Effect of Electric Vehicle Parking Lots equipped with Roof Mounted Photovoltaic Panels on the Distribution Network

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Abstract

In this paper, the integration of a solar power plant to an electric vehicle (EV) Parking Lot is analyzed in terms of reduction of power consumption and losses for various scenarios and operating conditions in a distribution system. The parking lot is designed for EVs and is fed by both grid and roof mounted photovoltaic (PV) panels. The energy management system is designed for charging EVs for various scenarios combined with solar radiation data varying during daytime and the seasons. The energy transactions are simulated in accordance with daytime Solar Power Plant (SPP) generation and EV energy response on Electrical Power System Analysis Software (ETAP) environment. EVs based power consumption is calculated by considering the variation of charging sequences of different car brands. The study represents the results for daily change of power consumption for summer and winter conditions along with the reduction of power consumption, reduction of power losses, decreased main feeder ampacity, restoration of voltage level during SPP operation, and comparison of different scenarios and operation sequences. Finally, the effect of the SPP is presented in terms of reducing the peak and continuous power demand of the parking lot for various EV operations.

Keywords: Electric vehicle; parking lot; photovoltaic energy; smart grid; solar power plant integration.

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1. Introduction

Nowadays, the power grid and the distribution systems are being transformed into smart grids, which propose the better integration of the renewables and next generation consumers with variable power consumption such as electric vehicles (EVs). The usage of EVs is expected to increase to 62% by 2050 as stated in the studies of Electric Power Research Institute (EPRI) [1] in US where a survey indicates that the 80% of car owners may be considering replacing conventional cars with EVs in UK [2]. The introduction of EVs to the existing network comes along with significant effects on the distribution systems [3]. The various characteristics of EVs should be considered for different type and applications of EVs [4].

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At this stage, it becomes necessary to evaluate the effects caused by the characteristics of the integrated renewables and consumer elements on the existing networks. The increasing usage of EVs should be considered for the design of distribution network models in the concept of the smart grid. Here, the parking lots are considered to be used as a charging point for hundreds of EVs [5]. EV charging station investments in parking lots therefore should be analyzed in detail in terms of supplying the huge demand of such loads [6]. The increasing penetration of EVs is a major factor to be considered to design EV parking lots considering charging sequences and scenarios, and therefore includes high level of stochasticity. In this manner, the EV parking lots equipped with solar power plant (SPP) can also be useful for reducing grid power losses, regulate voltage level and provide economic benefits compared to the parking lots without such distributed generation (DG) units [7,8].

There are numerous studies in the literature considering the topic of EV parking lots from different points of view. As the first category, some studies considered the energy management within an EV parking lot considering the re-allocation of EV charging schedules. Among them, Kuran et al. [9] provided an EV charging sequence scheduling oriented EV parking lot energy management system by categorizing arriving EV types as regular and irregular and aiming to maximize parking lot owner's benefits and satisfy the EV owners' charging requirements. Zhang and Li [10] proposed a game-theoretic approach for EV charging scheduling based energy management in a parking lot. Rezai et al. [11] performed an analysis by an online intelligent energy management approach in a smart EV parking lot.

Rahmani-andebili [12] proposed a methodology for EV parking load equipped with PV panels in the perspective of minimize the charging cost of EVs. Shaaban et al. [13] also proposed a real-time coordination method for EV charging points in smart distribution networks where an optimization process based on charging schedule of EVs is presented in [14]. The reliability analysis of such proposed network model was presented in [15].

There are also studies considering the EV parking lots from electricity market and demand response points of view. Among them, Mohan et al. [16] discussed a sorting ratio based portfolio optimization method for a microgrid's electricity market integration including EVs and renewable energy units. Shafie-khah et al. [17] proposed the use of EV parking lots as demand response agents in electricity markets. Neyestani et al. [18] also discussed the electricity market integration of EV parking lots. There are also different studies in the literature considering the topic of EV parking lots from different perspectives. To minimize and eliminate the drawbacks of expanding usage of EVs in the power system, the consumption characteristics of EVs would be investigated and necessary control strategies should be adopted [19]. The major control and sizing methods for EV charging stations were mentioned in [20, 21, 22]. The State of Energy (SoE) characteristics of the EVs has a major impact on the losses and voltage regulation of the distribution networks.

In recent studies, the charging and discharging sequences of EVs were investigated along with the effect of EVs on the distribution network [23, 24, 25].

The integration of EV parking lot to the network considering the behaviours of EVs' drivers along with hourly SoE analysis and the economical impact of EV parking lot with stochastic approach was investigated in [26]. The control and operation obstacles on the network which is foreseen to be generated by widely used EVs was investigated in [27] and a sustainable model was proposed considering social and economic behaviour of EV drivers.

