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Analysis of the impact of Electric Vehicles penetration on distribution systems

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Table of Contents

List of Tables

List of Figures

Executive Summary

The current planning and operation of existing electrical power grids is facing fundamental challenges in view of the envisaged decarbonisation of the power industry. In this domain, a key concern is also the widespread integration of Electric Vehicles (EVs) that can lead to an increase in peak demand that is disproportionately higher than the corresponding increase in annual electricity demand, hence the impact of EVs requires further investigation. Furthermore, the transition of the transport sector in the direction of using renewable energy as the energy source, is another major challenge. According to forecasts 50,000 EVs will be used in Cyprus by 2030 while in 2040 this number is forecasted to be four times higher (200,000 EVs).

In this domain, the steps taken in this analysis starting from the definition of the EV charging profiles that will arise from high penetration levels of EVs in Cyprus, the simulation of the impact of a large integration of EVs and photovoltaic (PV) in the reference grid of Cyprus, are presented. In all simulated cases, specific considerations were taken into account for the EVs plugged-in to the grid such as the quantity of EVs, charging profiles, mode of charging and mobility patterns (via the percent variation of energy charged [1]).

This report summarizes the methodology and results obtained from the analysis of the distribution system of Cyprus in the increased penetration of EVs. More specifically, three charging scenarios were examined. The first scenario investigates uncontrolled charging in which the EVs are charged based on a charge start time probability profile, emulating the case when most charging occurs at households and workplaces [1]. In this scenario the mobility curves are not considered and a constant semi-fast charge mode is used for the simulations. Secondly, an uncontrolled charging scenario considering mobility curves is examined, in which the start time of charging and duration of charge is considered able to emulate people's driving patterns. Lastly, a controlled EV charging (smart charging) scenario is investigated, in which the charging of EVs is controlled by the grid operator in order to optimise generation and grid capacity based on the profile of the aggregated per transmission level substation load curves. All three scenarios were simulated initially without PV systems connected to the grid (baseline scenario) and then with a large integration of PV within the investigated grid. For the aforementioned scenarios the main assumption made was that all EVs are equipped with a 36 kWh Li-Ion battery which is expected to dominate the market in the near future [2].

From the results obtained for the three EV charging scenarios simulated on typical feeders of a reference High Voltage (HV) substation, it is evident that even in the most load demanding case, which is the "Uncontrolled-Full Charging" scenario, no violations of element/voltage limits are observed. The operation of the investigated feeders with a high level of EVs is found to be within the nominal range and within the system limits. More specifically, the voltage levels at low and medium voltage (MV) buses, are slightly reduced and the lines are slightly loaded in comparison with the base scenario with no EVs. Finally, the results obtained when simulating the "Controlled EV charging" scenario, demonstrated that there is only minor change on the operation of the investigated feeders/substation in comparison to the base scenario with no EVs. This further signifies the importance of controlled charging (smart charging).

Accordingly, by introducing both the EVs and PV integrated into the MV reference grid, the voltage levels are improved in comparison to the base case simulated when no PV are included. The results showed that the lines are not significantly affected when the surplus energy consumed by EVs charging is covered by the local PV system production.

Finally, amongst the simulated voltage regulation methods investigated for the inverter settings of PV (operating at power factor 1, 0.95 and cosφ(P)), the operation at power factor equal to 0.95 showed better performance in terms of voltage levels compared to the other voltage regulatory methods. This voltage regulatory scheme can therefore contribute in the improvement of the voltage levels at both low and medium voltage side. The results also showed that the introduction of PV reduces the net load with positive results capable of counterbalancing the effect of large scale EV integration.

1. Introduction

The EU's short-term 2020 and medium-term 2030 agenda for emission reductions, increased renewable penetration and efficiency improvements is fostering the development of decentralized generation and EVs. EVs present a promising direction in the transportation section for decreasing both reliance on fossil fuels and emission of greenhouse gases. In addition, driving on electricity has been found to be less expensive per kilometre compared to fossil fuel [3]. While the roll-out of EVs presents both environmental and financial benefits, the potential impacts on the electric grid, especially the distribution system, could be an issue if EV charging is totally uncontrolled. With a great number of EVs expected in the near future connected to the grid, the randomness of their charging and discharging could affect seriously the operation of the existing power system. To support the emerging load mix the power system will need to become smarter. In this sense, EVs will therefore represent a significant new load on the existing distribution networks, which must be further studied in term of power quality in combination with the dispersed PV generation to depict possible negative operational issues.

The additional charging load will typically be supplied by distribution transformers either in residential/commercial or industrial areas. A charge for 50–65 km of driving will require 6.5–12.4 kWh of power, since most plug-in vehicles require 0.13–0.19 kWh of charging power for a km of driving [4]. This can therefore significantly add load to the distribution network as the penetration level of EVs increases. Major changes in load levels and load patterns may require upgrading the distribution transformers or distribution/transmission lines or alternatively impose the adoption of smart load strategies like load shifting and peak clipping. Abnormal conditions, resulting from an increasing number of EVs, could result in degradation of power quality, increased harmonics, voltage violation problems while also potentially damage utility and customer equipment. In addition, significant changes in load patterns can impact line voltages, especially over long feeders. Several EVs plugged into a secondary circuit, or a larger number of cars in a parking lot connected to a lateral feeder, could cause a localized overload on the distribution circuit and transformers. Many distribution circuits may be operated close to their operating limits and the additional load may push them above those limits. For example, a 25 kVA or 50 kVA distribution transformer on a single-phase lateral may not be able to sustain the charging loads of several plug-in vehicles while it is subjected to variations in demand due to normal customer activities.

According to forecasts, approximately 200,000 EVs will be used in Cyprus by 2040. At such penetration, the electricity grid could begin to require significant and costly capacity upgrades to support the additional demand of EV charging, if EV charging is left unmanaged as per the unconstrained charging scheme. To investigate the impact and the effectiveness of different approaches for mitigating the potential overloading of the distribution network due to electric vehicle charging, charging profiles were defined, simulated and evaluated using DIgSILENT PowerFactory.

2. Background theory

In this section information on the existing situation of EVs, charging profiles and mobility patterns in Cyprus is described.

2.1 Electric vehicles connected to the grid

Even though, this report focuses at grid to vehicle (G2V) charging modes it is worth noting that future technologies are expected to utilize both G2V and Vehicle to grid (V2G) options. In particular, V2G describes a system in which EVs communicate with the power grid to sell demand response services by delivering electricity into the grid or throttling their charging rate based on grid control signals. EVs can serve as stored and distributed energy resources as well as reserves for unexpected outages when they have proper on-board power electronics, smart connections to the grid and interactive charger hardware control [5]. In this aspect, a bidirectional charging system is essential to support energy injection into the grid [6]. The car batteries are charged with different charging patterns which causes the load in the different substations to be higher than before with the introduction of EVs.

Economic costs, emissions benefits and distribution system impacts of EVs depend on vehicle and battery characteristics as well as charging and recharging frequencies and strategies. In general, the implications of EV charging to the grid depend on:

- Whether EVs are charged during the peak or valley periods of the load curve which determines the loading of the consumption. In particular, integrating off-peak charging generally requires fewer modifications to system capacity, since the system is already built to handle load increases up to the projected peak.
- How the EV charging impacts the supply curve which determines the bulk power price impact and the emissions from the added electric power generation.
- How fast an EV is charged (i.e. the capacity and charging mode of the EV) which determines the increase of the required load.
- The location where an EV is charged which has a direct bearing on the costs of integration, since the load curve, costs and fuel mix are highly location-dependent.

When no smart charging schemes are available, EVs charge like any other load. Coordinated smart charging and discharging in the scope of optimizing both time and power demand appears to be the most beneficial and efficient strategy for both the grid operator and EV owners in the coming future [2]. A smart charging system utilizing V2G technology and proper load management can shift loads and avoid peaks while also minimizing the impact of EVs on the utility grid.

2.2 Charging modes permitted in Cyprus

In Cyprus the standards followed for EV charging are the IEC 61851 "Electric vehicle conductive charging system" [7] and IEC 62196 "Plugs, socket-outlets, vehicle couplers and vehicle inlets – Conductive charging of electric vehicles". The modes of charging permitted are:

- Mode 1 - AC Charging - Standard charge / Slow-charge: This is a direct, passive connection of the EV to the AC mains, up to 250 V single-phase, at a maximum current of 16 A and 3.7 kW (single phase). It requires up to 8-14 hours to fully charge a battery depending on the initial state of charge and capacity of the battery. This charging mode is ideal for overnight residential charging purposes, but is not recommended for quick commercial or public charging purposes.
- Mode 2 - AC Charging - Standard charge / Semi-fast charge: This is a direct, semi-active connection of the EV to the AC mains, up to 250 V single-phase at a maximum current of 32 A and 7.3 kW (single phase). There is a direct, passive connection from the AC mains to the EV Supply Equipment (EVSE), which must be part of, or situated within 0.3 metres of the AC mains plug. From the EVSE to the EV, there is an active connection, with the addition of the control pilot to the passive components [8]. The EVSE provides protective earth presence detection, residual current, over-current and over-temperature protection and functional switching depending on vehicle presence and charging power demand. EVs require about 4-8 hours to fully charge their battery, depending on the capacity and state of charge (SOC) of the battery. It is the most common charging level found in homes and commercial areas.
- Mode 3 - AC Charging - Industrial type charging appliance / Fast-charge: This is an active connection of the EV to a fixed EVSE, up to 250 V 3-phase including earth and control pilot. This is performed either, with a mandatory captive cable with extra conductors, at a maximum current of 250 A or, in a manner compatible with mode 2 with an optionally captive cable, at a maximum current of 32 A and 3-phase 22 kW [9]. The charging supply is not active by default, and requires proper communication over the control pilot to be enabled. The communication wire between car electronics and charging station allows for an integration into smart grids.

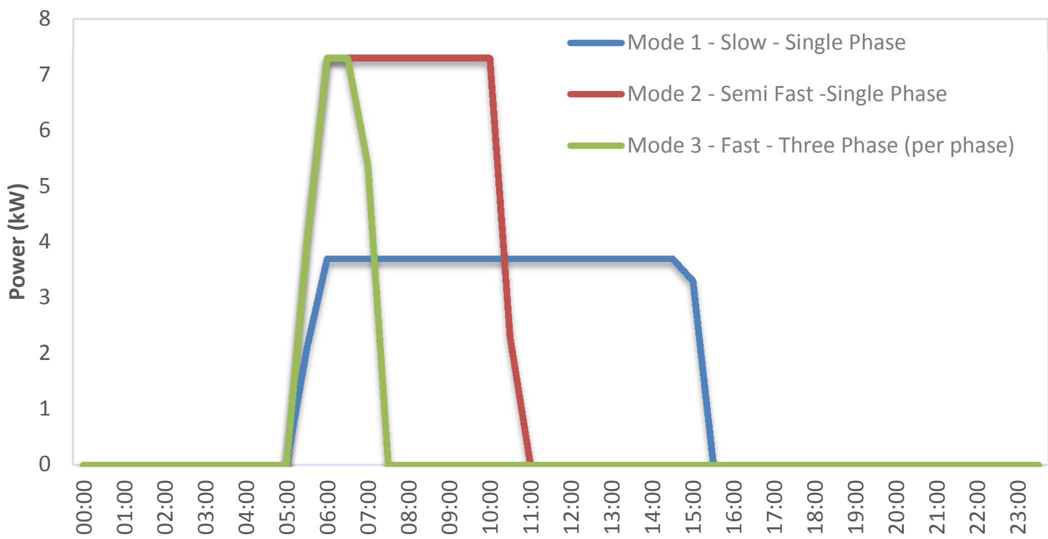

Figure 1. Example of charging rate for slow, semi-fast and fast-charge.

The charging profile of an EV depends primarily on the:

- Battery capacity;
- Battery SOC;
- Type of charging infrastructure and mode.

The Table below provides a general summary of the main technical characteristics of the batteries for most current EVs [10].

Table 1. Battery technical characteristics of EVs [10].

Types	Acronym	Autonomy (km)	Energy (kWh)
Battery electric vehicle	BEV	< 150 – 400	17 – 60
Plug-in Hybrid electric vehicle	PHEV	< 60	3 – 26.4

Furthermore, a review of the technical characteristics of several battery electric vehicles (BEVs) currently in the market is provided in Table 2.

Table 2. Technical characteristics of typical BEVs in the present market.

EV	EPA Range (miles)	Battery Size (kWh)	Charging Rate (kW)
Chevrolet Volt	200	60	7.2
Volkswagen E-Golf	83	24	7.2
Smart Electric Drive	68	17	3.3
Nissan LEAF	107	30	6.6
Mercedes B-Class ED	85	28	10
Ford Focus Electric	76	23	6.6
Chevrolet Spark EV	82	19	3.3
BMW i3	81	22	6.6

Additionally, the Figure below shows all the current EV charging stations in Cyprus (total of 16 charging stations, Mode 2 charging).

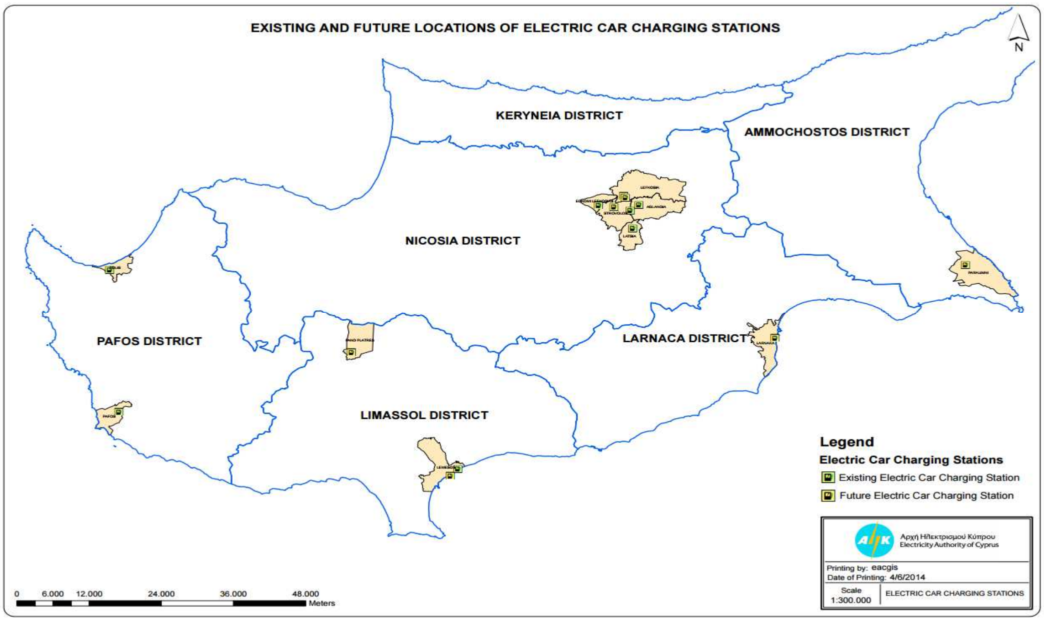

Figure 2. Charging stations currently present in Cyprus.

As an example of EV charging in Cyprus, the Figure below illustrates a charging profile as obtained for an EV charging at a Mode 2 charging station administered by the Electricity Authority of Cyprus (EAC).

