher than investments of small companies with conventional engine. However, savings are achieved by reducing operating costs, which is shown in this paper. Future studies of optimization of EV charging/discharging and reducing operational costs should be done, especially with taking into consideration more constraints (temperature of EV battery, more complex model of battery state of charge, taking into account power lines loads, etc.). By doing so, more precise estimations and results of operational costs will be achieved.

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Contact address:
Ivan Anastasijević,
Department of Power Engineering,
Faculty of Electronic Engineering,
University of Nis, A. Medvedeva 14,
Nis, Serbia