The requirements for optimal placing of EV parking lots were mentioned in [28] along with generation of power profiles of EVs. The line and transformer losses were mentioned in [29] which may reduce the lifetime of equipment during peak loading. The sizing criteria of SPP and effect of SPP to the network was recently studied in [30] where the application of EV charging station equipped with PV panels as a microgrid is investigated in [31]. The economical impact analysis of a microgrid based EV charging stsation is mentioned in [32].

Even there are numerous valuable studies in the existing literature more than the studies cited herein, minority of them considered the availability of DG units in such consumption centers and their impact analysis on the distribution system operation to aid firstly the impact of EV parking lot load and then the aid of available on-site DG units for reducing the drawbacks occurring due to such consumption centers with new electric load characteristics.

In this manner, this paper presents the effect of an EV parking lot equipped with roof mounted photovoltaic (PV) type SPP on the distribution network along with the simulations in Electrical Power System Analysis Software (ETAP) environment considering physical location limitations. The study addresses the questions of optimal operation and sizing criteria during the design stage of SPP mounted EV parking lot. The effect of EV charging to the grid is observed and the SPP is sized within the grid operational limitations to obtain a reliable solution for EV parking lot charging requirements. The proposed methodology for EV parking lot operation consists of scenario based analysis for stable operation of existing network for voltage regulation while reducing the line losses. These two main criteria for sizing and operating the EV parking lot are considered while the EV power consumption characteristics are generated as randomized arrival and departure durations to simulate the worst case loading scenarios. The contributions of the study can be stated as follows:

- The combinatorial effects of EV parking lots and SPPs connected to the same distribution system point are considered.
- The system is analyzed from applicability point of view and therefore the contribution is offered not mainly from a theoretical point of view, but more from application-based considerations side.
- The proposed energy management strategy depends on the energy production of SPP and the EV power consumption. The EVs are randomly selected to simulate parking lot power consumption with hourly intervals, which depends on the arrival and departure times of EVs. The SPP power generation is calculated in accordance with solar radiation data of Istanbul, Turkey. The study investigates the effect of seasonal weather changes as well.

- The study consists of the design and calculation of EV parking durations and SPP power generation, which are major factors in order to observe the effect of the proposed system to the network.
- This paper also reviews the key factors for the EV parking lot equipped with SPP considering the optimal operation of the parking lot and aiming for the reduction of line losses and voltage regulation.

The remainder of the study is organized as follows: Section 2 presents the methodology and the background information for the performed simulation studies. Section 3 gives the simulation results with the relevant discussions. Finally, Section 4 includes the concluding remarks.

2. System Methodology and Simulations

IEEE 13 Bus Test System [33] is built along with necessary load, transmission line and transformer parameters in ETAP environment. The parameters of the elements are applied to the network model in accordance with IEEE standard test system. The study consists of the modelling stage of IEEE 13 Bus Test System, design of the SPP along with solar radiation data with seasonal effect factors, integration of the consumption profile of randomly selected EVs to the simulation environment. Here, the load flow is the optimization part of the problem that is realized by well-known Newton-Raphson approach already available in the relevant software used for the simulations that will be detailed in Section 3.

The parking lot is equipped with medium voltage (MV) / low voltage (LV) transformer to meet the connection criterion of existing network. SPP is rated at LV level and directly connected to EV distribution feeder bus. The model of the parking lot distribution system is indicated in Fig. 1.

"Insert Figure 1 here"

The SPP is sized in accordance with physical limitations of a parking lot for 100 cars. The building is considered as 3 floors with the dimensions of 65*15 meters. The SPP model consists of PV modules, inverters and all necessary cabling, distribution and protection equipment.

As the first stage of the study, Kyocera PV panel is modelled in accordance with the parameters indicated in Table 1.

"Insert Table 1 here"

The maximum power generation of the panel, voltage and current parameters are calculated and PV module is sized as indicated in Table 2 in accordance with physical limitations of the parking lot.

"Insert Table 2 here"

After the modelling stage of the PV module, the inverters are sized with the parameters indicated in Table 3. The inverters are designed in accordance with power generation data of the PV modules.

"Insert Table 3 here"

As the final stage of the SPP design, 4 inverters - PV module sets are connected to PV Plant Main Bus with the maximum power generation capacity of 120 kVA as indicated in Fig. 2.

"Insert Table 4 here"

After the completion of the SPP design stage, the power generation of SPP is calculated with the average solar radiation data of Istanbul for both summer and winter conditions using Eq. (1):

$$E_g = A_{PV} * r * H * PR \tag{1}$$

where E_g is the energy, A_{PV} is the total solar panel area, r is the solar panel efficiency, H average solar radiation and PR is the performance ratio to define losses. The solar radiation data and power generation values are listed in Table 4.