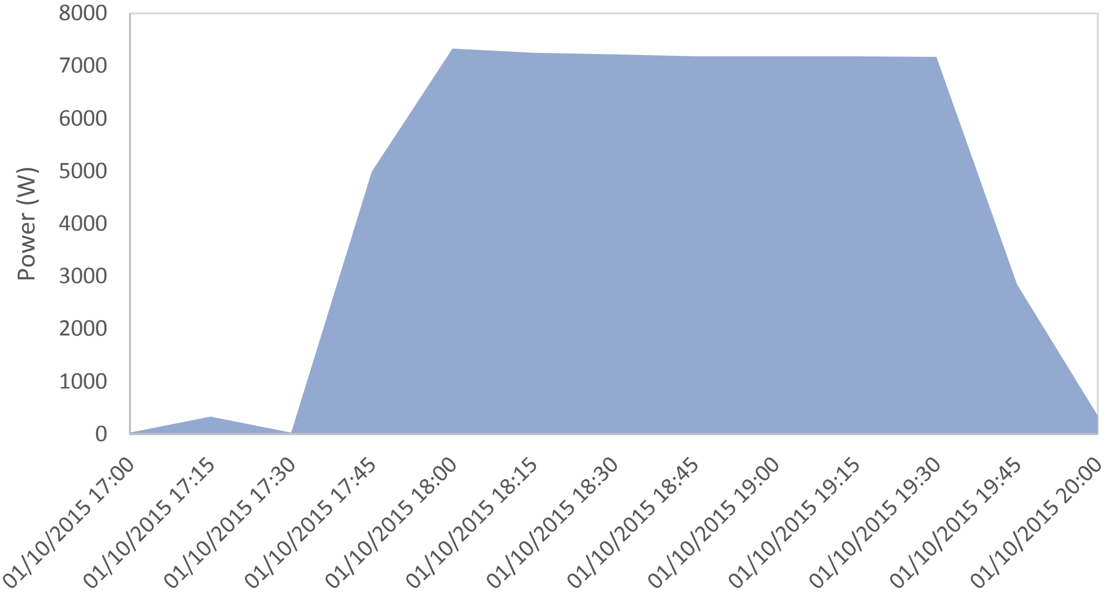

Figure 3. Typical semi-fast EV charging profile as obtained from a charging station administered by the EAC (provided by the EAC).

2.3 Mobility patterns

Mobility patterns and driving behaviours are particularly useful for EV impact analysis to the grid. A number of studies have previously correlated the charging behaviours with mobility curves in order to define charging profiles [11][1].

For the scope of this investigation the mobility patterns acquired by the Diavlos platform [12] of the Cyprus Ministry of Communications & Works (MCW) have been utilised. The main objective of the Diavlos platform is the integration of best practices, existing operations and studies and EU directives for the development of Intelligent Transport Systems in urban and suburban environments with similar characteristics, such as island medium sized cities. In addition, through the platform proven technologies as well as completely innovative solutions with high matching investment, such as detectors recording travel times via wireless technology are implemented in some cities in Cyprus.

The following Figure depicts the typical daily average mobility pattern of conventional passenger cars for a typical day during the week and the weekend in Nicosia. The plot of the weekday typical mobility pattern clearly shows two peaks in mobility behaviour which are due to the trips of people to their workplaces and households.

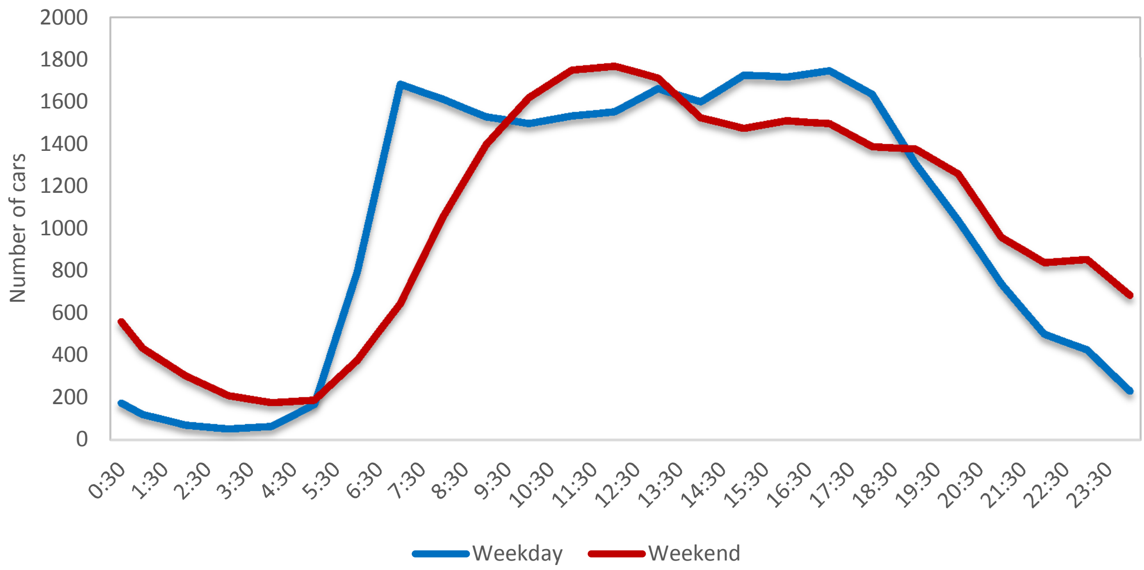

Figure 4. Daily average mobility pattern of conventional passenger cars for a typical weekday and weekend in Nicosia.

3. Methodology

In this section the methodology followed to define EV charging profiles and to analyse their effectiveness on the electricity grid is explained.

The flowchart below summarizes the methodology followed and steps taken to define EV charging profiles at aggregate per transmission level substation and to simulate a large integration of EV and PV in the MV grid of Cyprus. Detailed explanation on the methodology followed for each step is provided in the following sections.

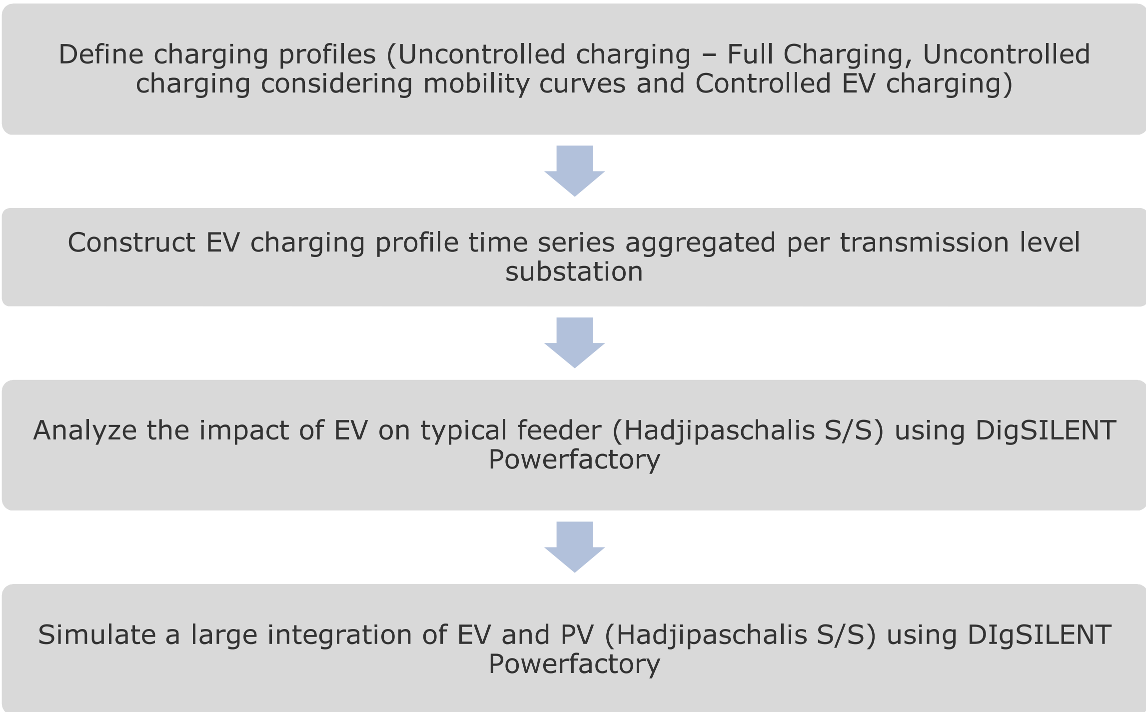

Figure 5. Flowchart of methodology followed and steps taken to define the EV charging profiles and investigate their impact on the electricity grid.

3.1 EV charging strategies

For the purpose of analysing the impact of EV penetration to the grid of Cyprus, three different charging scenarios were examined:

- **Uncontrolled charging – Full Charging**: In this scenario EVs are charged based on a charging start time profile [1] emulating the case when most charging occurs at households and workplaces. The mobility curves are not considered, thus representing the "worst case scenario" when all EVs charge fully (perform a full charge) during the same day. Another important parameter considered is the mode of charging to be semi-fast charging.
- **Uncontrolled charging considering mobility curves**: In this scenario the EV charging profile is consistent with people's driving behaviours (considering therefore the mobility patterns) by taking into account the charging start time and the relative duration of energy recharged [1]. In this way, this scenario represents the anticipated typical behaviour of charging of an average day. The mode of charging adopted in this scenario is semi-fast charging.
- **Controlled EV charging (smart charging):** In this scenario controlled EV charging (smart charging) is considered in which the charging of EVs is controlled by the grid operator in order to optimise generation and grid capacity based on the load curve characteristics. The mode of charging adopted in this scenario is slow charging.

All above scenarios were simulated initially without PV systems present within the grid (baseline scenario) and then with a large integration of PV within the investigated grid.

3.2 Assumptions for the EV characteristics

As EVs are not yet introduced in large scale in Cyprus (in both rural and urban areas and there is very limited information with respect to this), it is necessary to consider the following parameters for the EV charging impact analysis:

- Number of EVs charging per transmission level substation;
- Battery capacity information of EVs charging;
- SOC of EV battery;
- Profile of charging which is dependent on EV (usually constant profile);
- Mobility transportation patterns in Cyprus.

It must be noted that the EV charging profile is complex to be modelled in a deterministic way because it depends on factors such as transportation mobility patterns at a location during the day, technical battery features (such as capacity and charging method) and the number of EVs being charged at the substation in the investigation area.

Based on the above facts daily EV charging profiles were defined in a probabilistic way (for a typical weekday and weekend) for an EV with Li-Ion battery of capacity 36 kWh which is expected to dominate the corresponding market based on the latest Eurelectric policy paper of 2015 [2].

Accordingly, the defined EV charging profiles at the transmission level were evaluated for each HV substation by considering the patterned EV stress for the future years of 2030 and 2040 using the total forecasted amount of EVs in Cyprus (50,000 and 200,000 EVs, respectively). More specifically, the load capacity of each HV transmission substation in Cyprus for the future year 2030 was used to produce load growth related scaling factors. These load growth scaling factors were then used in order to proportionally distribute the forecasted number of EVs and based on this allocation evaluate the charging profiles of the EVs of each HV substation.

Finally, charging profile time series were constructed for typical feeders of a reference HV substation. The number of EVs connected to the feeders under investigation was calculated based on the total capacity of the transmission substation feeding the specific feeders and taking also into consideration the total number of EVs. The EV charging profiles aggregated per transmission level substation are attached in Appendix 1.

3.3 EV charging profiles

The methodology followed to define EV charging profiles is summarized in this section.

3.3.1 Uncontrolled charging – Full Charging

In this report the term "uncontrolled charging" describes the charging regime of the vehicle battery which starts immediately after reaching a location equipped with a charging infrastructure without any limitation based on any time-of-use or other smart options to control the charging mode of the EV.

In particular, this uncontrolled scheme emulates the scenario when all EVs charge fully (perform a full charge) during the same day, representing in this way the "worst case scenario". In addition, most EV charging occurs at households and workplaces. The uncontrolled scheme is intended to give an indication of the timeframe over which the electricity supply industry needs to implement a mitigation strategy to reduce the respective impact.

It is worth noting that several studies have performed EV penetration grid impact analysis, using a constant recharge load model [11]. Specifically, for this scenario, it was assumed that each EV on average consumes 36 kWh electricity from the power grid on a daily basis. In summary, the following assumptions were made for this charging scenario:

- EVs will have its battery completely discharged (SOC 0 %) in order to start a recharge process;
- Profile of charging is constant;
- Semi-fast charging mode is used.

For this uncontrolled charging scenario, EV charging is spread throughout the afternoon, evening, and night time hours [13], based on the charging start time distribution of EVs [1], demonstrated in Figure 6. The plot shows that vehicle owners tend to favour the charging of their EVs between 7 am and 6 pm at their workplace as well as late evening in their households, given that the typical arrival times from work are between 6 pm and 9 pm. This will lead to more concentrated EV charging during the typical peak system power demand [14].

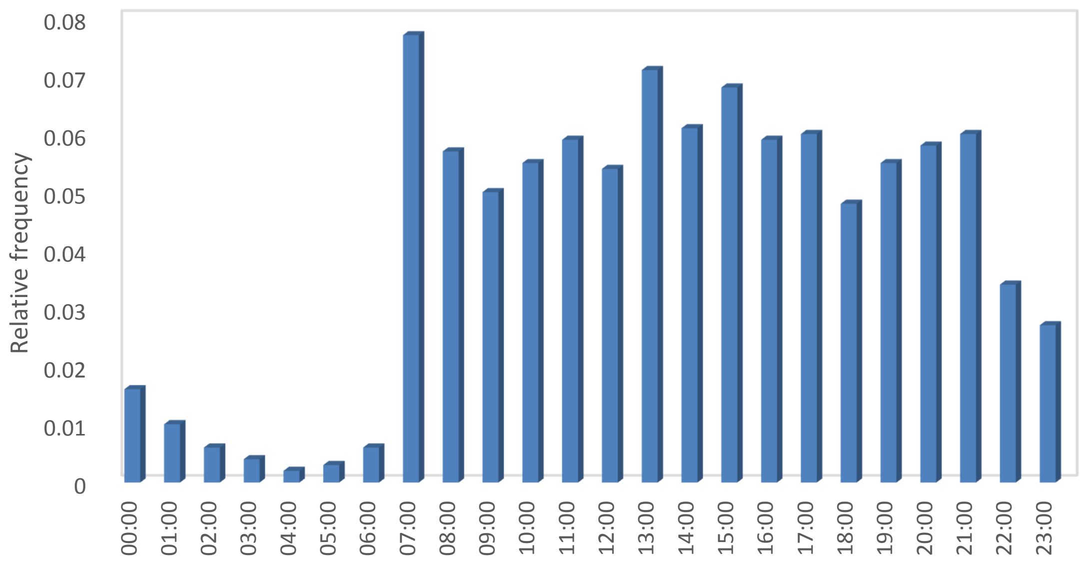

Figure 6. Charge start time distribution [1].

In the scope of defining EV charging profiles both the charging start time distribution, energy required per charge event, charge parameters are considered. The EV charging profile parameters for constant charging are demonstrated as an example in Figure 7.

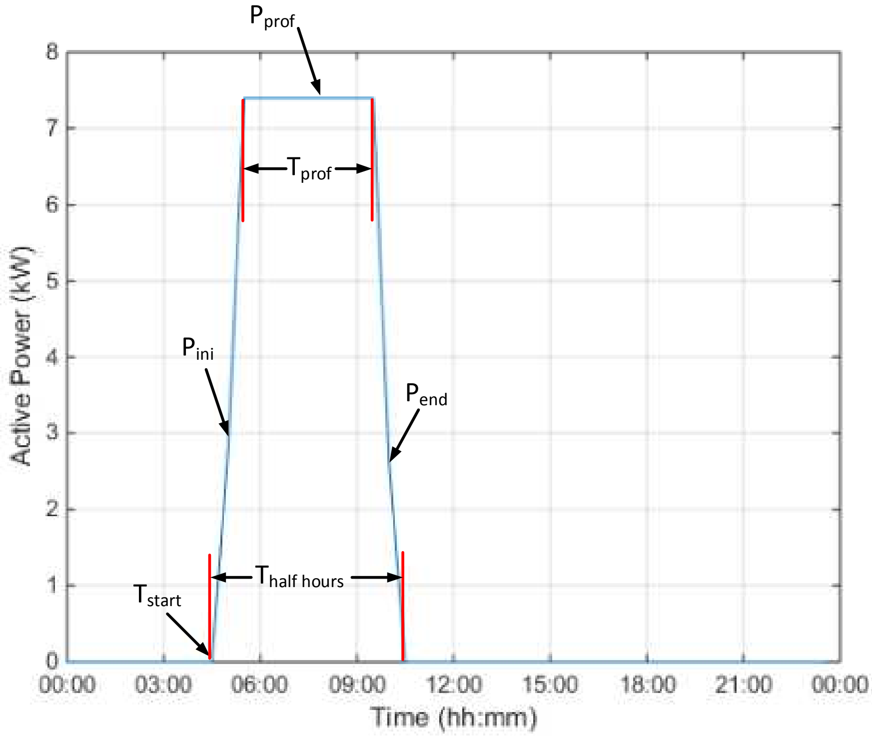

Figure 7. Typical EV profile for a 36 kWh EV (constant charging).

In more detail, the start time, T_{start}, is obtained from the charge start time distribution depicted in Figure 6. The P_{prof} is the constant power consumed by an EV which is defined by the charging mode (for example for slow charging mode the P_{prof} is 3.7 kW). The P_{ini} is the active power consumed initially by the EV and depends on the time of connection in the first half hour. As the active power is averaged over half hour periods and by considering that the EV charging power is constant over the whole charging duration, the P_{ini} can take a value between zero and P_{prof} (a normal distribution is used to obtain P_{ini} in a probabilistic way having values in the aforementioned range). For the "Uncontrolled charging – Full Charging" scenario, the remaining parameters shown in Figure 7 are calculated by using the battery capacity, B_{cap} (36 kWh):

$$P_{end} = 2 \cdot \text{modulo}(\{\text{B}_{cap} - P_{ini} \cdot 0.5\}, P_{prof}) \tag{1}$$

$$T_{prof} = \frac{2 \cdot (\text{B}_{cap} - P_{end} \cdot 0.5 - P_{ini} \cdot 0.5)}{P_{prof}} \tag{2}$$

$$T_{half\ \ hours} = T_{prof} + 2 \tag{3}$$

Where, T_{prof} is the amount of half hour slots at which the active power is equal to $P_{prof.}$

Furthermore, by repeating the aforementioned process for the construction of EV charging profiles it is possible to obtain an aggregated EV profile for any number of EVs.

The following Figure shows the aggregated per transmission level load profiles with the uncontrolled EV charging load of 50,000 EVs, of the average weekday and weekend for the future year 2030. The plot clearly shows that EV charging will constitute a large part of the overall energy use.

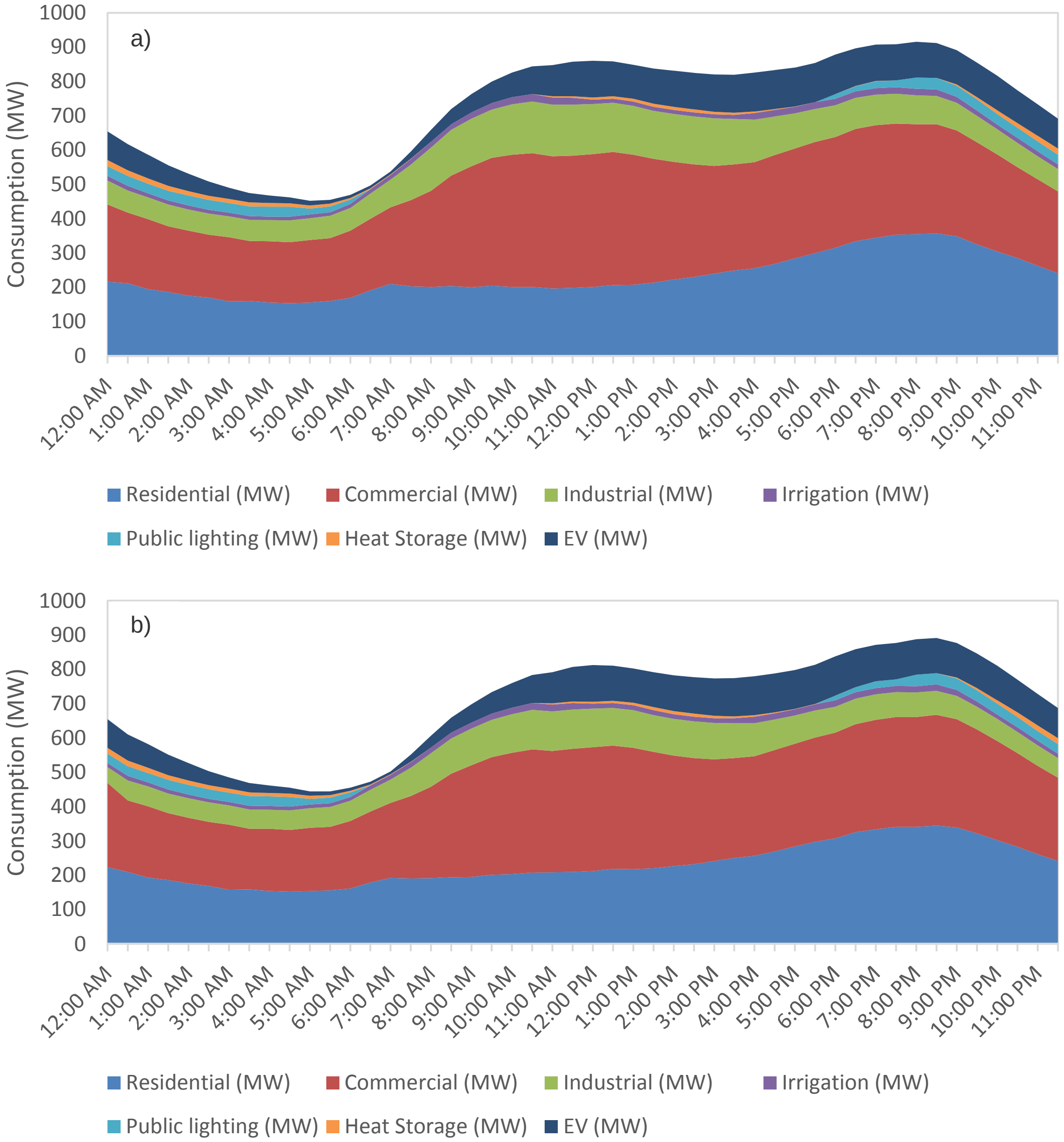

Figure 8. Aggregated per transmission level load profiles with the uncontrolled EV charging load of 50,000 EVs, for the future year 2030 for the average a) weekday and b) weekend.

3.3.2 Uncontrolled charging considering mobility curves

In order to model the charging demand (occurrence and duration of charging) of EVs, it is necessary to consider the driving pattern of EVs. For this reason, the mobility behaviour in Cyprus was modelled in a probabilistic way based on the charging start time distribution presented in [1] and exhibited in Figure 6, along with the relative frequency of energy per charge event, shown in Figure 9 [1], which can be easily converted into duration of charge if the charging mode is known.

This is a more realistic approach compared to the "Full Charging" scheme which does not take into account the fact that the battery is not fully discharged after a trip. More specifically, the energy required per charge event has been found to follow the probability distribution shown in Figure 9.

For this scenario, the EVs charging profile is obtained by applying equations (1), (3) and (5) and by adopting a semi-fast charge mode at 7.3 kW (single phase). The following equation is used to calculate T_{prof}:

$$T_{prof} = \frac{2 \cdot (E_{per\ charge} - P_{end} \cdot 0.5 - P_{ini} \cdot 0.5)}{P_{prof}} \tag{5}$$

Where, $E_{per\ Charge}$ is the energy required per charge event which is obtained from the energy required per charge event probability distribution function [1] shown in Figure 9.

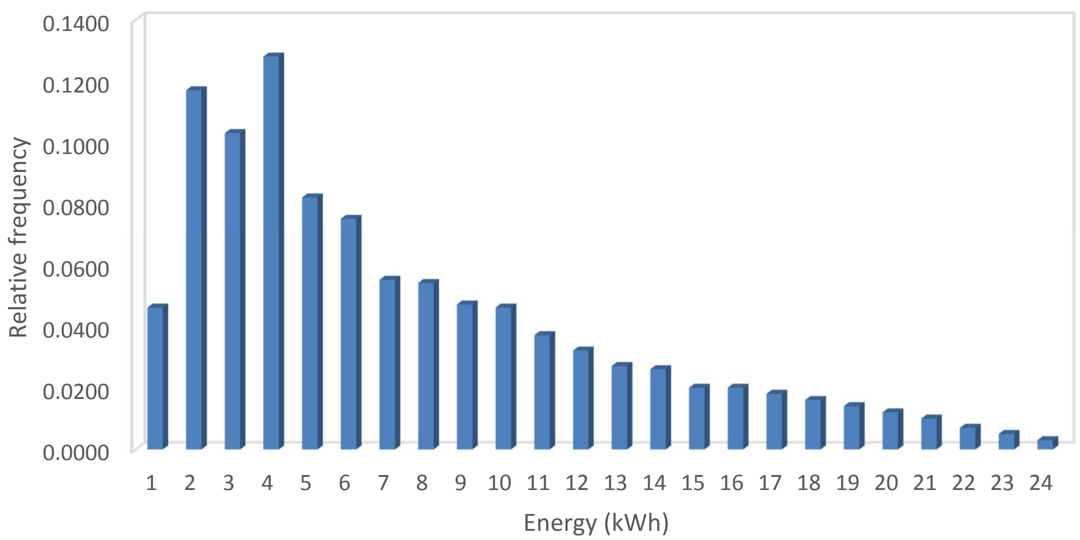

Figure 9. Probability distribution of energy required per charge event [1].

The following Figure exhibits the aggregated per transmission level load profiles with the uncontrolled EV charging load of 50,000 EVs considering also the modelled mobility behaviour, for a typical weekday and weekend for the future year 2030. The shape of the load curve is consistent with people's driving needs between their households and workplace / day activity. As a result, the total load due to EV charging overlaps the peak hours of the original electric load in the evening. This in turn, could further stress the electric power system and have negative consequences on the operation of the electricity grid and on electricity prices. Distribution grid lines congestion due to power peaks, voltage level reduction, requirement of expensive grid reinforcements, as well as wider societal and environmental effects can be caused. Such situations could easily be overcome if the charging was actively managed/controlled to make better a use of the available generation and grid infrastructure.

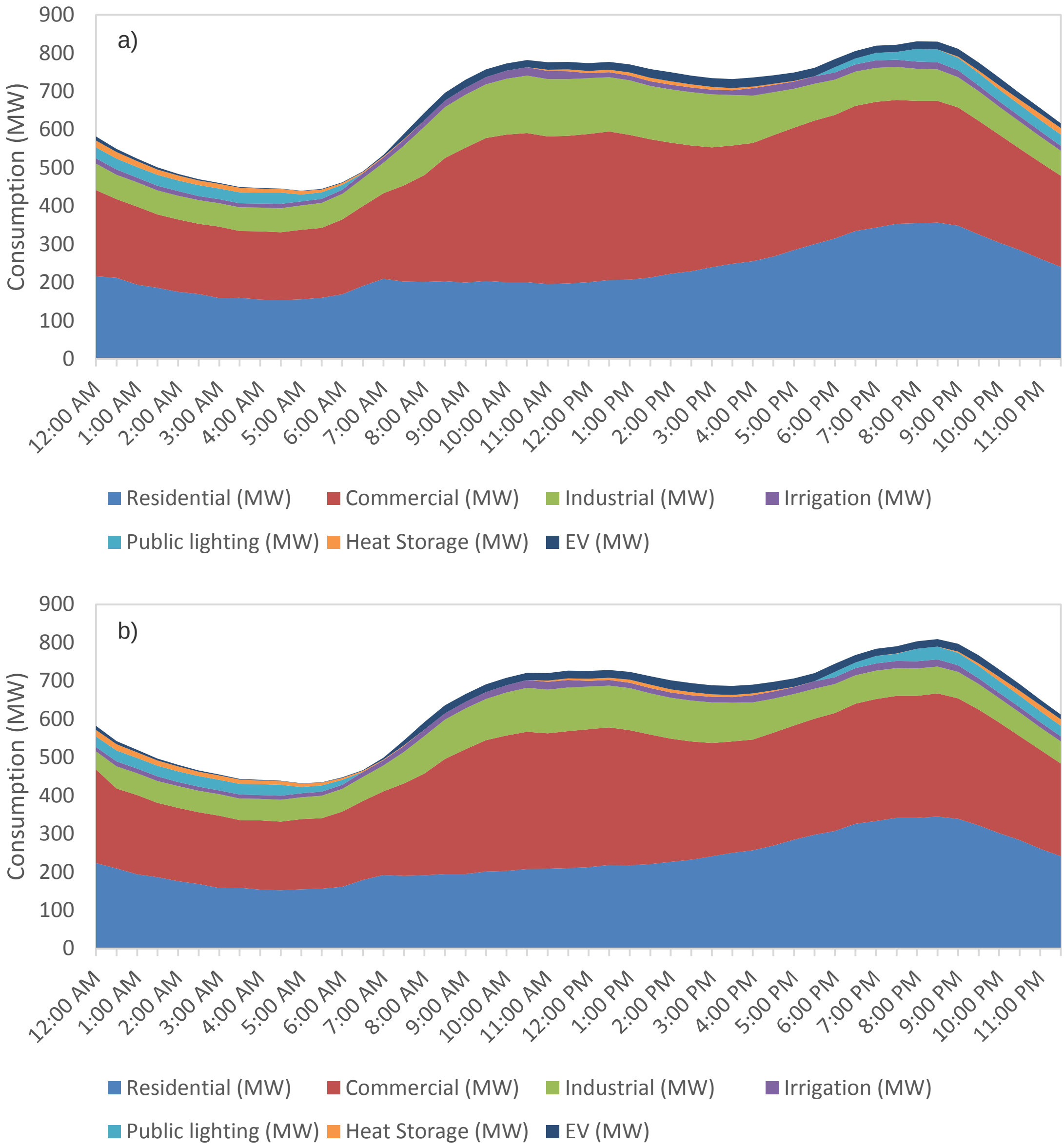

Figure 10. Aggregated per transmission level load profiles with the uncontrolled EV charging load of 50,000 EVs considering mobility patterns, for the future year 2030 for the average a) weekday and b) weekend.

3.3.3 Controlled EV charging (smart charging)

Smart charging is defined as the EV charging scheme of which the start of charging or charging cycle can be altered by external events, providing the EV with the ability to integrate into the whole power system in a grid- and user-friendly way [2]. Smart charging must facilitate the security (reliability) of supply while also meeting the mobility constraints and requirements of the user.

Another consideration is the fact that based on the Eurelectric policy paper of 2015 [2], smart charging should be incentivised so that charging takes place at times when electricity supply is plentiful i.e. from excess renewables and when prices are low. Equally important is the grid friendliness to the charging process by taking into account volatile grid capacity on the local level to avoid unnecessary grid extensions.

In general, when utilities are able to shift load, they can take better advantage of generation from renewable energy sources or manage and control the load factor of the consumption. The objective is to model a smart EV charging scheme which will have the minimum impact/contribution on peak load.

Therefore, for the Controlled EV charging (smart charging) scenario, the probability distribution for the start time is altered in such a way to favour charging operations during times of low load demand. Consequently, for this case a new probability distribution for the start time is defined. In order to achieve this, an algorithm is developed to convert the load curve into a probability distribution having the highest values at low load values. By applying equations (6) to (9), the load profile of Figure 11a is transformed into the probability distribution function of the reverse load behaviour $P^{L}_{\mathrm{Re}verse}$ of Figure 11b.

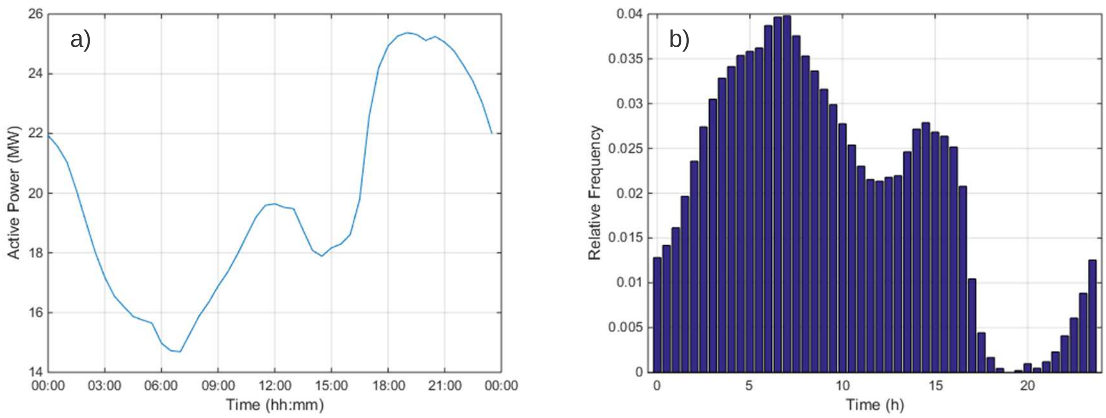

Figure 11. Load profile/probability distribution for inverting load behaviour, a) Sample of load profile and b) Probability distribution for inverting load behaviour.