The simulation range is chosen as 6am to 8pm considering sunrise - sunset time and parking lot usage data which is between 7am and 7pm. The effect of season conditions is implemented to PV modules as solar radiation data of summer and winter conditions. The power generation variation of the SPP is indicated in Fig. 2 for summer and winter conditions.

"Insert Figure 2 here"

The SPP generated power may have significant effects on the grid depending on the generation and consumption characteristics of the network. The power consumption characteristics of the EVs are calculated along with the charge needs of the EV parking lot and SPP is designed in such a way to avoid any negative effect on the grid. At this stage, a reference list is generated to calculate total power consumption and loading curve of the parking lot during day time usage along with the EV based charging power needs of the parking lot. The list is designed as the 10 of each EV type to reach the total number of 100 EVs. The EVs which are modelled as consumers of the parking lot are listed in Table 5.

"Insert Table 5 here"

The EVs are modeled with random arrival and departure times with the status of having the minimum SoE during arrival. Each EV is considered as being charged until reaching maximum SoE which is equal to battery capacity without any interruption to model the worst-case situation.

Here, the SoE of each EV is calculated using Eq. (2):

$$SoE_{h,t} = SoE_{h,t-1} + CE_h \cdot P_t^{ch} \cdot \Delta T \quad (2)$$

where h is the set of EVs, t is the set of time, $SoE_{h,t}$ is the SoE value of EV h in period t, P_t^{ch} is the charging power of EV h in period t, CE_h is the charging efficiency of the charging station connected to EV h, and ΔT is the time granularity (interval duration).

The reference curve which indicates the loading sequence of parking lot based on randomly selected arrival and departure times of the EVs is indicated in Fig. 3 with 1-hour intervals.

"Insert Figure 3 here"

After the implementation of solar radiation data to designed SPP, the integration studies are performed. The SPP is connected to Bus 692 of the IEEE 13 bus network via 500 kVA transformer which supplies the energy requirement of the EVs located in the parking lot. The final configuration of the network is indicated in Fig. 4.

"Insert Figure 4 here"

The design and integration stage are completed along with implementation of randomly generated EVs to network model. The simulation results are presented in the Section 3 of the paper.

3. Results

The network model and the SPP model described in previous section is modelled and simulated in ETAP environment using the Newton-Raphson methodology for optimal load flow analysis as also mentioned previously [35].

To analyze and ensure the stability of the system, relevant simulations are performed based on the design data presented in previous section. Once the network and the SPP models are built in ETAP environment, the load flow analysis is performed for Summer and Winter conditions.

The scenarios for seasons are applied for randomly selected EVs. The EVs are modelled as variable loads varying for each hour of the parking duration. The obtained load flow analysis results present the required data for loading sequences of parking lot which is used to examine the behaviour of the implemented SPP. As the first step of the simulations, the performed load flow analysis results are observed and relevant comparisons are realized for different operation sequences. The loading sequence of SPP and EVs for different scenarios is indicated in Fig. 5.

"Insert Figure 5 here"

The obtained results indicate that the peak demand occurs at 9 am and maximum power generation of SPP is observed in the afternoon for summer conditions. The generated power from SPP covers the power demand of EV parking lot for 7 hours of parking duration during summer conditions where the duration is 4 hours for winter. As a result of the loading and consumption sequence determination, the power bought from and sold to the grid is indicated in Fig. 6.

"Insert Figure 6 here"

Once the loading characteristics of the SPP and EV parking lot are obtained, the effect of the SPP on the grid is observed. The SPP generated power leads the reduction of the transmission line losses.

The variation of losses depends on the EV parking lot consumption and SPP power generation indicated in Fig. 7 representing the main feeder line losses for 3 different conditions which are grid alone operation (Grid Alone –GA- Total Loss), SPP winter operation and SPP summer operation conditions.

"Insert Figure 7 here"

The line power losses are used for the calculation of total energy losses for both summer and winter SPP operations compared to the grid alone operation. Energy loss per day is calculated as 587 kWh for grid alone operation. Total daily energy loss is calculated as 570 kWh for winter where the total daily energy loss is 562 kWh for summer SPP operation. As per the calculation results, the total energy loss is decreased by 4.26 percent for summer and 2.89 percent for winter compared with grid alone operation.

After the line losses calculations, the main feeder ampacity variation is observed as per the load flow study results. The variation in main transmission line (Line 601_22) leads the reduction of line losses due to reduced power transmission from the grid. The results for each scenarios are indicated in Fig. 8.