The following equations describe the algorithm used to model the start time distribution function for the controlled EV charging (smart charging) scenario:

$$L_{norm}^{a} = (x_{t_1} \quad x_{t_2} \quad \ldots \quad x_{t_n})\Big|_{t_n=24:00}^{t_1=00:00} - \min((x_{t_1} \quad x_{t_2} \quad \ldots \quad x_{t_n})\Big|_{t_n=24:00}^{t_1=00:00}) \tag{6}$$

$$L_{norm}^{b} = L_{norm}^{a} / \max(L_{norm}^{a}) \tag{7}$$

$$L_{norm}^{c} = 1 - L_{norm}^{b} \tag{8}$$

$$P_{\mathrm{Re}verse}^{L} = L_{norm}^{c} / \sum_{i=1}^{n=48} L_{norm}^{c}(n) \tag{9}$$

Where, $P_{\mathrm{Re}verse}^{L}$ is the probability distribution function of the reverse load behaviour and x is the load value per half hour. The investigation of this specific scenario is undertaken by using the probability distribution shown in Figure 9 to define the energy per charge event considering an excess of 20 % safety margin (to let customers cope with shifted charging start time) and a slow-charging mode at 3.7 kW (single phase) to investigate the “best case” scenario.

Figure 12 presents the aggregated per transmission level load profiles with smart slow-charging of 50,000 EVs, for the average weekday and weekend for the future year 2030.

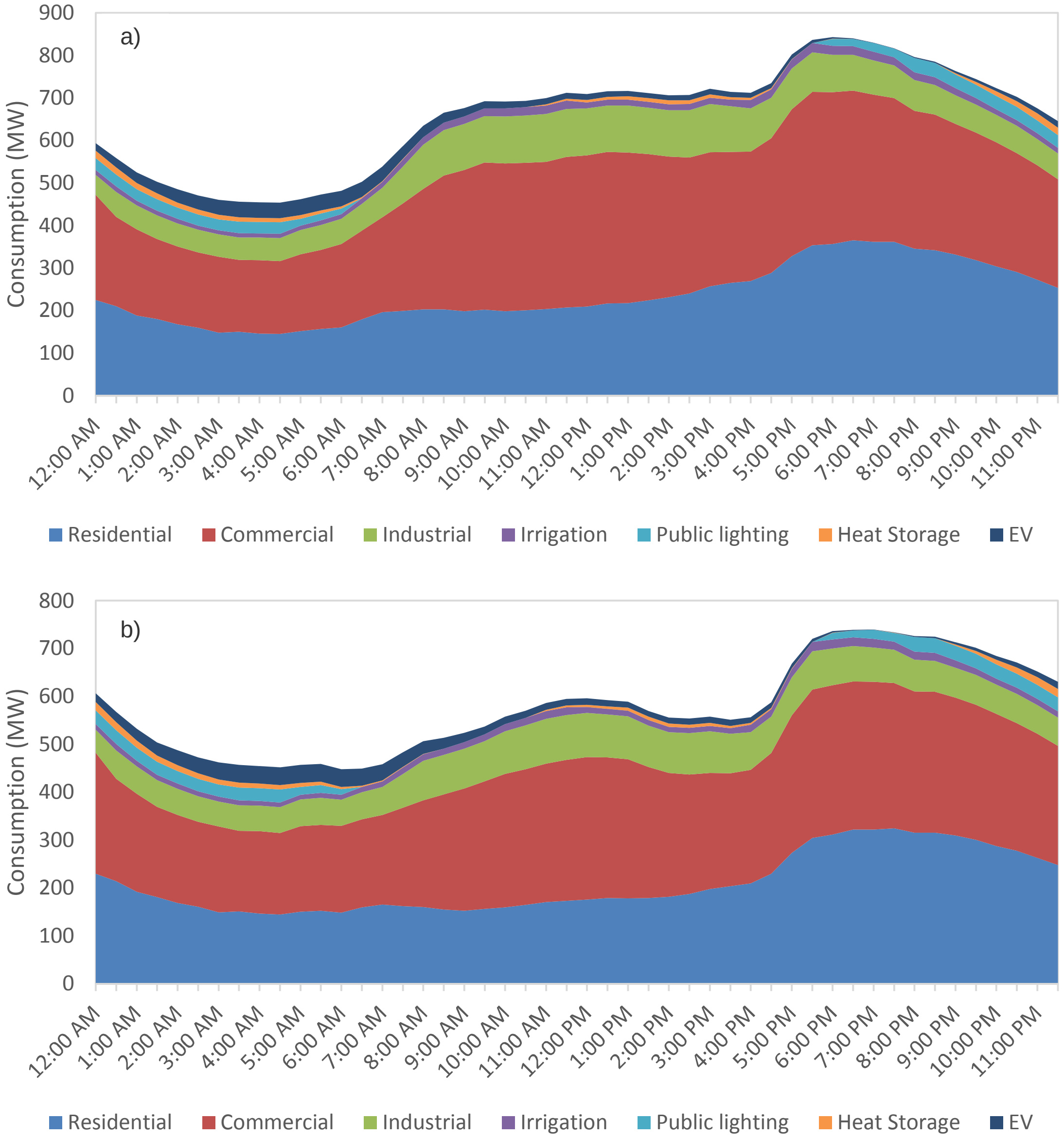

Figure 12. Aggregated per transmission level load profiles with the smart slow-charge of 50,000 EVs, for the future year 2030 for the average a) weekday and b) weekend.

3.4 Large integration of EV and PV in the reference MV grid

Most of the end-users preference is to charge EV when it is convenient rather than during periods of lesser demand. Thus, during daytime, in many local areas the public grid could be strongly stressed by EVs power demand. On the other hand, the energy transition leads to the incitation of policies that support the expansion of renewable energy sources, such as distributed energy generation, and their integration. One of the main challenges for operating the power system with renewables sources such as solar is related to their intermittent behaviour that is influenced by the stochastic nature of their primary energy sources.

The increasing distributed energy generation reveals an increasing complexity for grid managers by requiring better quality and reliability to regulate electricity flows and lessen the mismatch between electricity generation and demand. To overcome this grid issue, the distributed renewable generation tends to be in favour of self-consumption and therefore less stress is applied on the electricity grid.

The next task performed, following the definition of the three aforementioned EV charging scenarios, was to simulate a large integration of EV and PV in the reference MV grid. More specifically, the aim of this scenario is to investigate the effect on the power consumption profile when adding PV generation and electric vehicle load (different concentrations of EV and PV) and how its implementation is going to influence the power grid.

In particular, the impact of EVs, by simulating the previously explained EV charging scenario on a reference HV substation (Hadjipaschalis S/S), was investigated with and without PV. Specifically, the PV profile used for the simulations was that of the best PV production profile of the season for the day exhibiting the highest load profile. The installed PV were modelled as an aggregated plant connected at the low voltage side of the distribution substation and a Monte Carlo investigation was performed in order to cover a wide range of both EV and PV capacity combinations. In addition, the PV capacity of the PV plants connected to all the distribution substations within the reference grid were defined via a uniform density function.

Finally, by placing PV the voltage regulation methods for PV was also investigated at unity and 0.95 power factor and cosφ(P). This is performed in order to exhibit the effects of voltage regulation alongside with the large integration of EV and PV.

3.4.1 Impact of EVs on typical Substation/Feeders

The impact of EVs is simulated on typical feeders of a reference HV substation (Hadjipaschalis S/S) using DIgSILENT PowerFactory. More specifically, Hadjipaschalis S/S has 22 feeders of various lengths and capacities which are considered representative for the Cyprus MV grid, with three 40 MVA transmission transformers, a total distribution transformer capacity of 150.12 MVA, 206 distribution substations /transformers/busbars and 451 distribution lines either underground or overhead. Extremely long feeders located at rural areas are not tested for their capability to host high concentrations of EVs in this investigation since for such levels of penetration of EVs, it is not expected to have a large number of EVs in rural areas - as the majority of population is located in urban areas. The distribution substation model (which is the main active component of a transmission substation) and the associated element composition with labelling is shown in Figure 13.

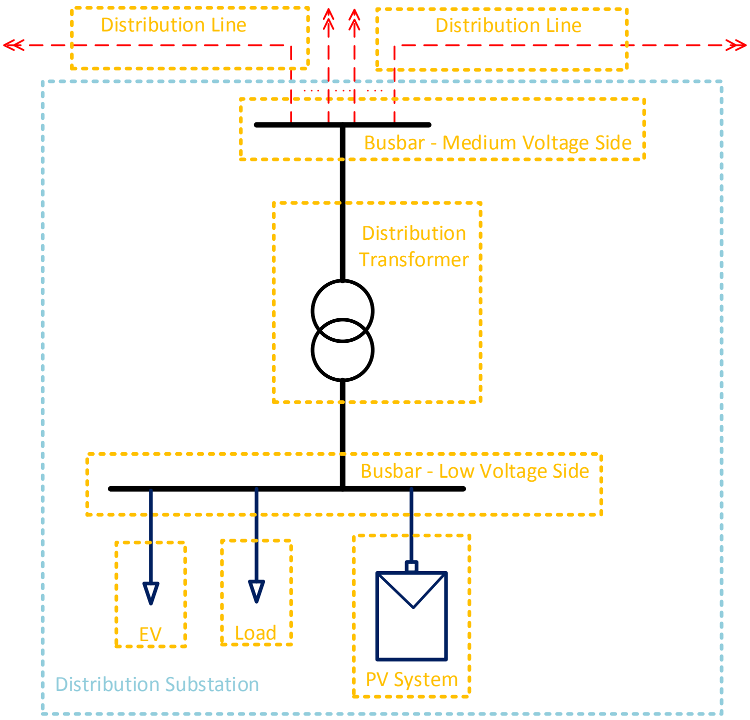

Figure 13. Composition of distribution substation model notations.

The EVs are modelled as aggregated additional load formulated by using the distribution probability functions of each scenario already described in the methodology. The number of EVs installed per substation are distributed equally amongst the line phases in a balanced manner and up to 30 % of the nominal power of each distribution substation. In particular, the EVs installed covered up to 30 % of the nominal power of each distribution substation, which is considered as the maximum upper threshold limit for the EV Monte Carlo simulation, in order to achieve primarily the proportional share of EVs corresponding to the investigated reference MV grid but also to simulate even a larger share than the corresponding one. This was performed for all the investigated EV charging scenarios. In addition, the worst daily substation profile having the highest load values is identified via data analysis (by using the time series of the total substation consumption) to simulate the worst EV scenario.

The maximum daily load is shown in Figure 14 and is determined with the use of the maximum load performance index *ML* given as:

$$ML = \max(x_{t_1} \quad x_{t_2} \quad \dots \quad x_{t_n})\Big|_{t_n=24:00}^{t_1=00:00} + \text{mean}(x_{t_1} \quad x_{t_2} \quad \dots \quad x_{t_n})\Big|_{t_n=24:00}^{t_1=00:00} \quad (10)$$

Where, ML is the Selection Criterion (SCr) for the maximum load determination calculated per day and x is the load value per half hour. The daily load profile with the highest load performance index is chosen. The load of the investigated reference substation is split according to the thermal limit of the transformers and the feeder consumption at each distribution substation (using DIgSILENT in order to cope correctly with the power losses). At each distribution substation an aggregated load is connected to the low voltage side of the distribution transformer and at this load element the calculated load profile is assigned.

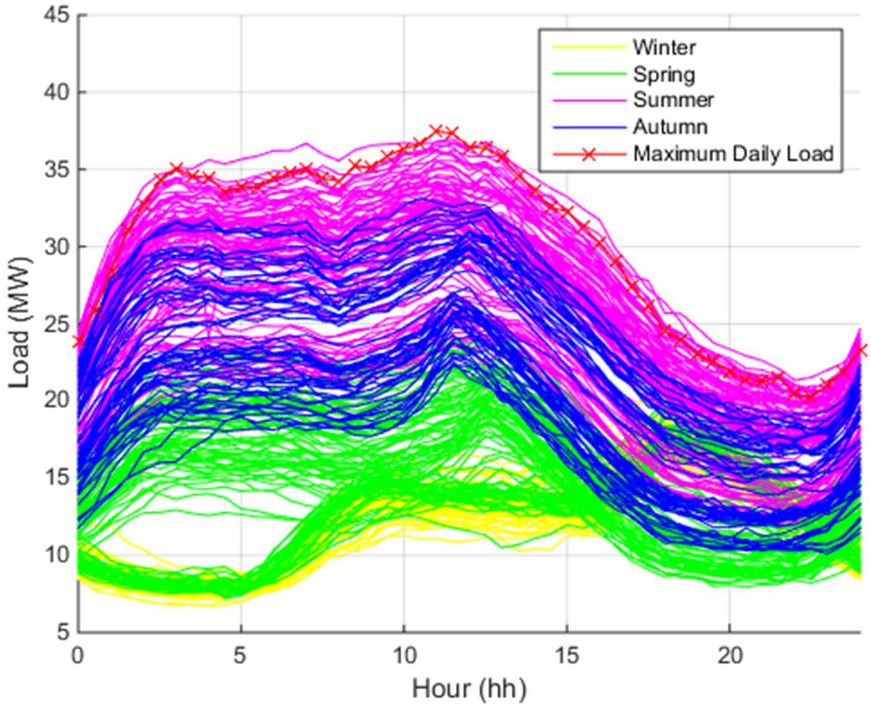

Figure 14. Maximum daily load profile.

In addition, the power quality (PQ) parameters under consideration are normalized according to their limit/range as stated in EN50160 [16]. Specifically, the PQ parameter for the Low Voltage side is shown in Equation 11:

$$V_{rorm}^{LV} = \frac{V_{LV}^{p.u.} - V_{\text{EN50160 Limit}}^{\text{Low Limit}}}{V_{\text{EN50160 Limit}}^{\text{Upper Limit}} - V_{\text{EN50160 Limit}}^{\text{Lower Limit}}} = \frac{\mathrm{V}^{LV} - 0.9}{0.2} \quad (11)$$

Where, V_{rorm}^{LV} is the normalized voltage for the low voltage side, $V_{LV}^{p.u.}$ is the voltage for the low voltage side obtained from simulations (p.u.), $V_{\text{EN50160 Limit}}^{\text{Upper Limit}}$ is the upper voltage limit recommended by EN 50160 standard (1.1 p.u.) and $V_{\text{EN50160 Limit}}^{\text{Lower Limit}}$ is the lowest voltage limit recommended by EN 50160 standard (0.9 p.u.). The PQ parameter for the Medium Voltage side is shown in Equation 12:

$$V_{rorm}^{MV} = \frac{V_{MV}^{p.u.} - V_{\text{EN50160 Limit}}^{\text{Low Limit}}}{V_{\text{EN50160 Limit}}^{\text{Upper Limit}} - V_{\text{EN50160 Limit}}^{\text{Lower Limit}}} = \frac{\mathrm{V}^{MV} - 0.9}{0.2} \tag{12}$$

Where, V_{rorm}^{MV} is the normalized voltage for the medium voltage side, $V_{MV}^{p.u.}$ is the voltage for the medium voltage side obtained from simulations (p.u.), $V_{\text{EN50160 Limit}}^{\text{Upper Limit}}$ is the upper voltage limit recommended by EN 50160 standard (1.1 p.u.) and $V_{\text{EN50160 Limit}}^{\text{Lower Limit}}$ is the lowest voltage limit recommended by EN 50160 standard (0.9 p.u.). The PQ parameter for the Line Loading is shown in Equation 13:

$$L_{norm} = \frac{L_{\%}^{sim}}{L_{\%}^{\text{Upper Limit}} - L_{\%}^{\text{Lower Limit}}} = \frac{L_{\%}^{sim}}{100} \tag{13}$$

Where, L_{norm} is the normalized line loading, $L_{\%}^{sim}$ is the line loading obtained from simulations (%), $L_{\%}^{\text{Upper Limit}}$ is the upper permissible line loading, and $L_{\%}^{\text{Lower Limit}}$ is the lowest permissible line loading.