"Insert Figure 8 here"

As the next step, the voltage regulation and effect of SPP at MV connection bus are observed. The voltage regulation should be kept in regulation limits during online and offline operations of SPP. The regulation is calculated with Newton-Raphson methodology based load flow study and the results are indicated in Fig. 9 where voltage regulation is remained in +-1% limitations.

"Insert Figure 9 here"

As the last step of the simulations, the comparison of power consumption is examined. The EV parking lot is fed via SPP for 4 hours in winter conditions where the SPP alone operation is 7 hours in summer conditions. Reduction of energy cost, reduction of line losses is observed with the both parallel and stand-alone SPP operation depending on EVs' variable parking lot usage duration.

4. Conclusions

In this study, the parallel and stand-alone operation of a SPP and the grid was studied for an EV parking lot. The variable parking lot duration of randomly selected EVs was implemented to a simulation environment to calculate the effect of EV charging periods to the network along with SPP generated power. The impact of different consumer profiles was applied to the network model as different EV car brands with variable charging and battery capacity profiles. The proposed operation strategy leads to the reduction of energy bought from the grid, reduction of transmission line losses along with no harmful effect on voltage regulation of the network, as aimed during the design stage. The obtained results of the study indicated the effect of the EVs and SPP on the grid considering optimal operation criteria within the expected limitations of voltage regulation. The proposed system and operation methodology leads to the reduction of line losses as indicated in the simulation results of the study. The roof mounted SPP was considered for a 3-floor parking lot for 100 EVs, which has the maximum generation capacity of 120 kVA within the physical limitations. After the design stage, the solar radiation data was implemented to the simulation model in ETAP environment. The obtained results indicate that the SPP will cover all the power consumption of the EV parking lot for 4 hours during winter conditions, while it is calculated as 7 hours during summer conditions. The presented study is considered as an example for an EV parking lot equipped with PV panels, which can be expanded in accordance with parking lot requirements. The proposed network model and methodology is aimed to be equipped with adaptive protection relays in future studies.

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Figure Captions

Fig. 1.	Parking lot and SPP integration scheme.
Fig. 2.	SPP power generation graphic for summer and winter conditions.
Fig. 3.	Loading graphic for the randomly selected parking duration of the EVs.
Fig. 4.	Single line diagram of the IEEE 13 bus network with integrated SPP.
Fig. 5.	Comparison chart of the EVs and SPP for summer and winter conditions.
Fig. 6.	Power buy & sell graphic of EV parking lot from the grid.
Fig. 7.	Main transmission line losses variation graphic.
Fig. 8.	Main transmission line ampacity.
Fig. 9.	Voltage regulation of parking lot MV bus.

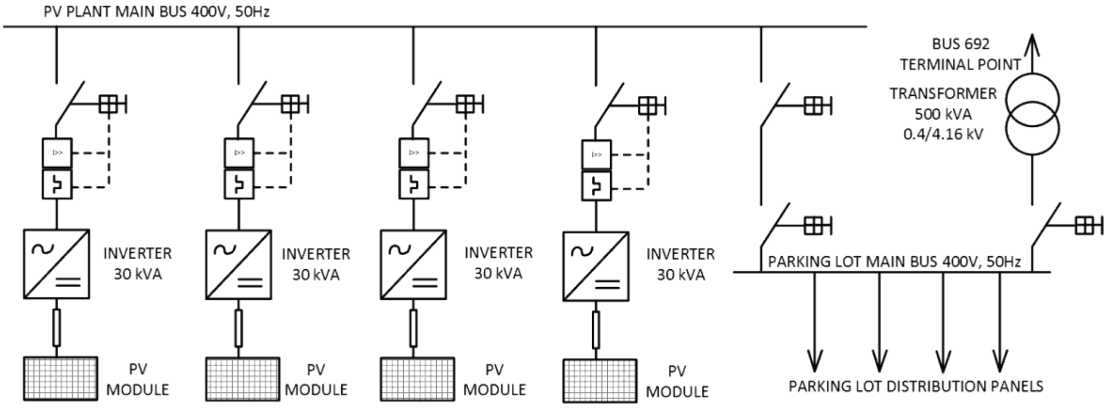

Fig. 1. Parking lot and SPP integration scheme.

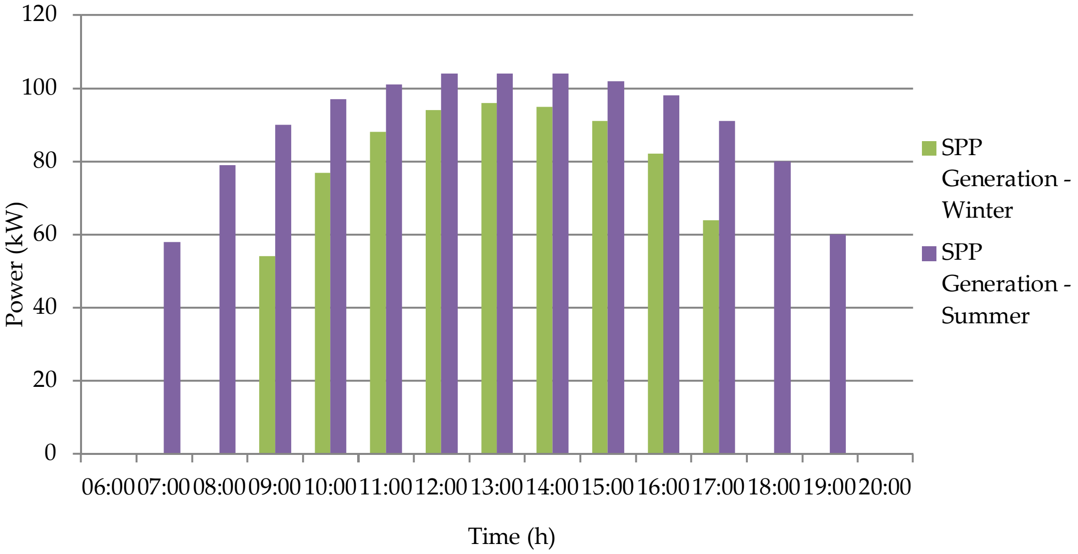

Fig. 2. SPP power generation graphic for summer and winter conditions.

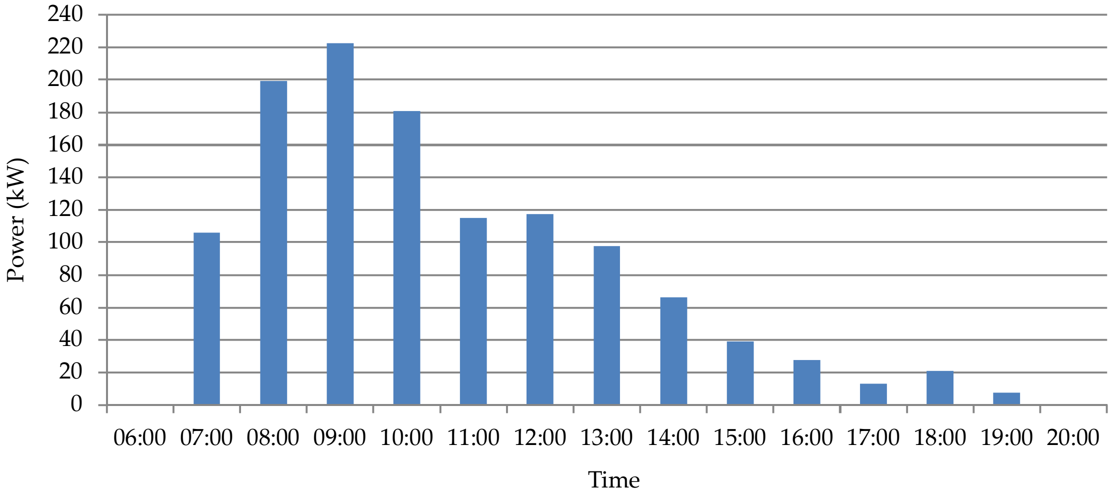

Fig. 3. Loading graphic for the randomly selected parking duration of the EVs.

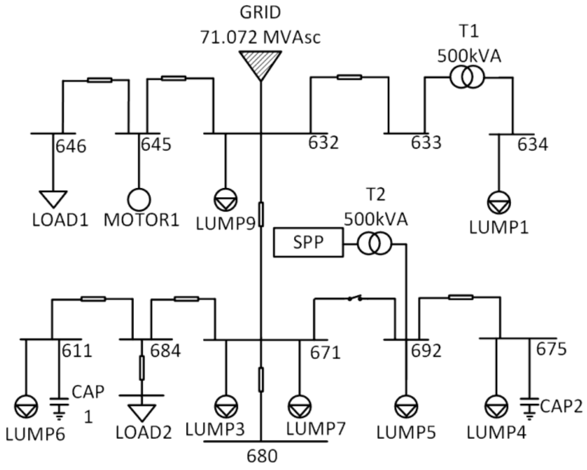

Fig. 4. Single line diagram of the IEEE 13 bus network with integrated SPP.