With respect to the simulation scenarios investigated, the first step is to assess the base scenario which is the case of no EVs. Subsequently, EVs are introduced into the grid at various concentrations, up to a number which corresponds to the substation load share of the total demand of Cyprus. Following this apportionment, a figure of 2200 EVs is expected to be reached by 2030 and be fed from the network connected to Hadjipaschalis substation. As indicated above, by limiting the connection of EVs per distribution substation up to 30 % of its nominal power, the connected number has reached a maximum figure of 3000 EVs for semi-fast charging mode and 6000 EVs for slow charging mode which corresponds to the scale level required.

In the next step, the PV systems are inserted into the grid at each distribution substation. The nominal power of PV systems per substation is again limited to 30 % of substation transformer capacity. Furthermore, it is assumed that the inverter of the PV system is oversized by 10 % (in respect to the PV array) as imposed by newly adopted Cyprus regulations for distributed generation to provide the reactive power support for voltage regulation purposes as imposed by EN 50438 [15].The simulation of EV and PV scenarios was initially performed while considering no voltage regulation schemes (power factor equal to unity). The specific simulation cases were then repeated for another two voltage regulation methods: the fixed power factor adjusted to 0.95 and the cosφ(P) method as depicted in EN 50438 [15] with curve characteristics shown in Figure 15.

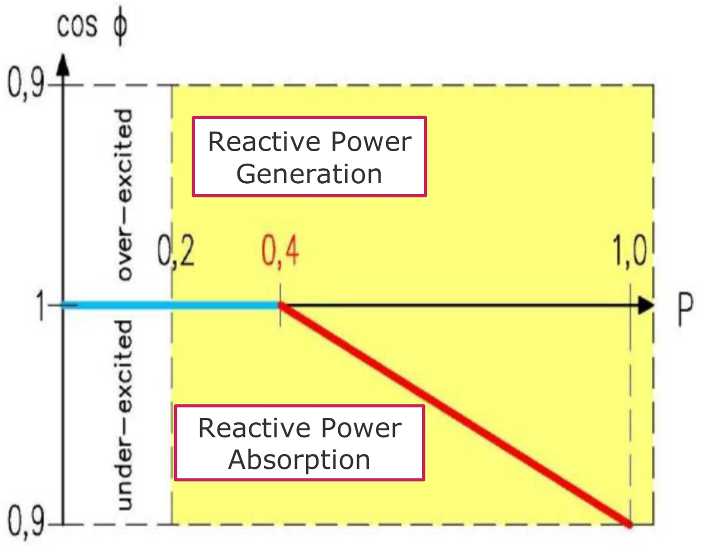

Figure 15. Characteristic curve cosφ (P) of power factor in relation to the generated power.

The results for all buses/lines for each PQ quantity are inserted into single data vectors and then statistically analysed. It must be mentioned that the PQ parameters are normalized in order to be able to define universal limits/range for comparison purposes.

Finally, statistical analysis is undertaken for all the simulated PQ parameters. In more detail, the results are represented by a boxplot which is a standardized way of displaying the distribution of data based on the five number summary: minimum, first quartile, median, third quartile, and maximum. In the boxplot graph, outliners are also visible. Additionally, the probability distribution function (PDF) and cumulative probability distribution function (CDF) for the aforementioned PQ parameters are also depicted in a graphical manner.

4. Results

The results of the analysis performed on the impact of EVs on typical feeders and of the simulations performed to investigate the effects of a large integration of EV and PV in the reference Cyprus MV grid are presented in this section. In addition, the EV charging profiles aggregated per transmission substation are attached in Appendix 1.

4.1 Impact of EVs on typical feeders

This section summarizes the results of the analysis performed on the impact of EVs on typical feeders.

4.1.1 No EV scenario

The results of the statistical analysis when no EVs are present within the HV reference substation are shown in the Figures below. Figure 16 demonstrates the box-plots of the PQ parameters when no EVs are present within the HV reference substation. The results of Figure 16 are represented by a boxplot which is a standardized way of displaying the distribution of data based on the five number summary: minimum (lower black horizontal line), first quartile (lower blue horizontal line), median (red horizontal line), third quartile (upper blue horizontal line) and maximum (upper black horizontal line). In the boxplot graph, outliners are also visible (red points). As expected, the results clearly show that all line loading and voltage levels on both LV and MV buses are within the acceptable limits.

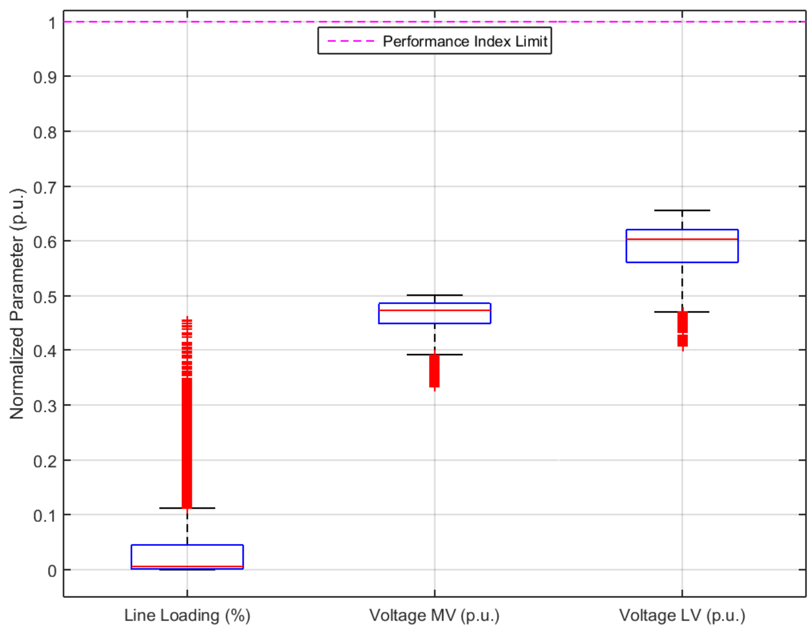

Figure 16. Power Quality parameters normalized to their limit – No EV.

The following Figures show the probability distribution and cumulative distribution functions for the LV level, the MV level buses and line loading within the HV reference substation when no EVs are present. The simulation results show that all voltage levels on both LV and MV buses and line loading are within the acceptable limits

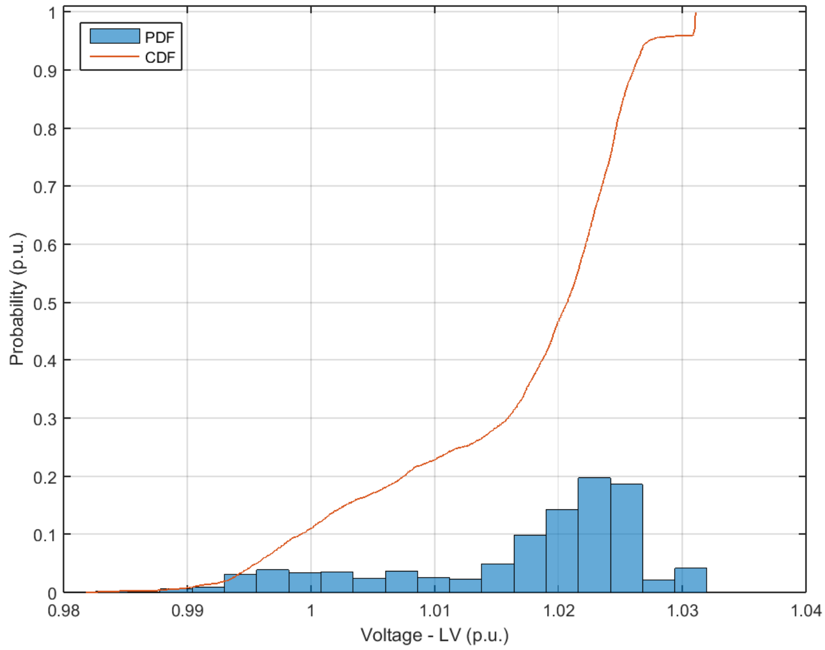

Figure 17. Probability distribution and cumulative probability distribution – Voltage at low voltage side – No EV.

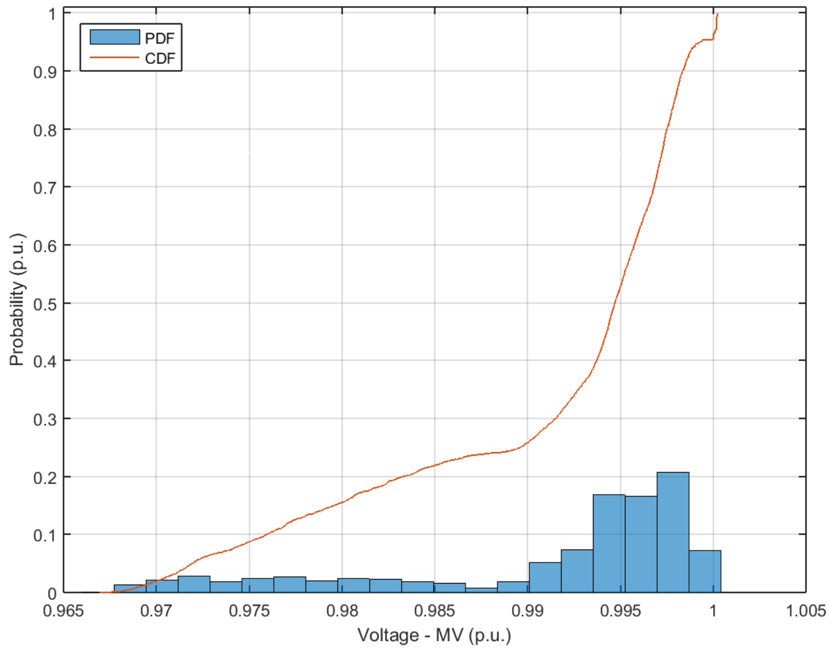

Figure 18. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – No EV.

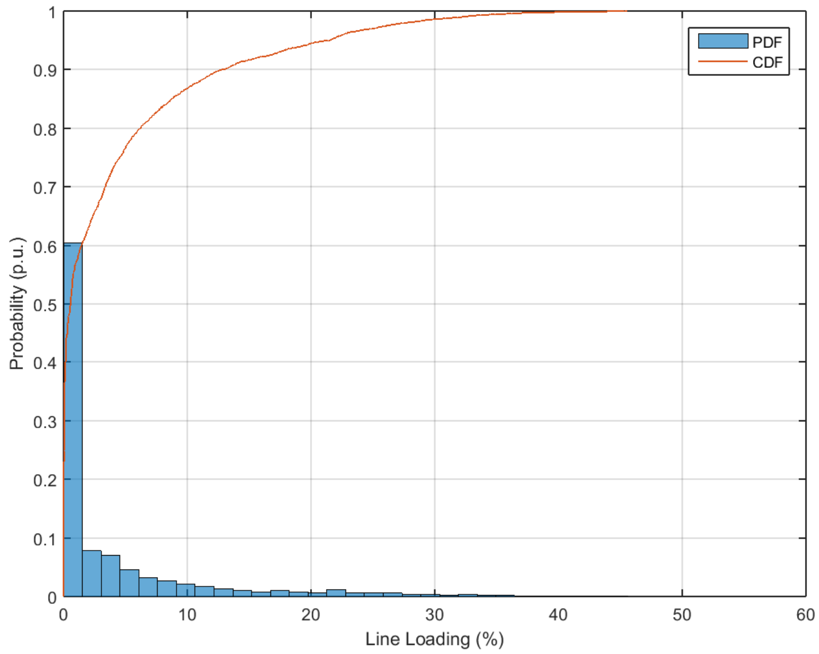

Figure 19. Probability distribution and cumulative probability distribution – Line Loading – No EV.

4.1.2 Uncontrolled Charging – Full Charging Mode

The results of the statistical analysis for the Uncontrolled charging – Full charging mode scenario for the HV reference substation (for all EV Integration Scenarios) are shown in the Figures below. Figure 20 demonstrates the box-plots of the PQ parameters when Uncontrolled charging - Full charging mode is considered. The results clearly show that all line loading and voltage levels on both LV and MV buses are within the acceptable limits.

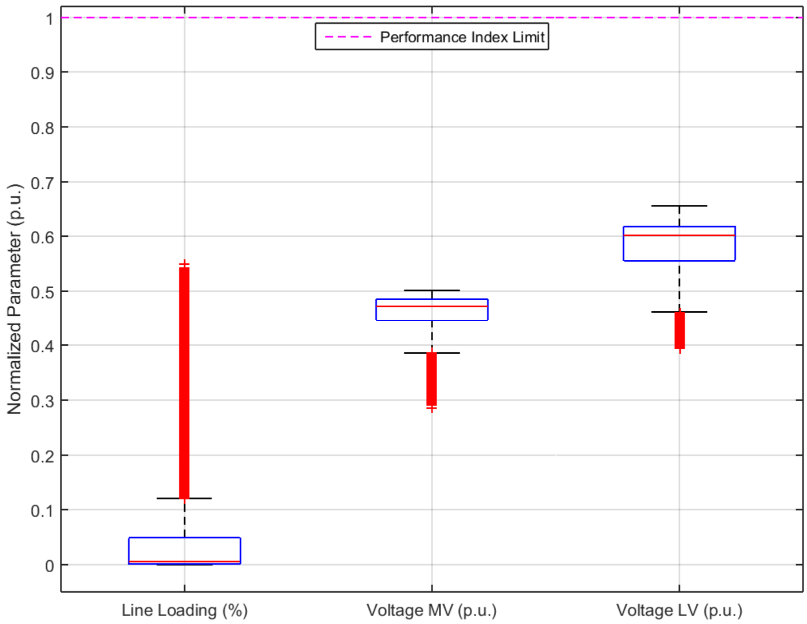

Figure 20. Power Quality parameters normalized to their limit - Uncontrolled Charging – Full Charging Mode.

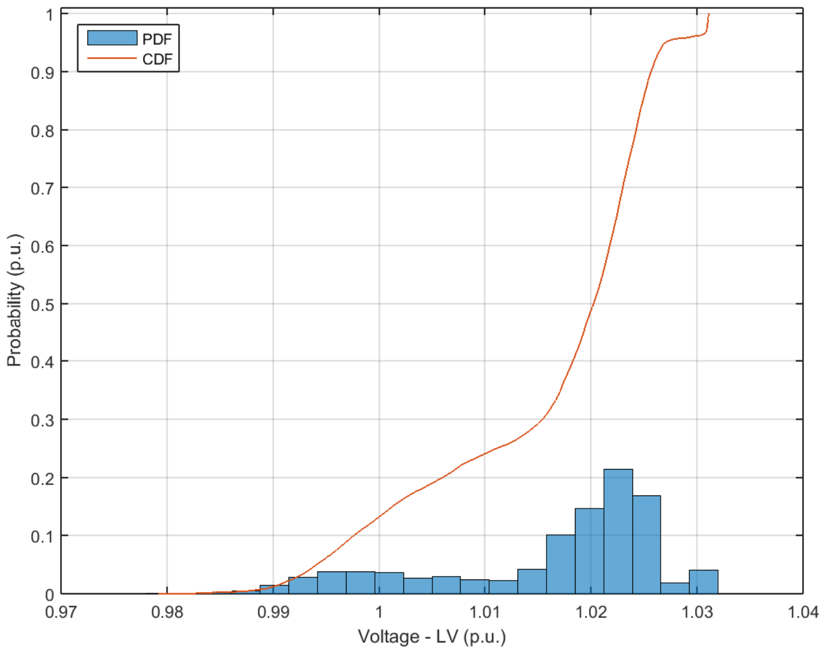

Figure 21. Probability distribution and cumulative probability distribution – Voltage at low voltage side – Uncontrolled Charging – Full Charging Mode.

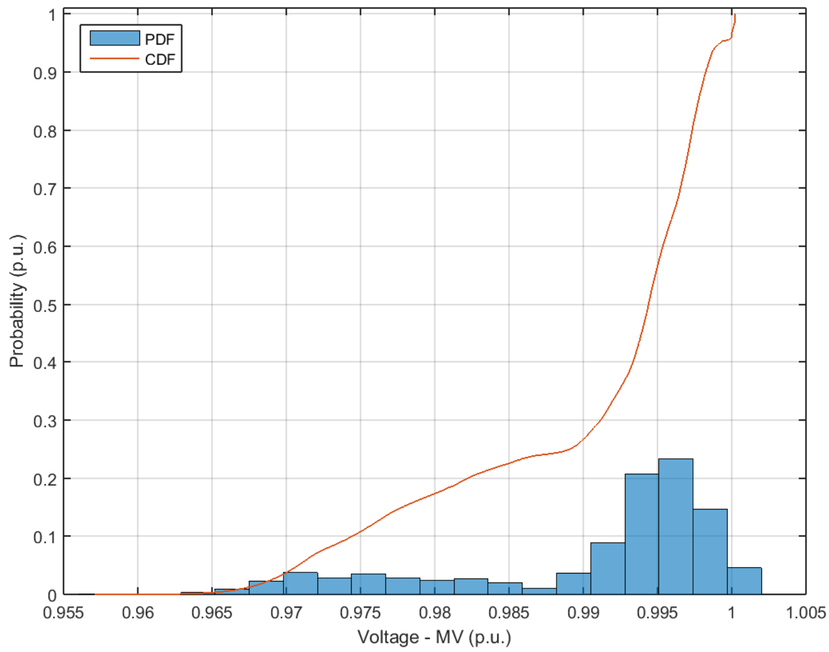

Figure 22. Probability distribution and cumulative probability distribution – Voltage at medium voltage side - Uncontrolled Charging – Full Charging Mode.

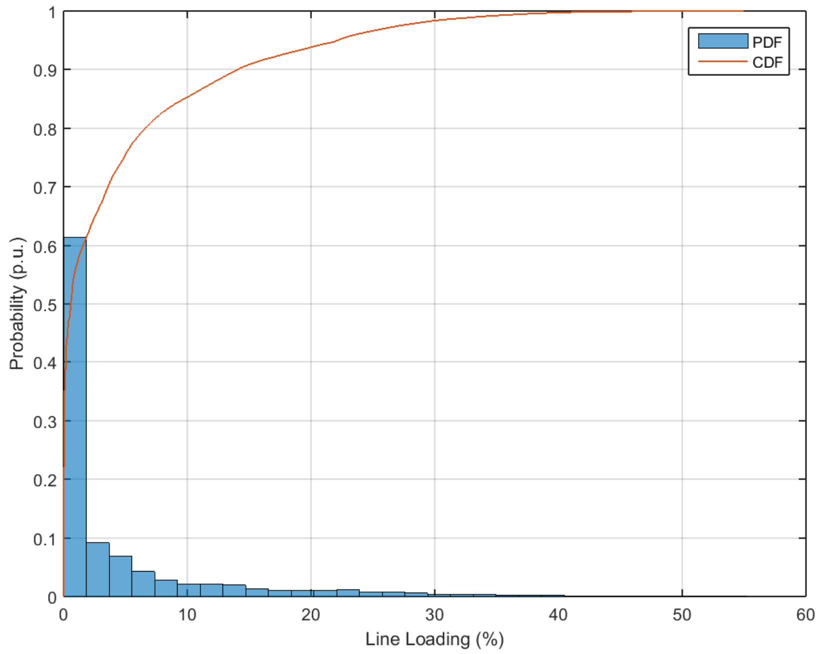

Figure 23. Probability distribution and cumulative probability distribution – Line Loading - Uncontrolled Charging – Full Charging Mode.

The PQ and Active/Reactive power results (captured at the substation's connection point with the transmission system) for different amounts of connected EVs are shown in the Figures below. The results show that while increasing the amount of connected EVs charging in an uncontrolled full charging mode has minor effect on the voltage levels at the LV and MV buses. At the highest amount of EVs charging the line loading increased by approximately 10 %. Accordingly, the results for the net load showed that at the highest amount of EVs charging the active power increased by 15 % while for the reactive power there was almost no change.

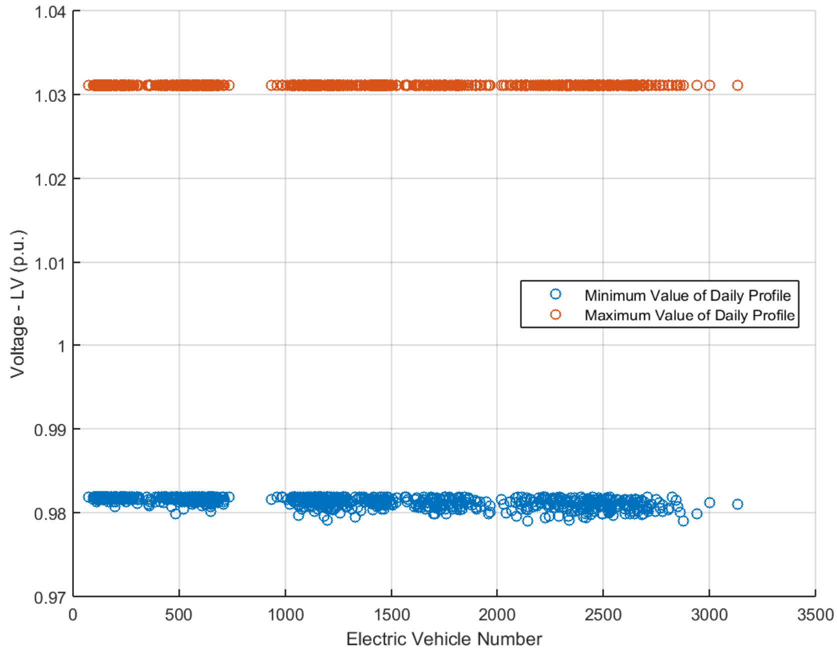

Figure 24. Voltage Variation at Low Voltage Side vs Electric Vehicle Number - Uncontrolled Charging – Full Charging Mode.

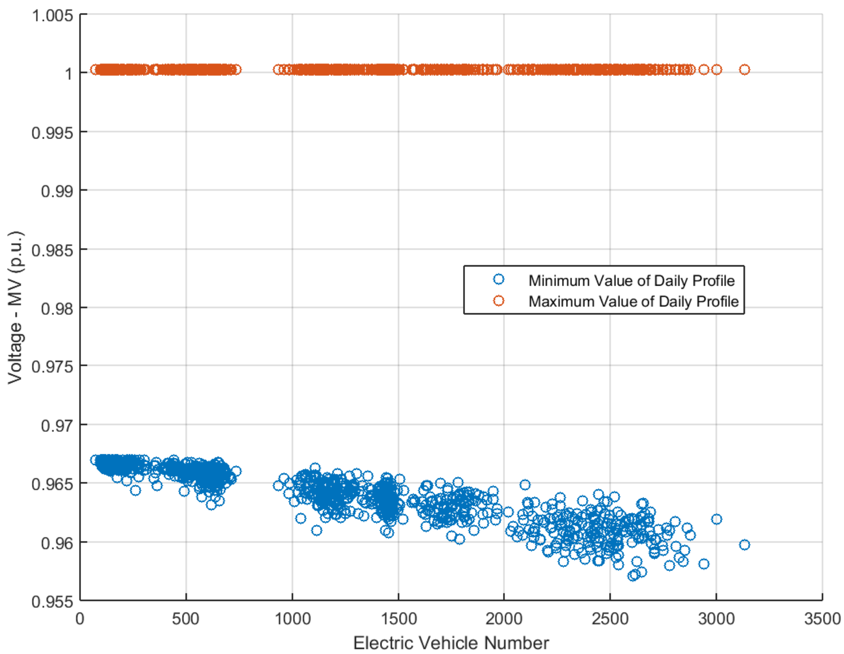

Figure 25. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number - Uncontrolled Charging – Full Charging Mode.

Figure 26. Line Loading vs Electric Vehicle Number – Uncontrolled Charging – Full Charging Mode.

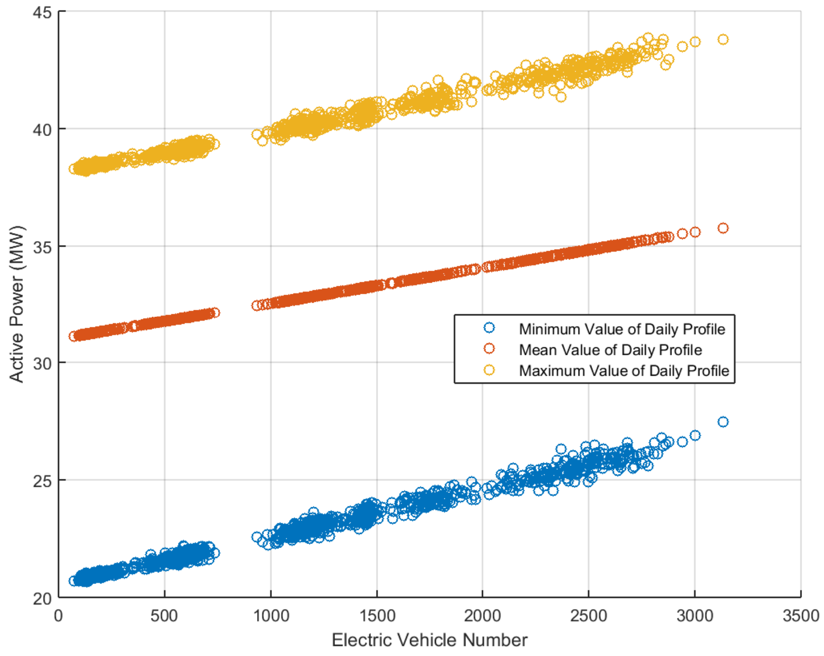

Figure 27. Active Power vs Electric Vehicle Number – Uncontrolled Charging – Full Charging Mode.

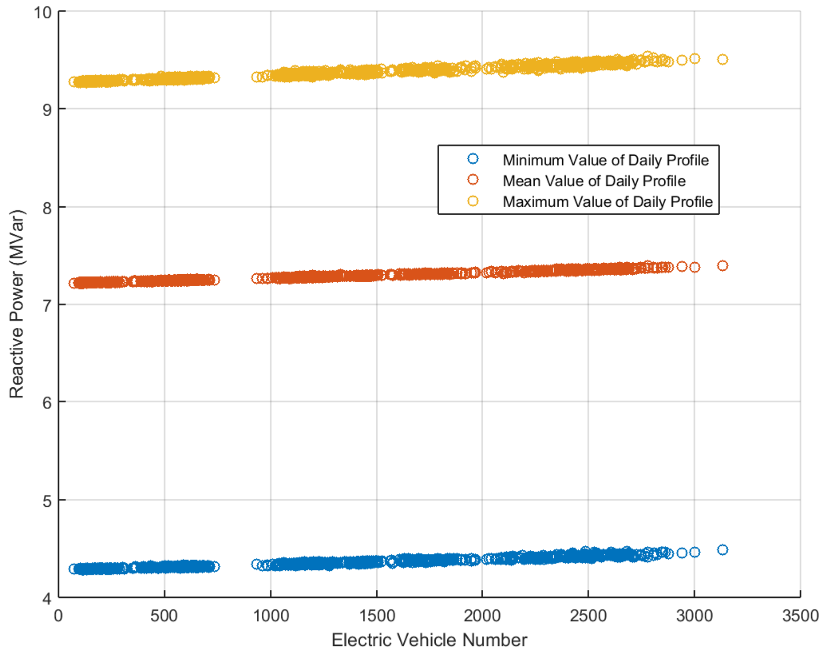

Figure 28. Reactive Power vs Electric Vehicle Number- Uncontrolled Charging – Full Charging Mode.

4.1.3 Uncontrolled charging considering mobility

The results of the statistical analysis for the uncontrolled charging considering mobility scenario for the HV reference substation (for all EV Integration Scenarios) are shown in the Figures below. Figure 29 demonstrates the box-plots of the PQ parameters when Uncontrolled charging considering mobility is simulated. The results clearly show that all line loading and voltage levels on both LV and MV buses are within the acceptable limits.

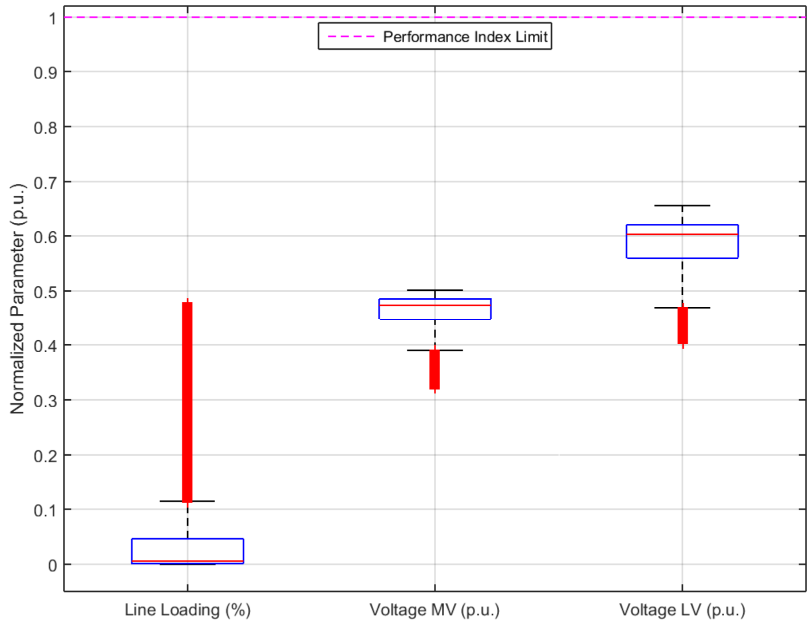

Figure 29. PQ parameters normalized to their limit – Uncontrolled charging considering mobility.

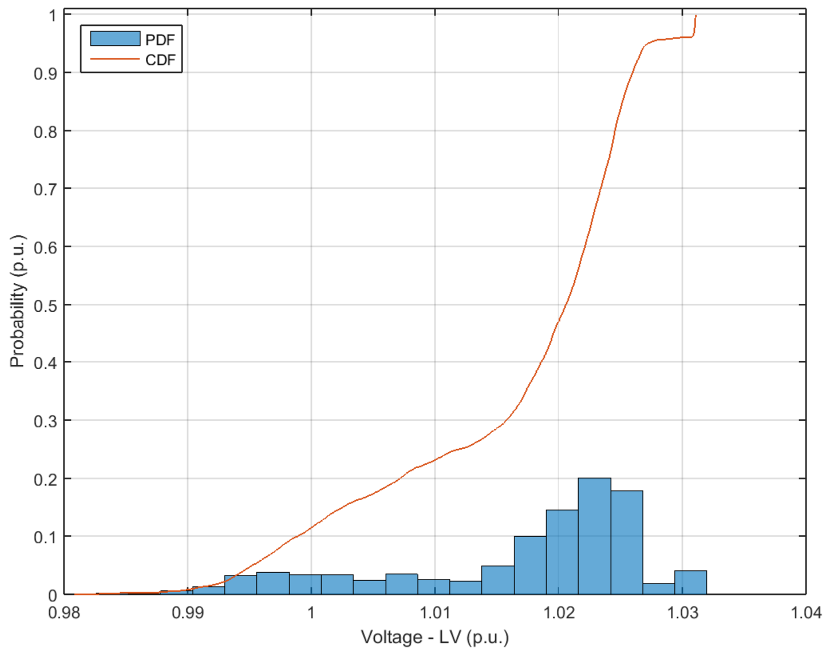

Figure 30. Probability distribution and cumulative probability distribution – Voltage at low voltage side – Uncontrolled charging considering mobility.