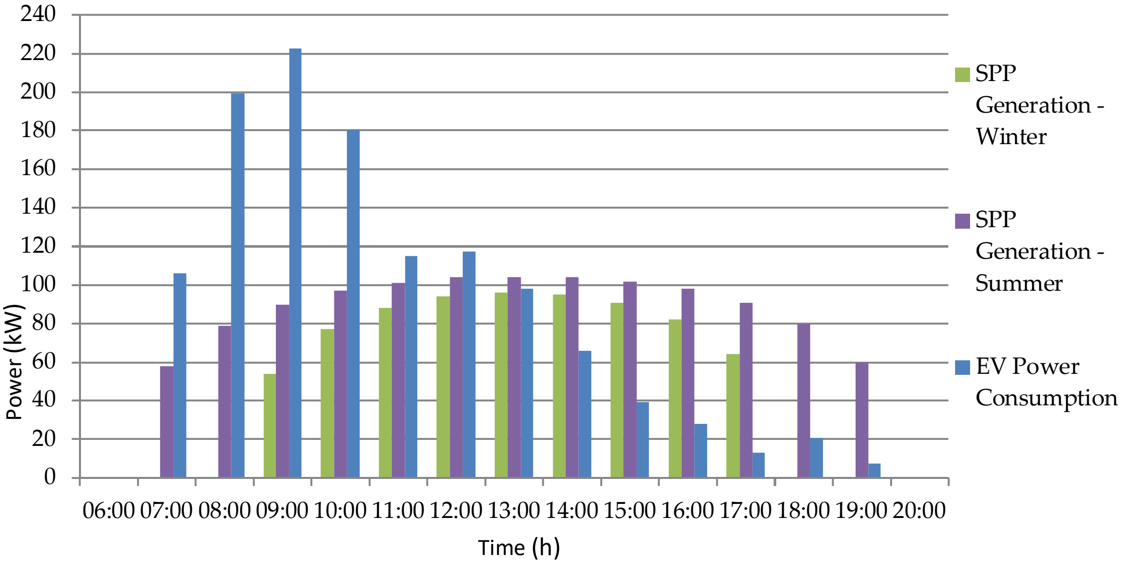

Fig. 5. Comparison chart of the EVs and SPP for summer and winter conditions

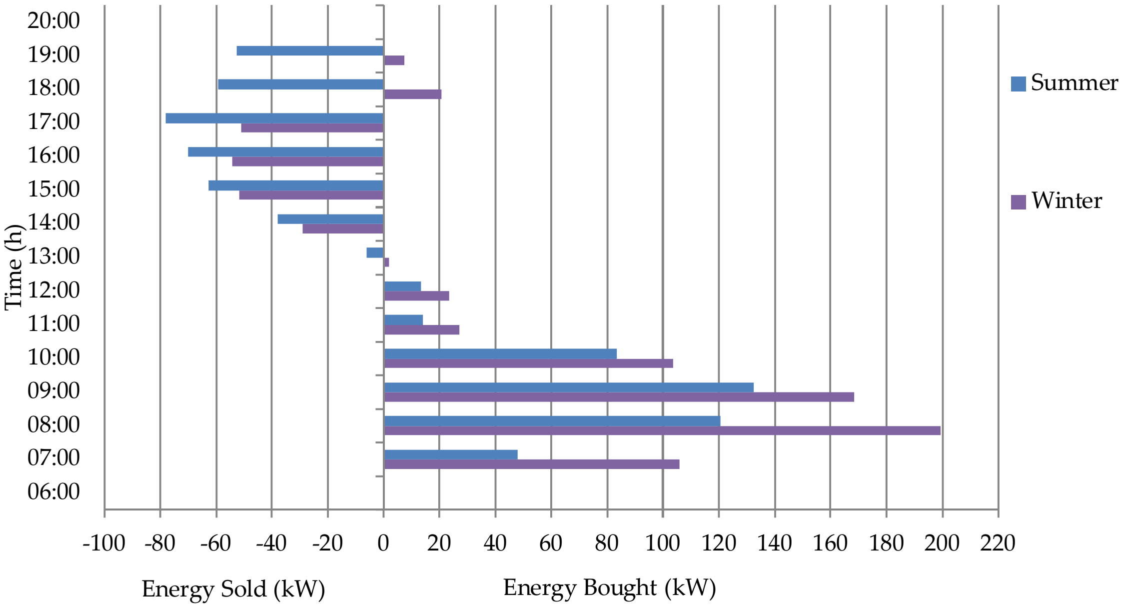

Fig. 6. Power buy & sell graphic of EV parking lot from the grid