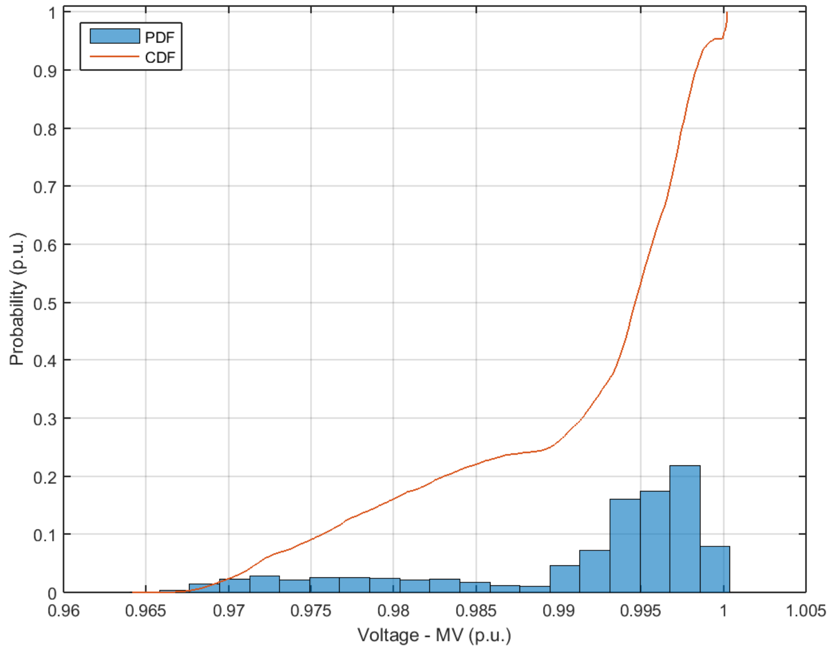

Figure 31. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Uncontrolled charging considering mobility.

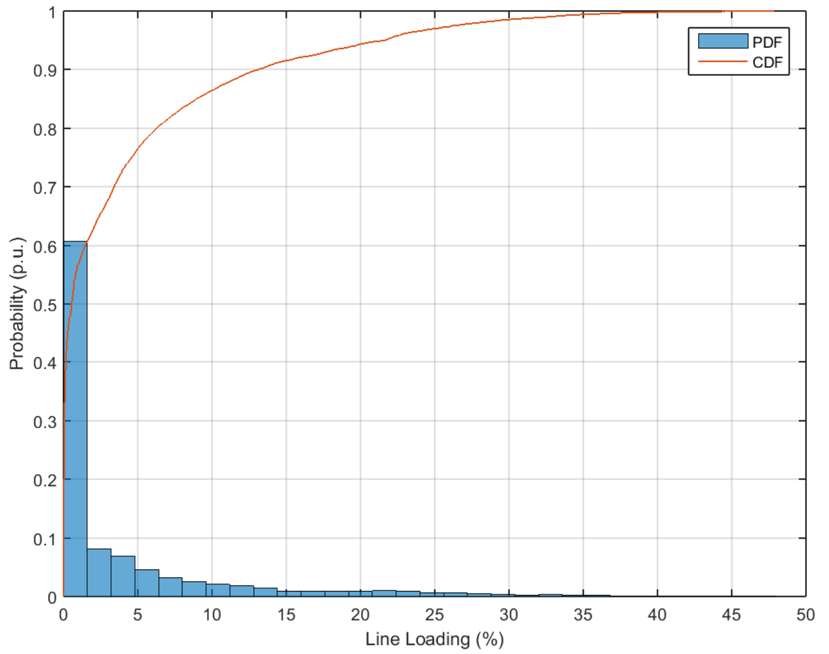

Figure 32. Probability distribution and cumulative probability distribution – Line Loading – Uncontrolled charging considering mobility.

The PQ and Active/Reactive power results (captured at the substation's connection point with the transmission system) for different amounts of connected EVs are shown in the Figures below. The results show that while increasing the amount of connected EVs charging in an uncontrolled charging mode considering mobility has minor effect on the voltage levels at the LV and MV buses. At the highest amount of EVs charging the line loading increased slightly (less than 5 %). Accordingly, the results for the net load showed that at the highest amount of EVs charging the active power increased by 5 % while for the reactive power there was almost no change.

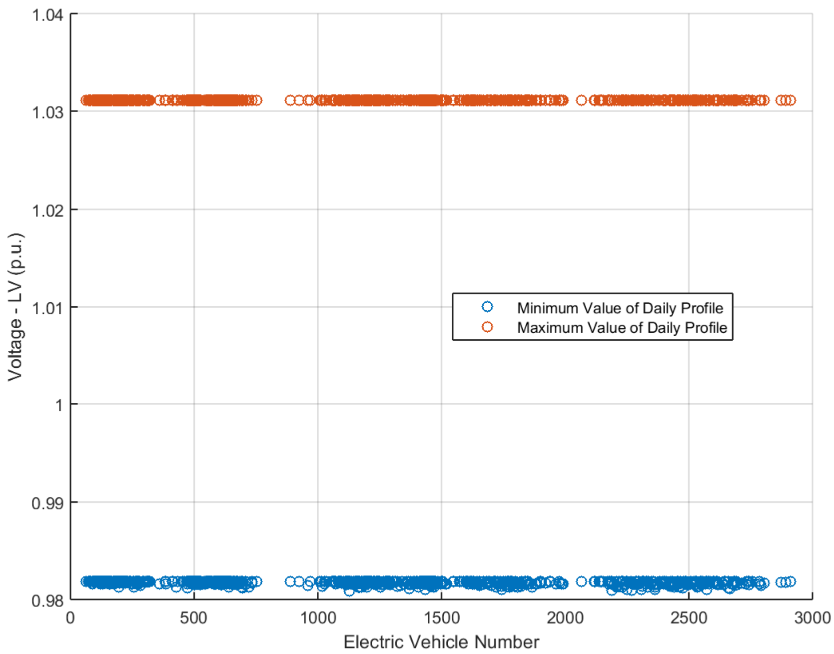

Figure 33. Voltage Variation at Low Voltage Side vs Electric Vehicle Number – Uncontrolled charging considering mobility.

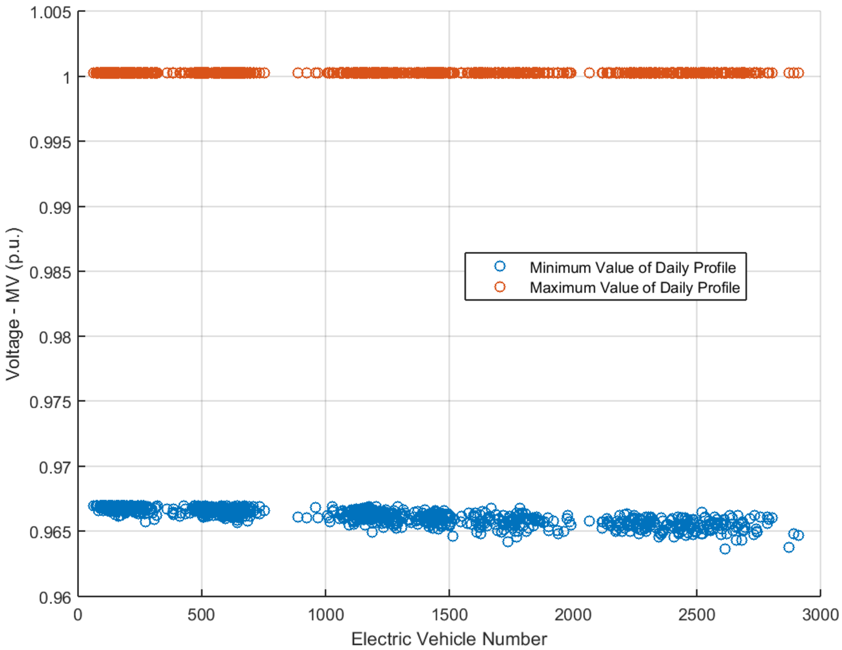

Figure 34. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number – Uncontrolled charging considering mobility.

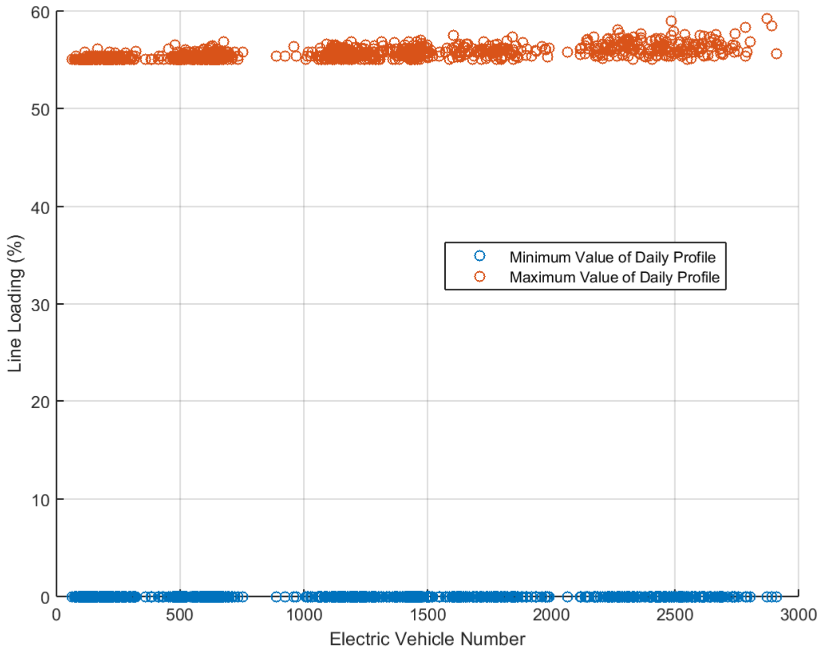

Figure 35. Line Loading vs Electric Vehicle Number – Uncontrolled charging considering mobility.

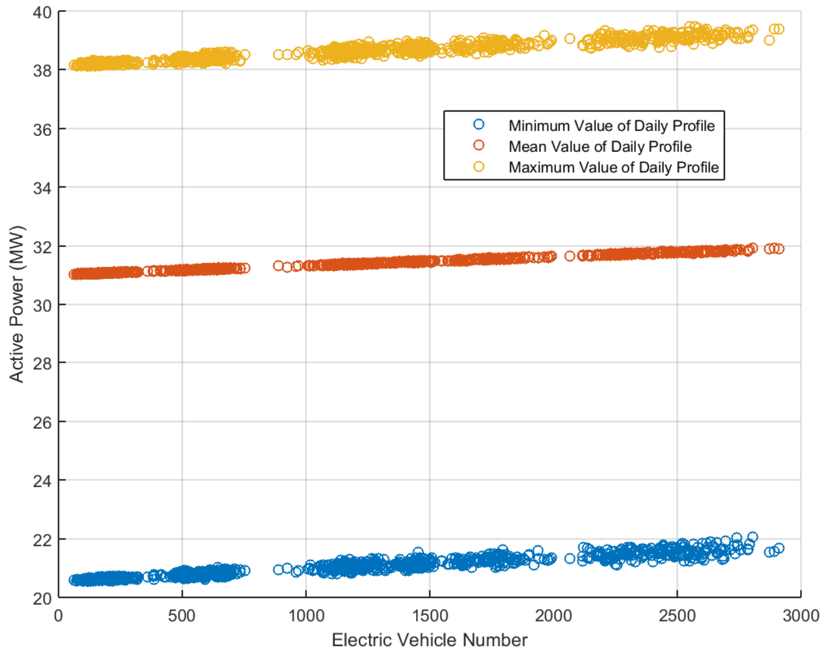

Figure 36. Active Power vs Electric Vehicle Number – Uncontrolled charging considering mobility.

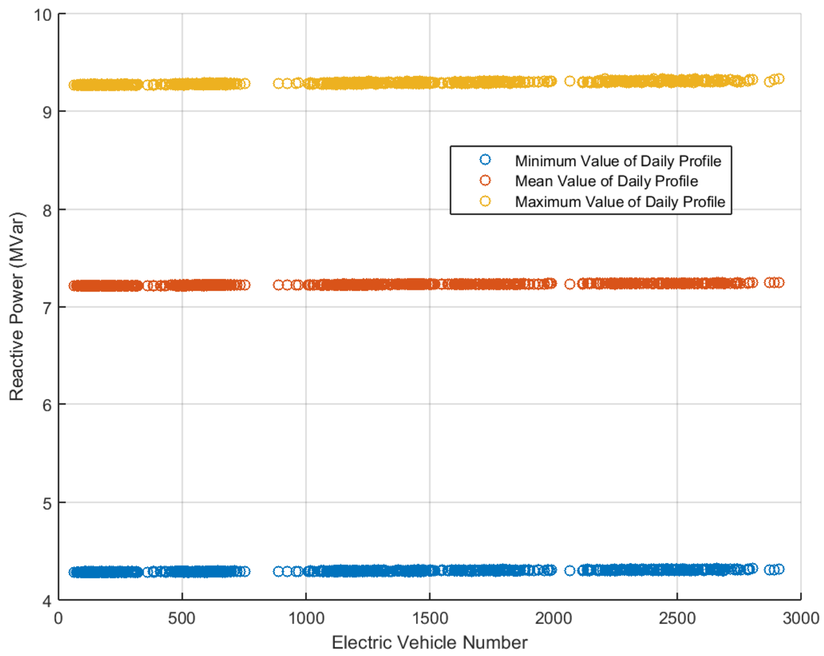

Figure 37. Reactive Power vs Electric Vehicle Number – Uncontrolled charging considering mobility.

4.1.4 Controlled EV charging (smart charging)

The results of the statistical analysis for the Controlled EV charging (smart charging) scenario for the HV reference substation (for all EV Integration Scenarios) are shown in the Figures below. Figure 38 demonstrates the box-plots of the PQ parameters when Controlled EV charging (smart charging) is considered. The results clearly show that all line loading and voltage levels on both LV and MV buses are within the acceptable limits.

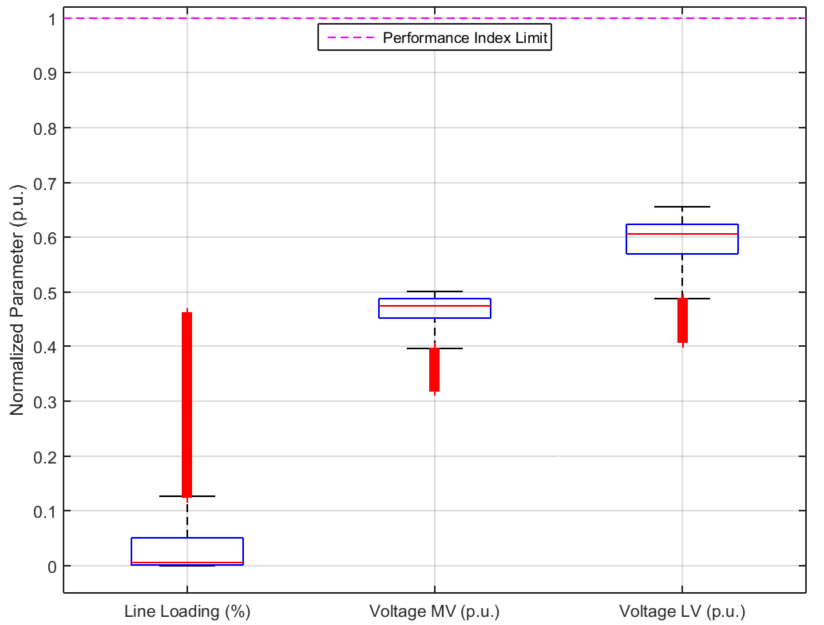

Figure 38. PQ parameters normalized to their limit – Controlled EV charging.