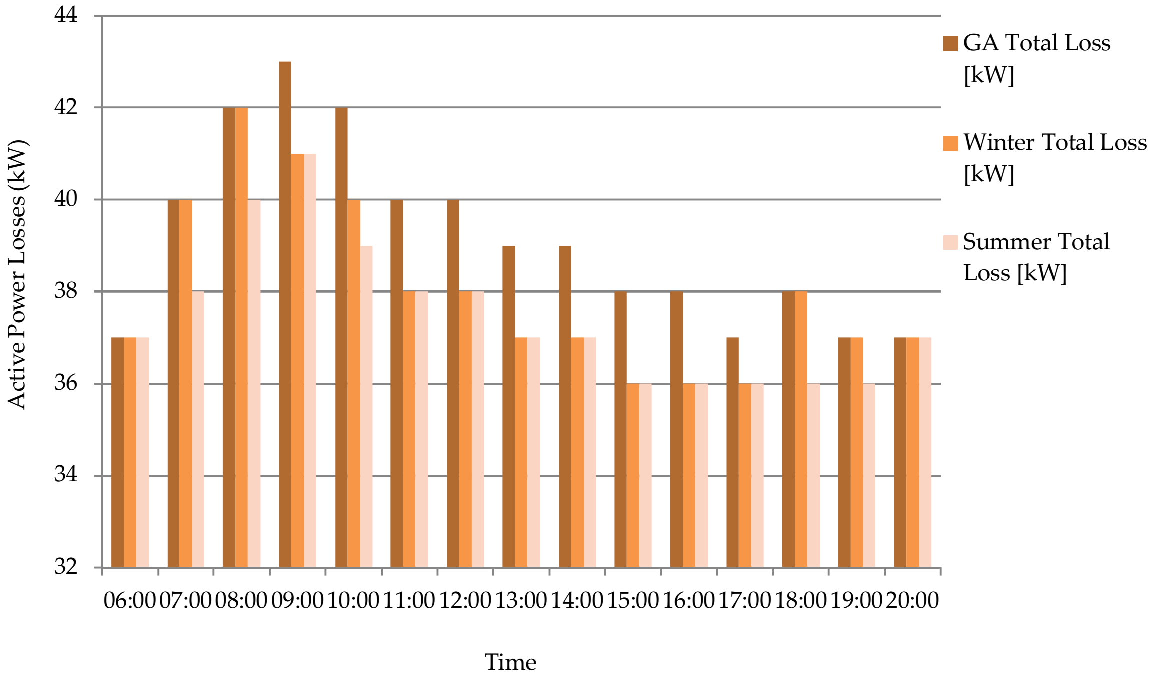

Fig. 7. Main transmission line losses variation graphic (GA – Grid Alone).

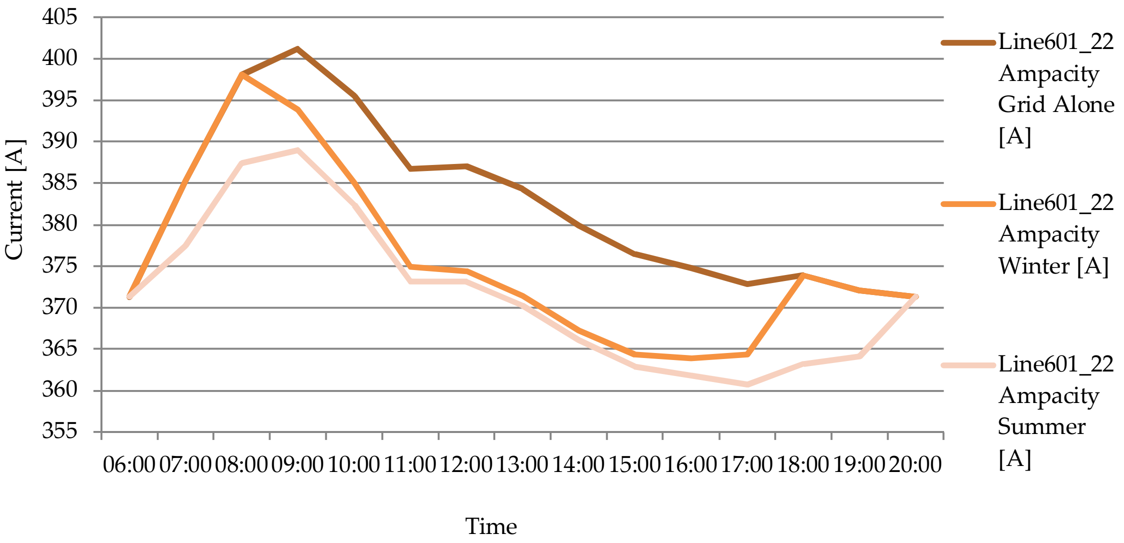

Fig. 8. Main transmission line ampacity.

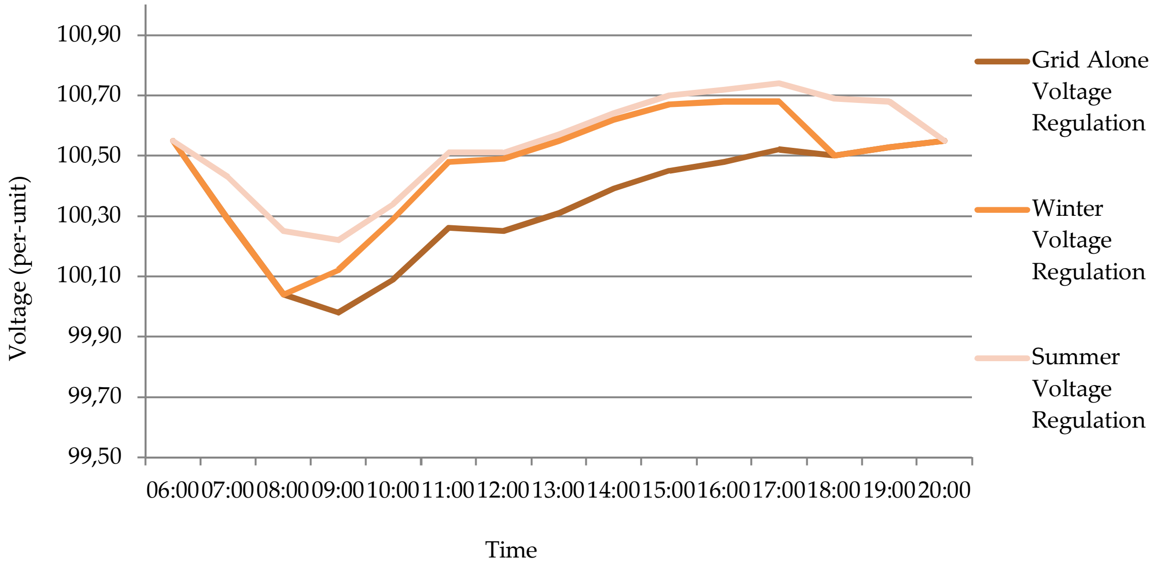

Fig. 9. Voltage regulation of parking lot MV bus.

Tables

Tab. 1. PV panel design data [27].

Tab. 2. PV module design data.

Tab. 3. Inverter design data.

Tab. 4. Solar radiation data and power generation variation for winter and summer.

Tab. 5. Technical data of selected EVs.

Tab. 1. PV panel design data [34].

Panel ID	Power (W)	Isc (A)	Vdc Max (V)	Power Tolerance
KD205GX-LPU	205	8.33	600	5%

Tab. 2. PV module design data.

Number of Panels	Vdc (V)	Pdc (kW)	Idc (A)
9*17=153	244.71	32.823	134.13

Tab. 3. Inverter design data.

DC Power (kW)	Voltage (V)	Vmax /Vmin	FLA (A)	Efficiency (%)	Imax (%)
34	220	%120 / %80	154.5	90	150
AC Power (kVA)	**Voltage (V)**	**Pfmax / Pfmin**	**FLA (A)**	**PF (%)**	**K Factor**
30	400	100 / 80	44.17	85	150%

Tab. 4. Solar radiation data and power generation variation for winter and summer.

Time	Solar Radiation [W/m^2]		Max. Power Generation [kW]	
	Winter	Summer	Winter	Summer
06:00	0	158	0	0
07:00	0	520	0	58
08:00	55	696	0	79
09:00	481	794	54	90
10:00	680	852	77	97
11:00	776	887	88	101
12:00	824	906	94	104
13:00	841	912	96	104
14:00	833	907	95	104
15:00	797	889	91	102
16:00	720	855	82	98
17:00	567	798	64	91
18:00	221	704	0	80
19:00	0	534	0	60
20:00	0	185	0	0

Tab. 5. Technical data of selected EVs.

Model of the Car	Battery Capacity (kWh)	Charging Power (kW)	Model of the Car	Battery Capacity (kWh)	Charging Power (kW)
Volkswagen E-Golf	24	7.2	Ford Focus Electric	23	6.6
BMW i-3	22	6.6	Kia Soul EV	27	6.6
Mercedes B-Class	28	10	Mitsubishi i-MiEV	16	3.3
Tesla Model - S	85	17.2	Chevy Volt	17	3.3
Fiat 500E	24	6.6	Nissan LEAF	24	6.6