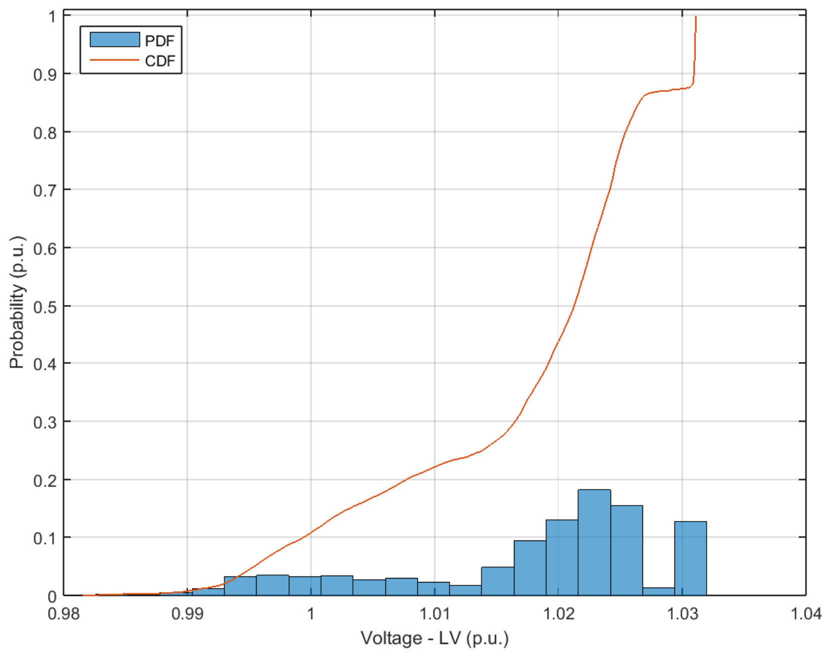

Figure 39. Probability distribution and cumulative probability distribution – Voltage at low voltage side – Controlled EV charging.

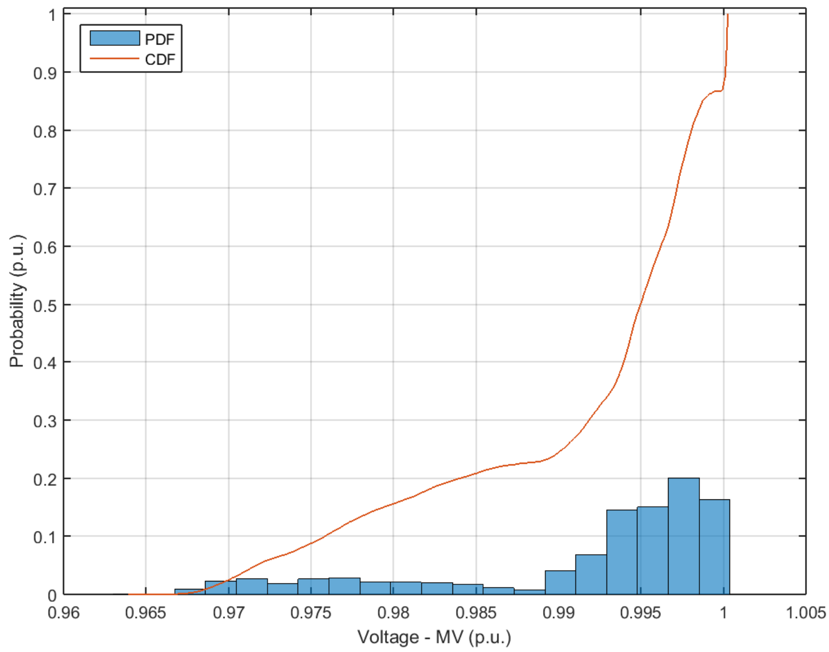

Figure 40. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Controlled EV charging.

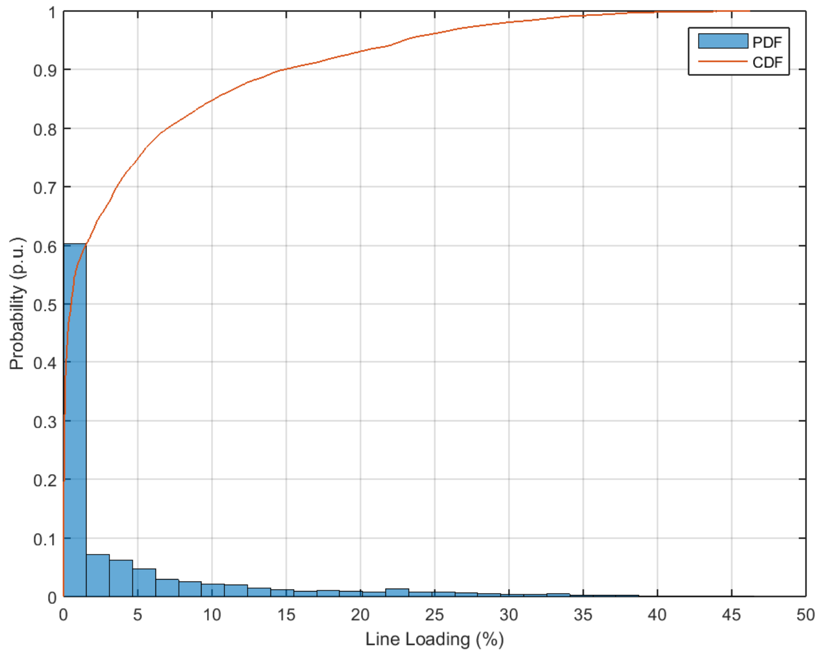

Figure 41. Probability distribution and cumulative probability distribution – Line Loading – Controlled EV charging.

The PQ and Active/Reactive power results (captured at the substation's connection point with the transmission system) for different amounts of connected EVs are shown in the Figures below. The results show that while increasing the amount of connected EVs charging in a controlled manner has minor effects on the voltage levels at the LV and MV buses. At the highest amount of EVs charging the line loading increased slightly (less than 5 %). Accordingly, the results for the net load showed that at the highest amount of EVs charging the active power increased by 3 % while for the reactive power there was almost no change.

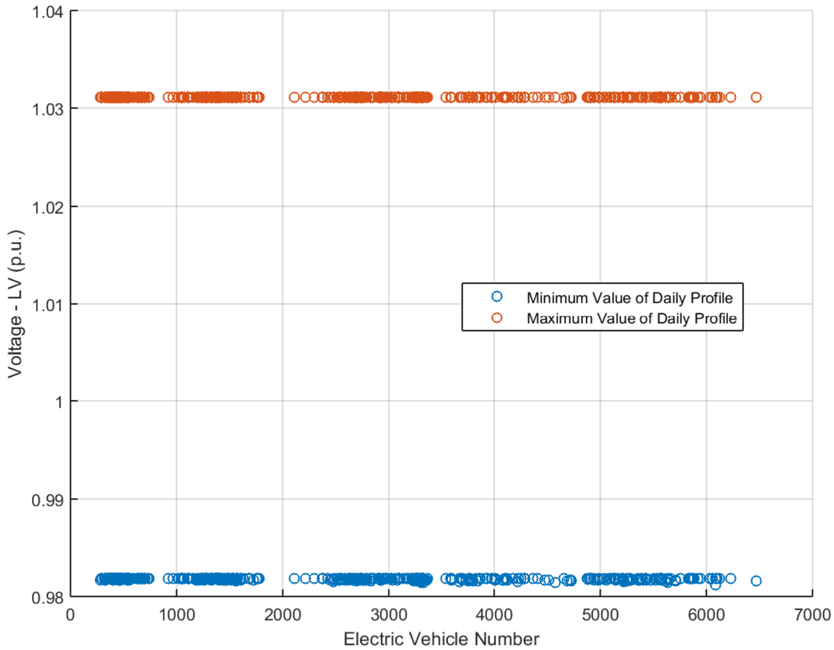

Figure 42. Voltage Variation at Low Voltage Side vs Electric Vehicle Number – Controlled EV charging.

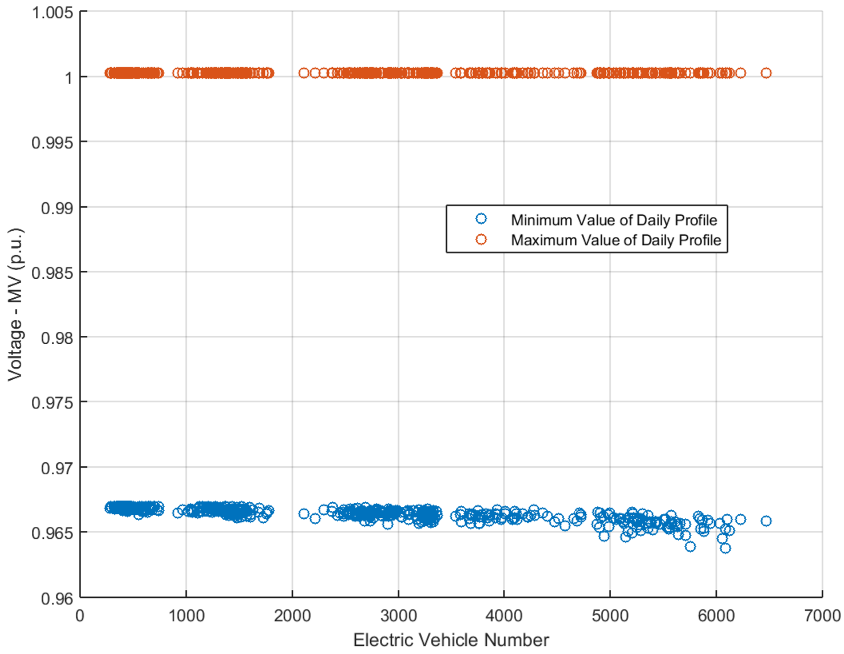

Figure 43. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number – Controlled EV charging.

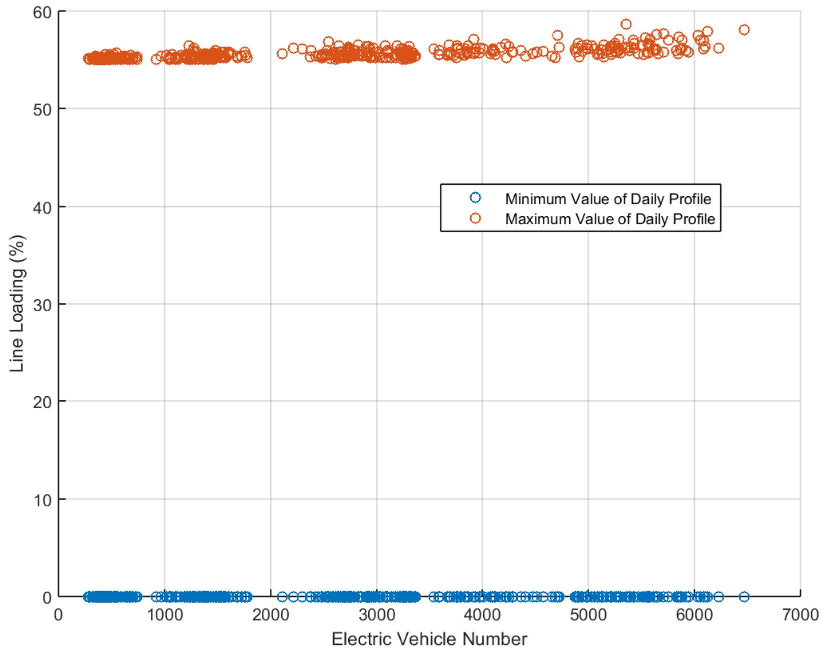

Figure 44. Line Loading vs Electric Vehicle Number – Controlled EV charging.

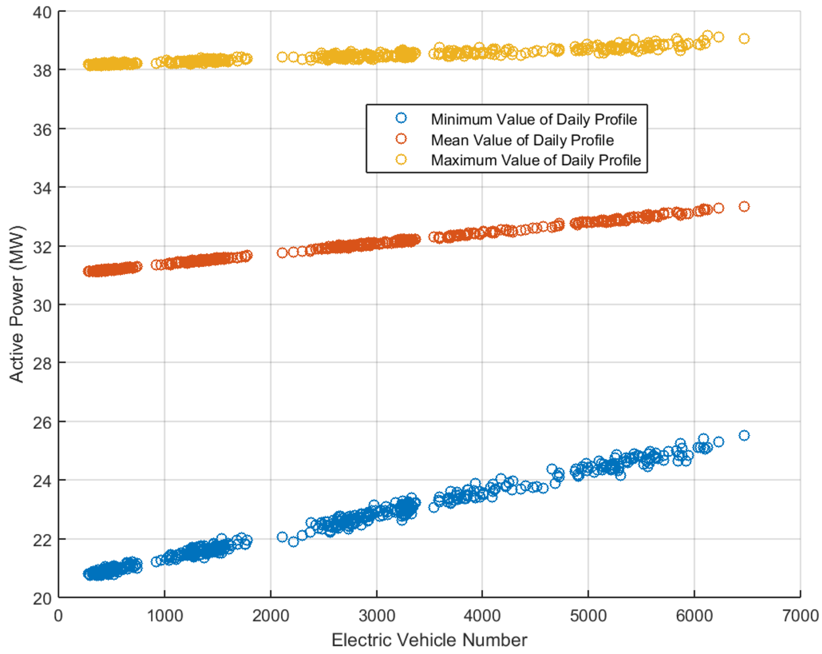

Figure 45. Active Power vs Electric Vehicle Number – Controlled EV charging.

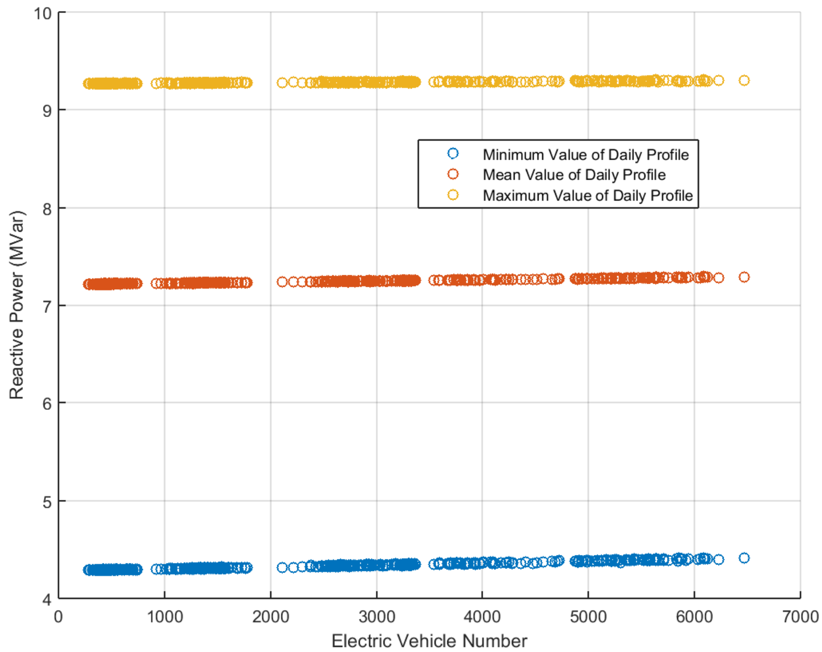

Figure 46. Reactive Power vs Electric Vehicle Number – Controlled EV charging.

4.1.5 EV charging without PV

The results obtained for the three EV charging scenarios simulated on the typical feeders of Hadjipaschalis S/S, are summarized in the Table below. It is evident that even in the most load demanding case, which is the "Uncontrolled-Full Charging" scenario, no violations of element/voltage limits are observed. The operation of the investigated feeders with a high level of EVs is found to be within the nominal range and within the system limits. More specifically, the voltage levels at low and medium voltage (MV) buses, are slightly reduced and the lines are slightly loaded in comparison with the base scenario with no EVs. Finally, the results obtained when simulating the "Controlled EV charging" scenario, demonstrated that there is only minor change on the operation of the investigated feeders/substation in comparison to the base scenario with no EVs. This further signifies the importance of controlled charging (smart charging).

Table 3. Statistical analysis of PQ parameters – EV charging scenarios.

		Scenario			
Normalized Parameter	Statistical Analysis	No EV	Uncontrolled -Full Charging	Uncontrolled-Mobility	Controlled-Mobility
Voltage – Low Voltage Side	Minimum	0.4092	0.3950	0.4043	0.4077
	25th quantile	0.5609	0.5554	0.5599	0.5589
	Median	0.6036	0.6013	0.6030	0.6030
	Average	0.5847	0.5814	0.5841	0.5839
	Standard Deviation	0.0511	0.0532	0.0515	0.0515
	75th quantile	0.6208	0.6181	0.6203	0.6202
	95th quantile	0.6364	0.6350	0.6361	0.6359
	99th quantile	0.6553	0.6551	0.6553	0.6551
	Maximum	0.6556	0.6556	0.6556	0.6556
Number of elements of which the limit is violated		0 out of 206	0 out of 206	0 out of 206	0 out of 206
Voltage – Medium Voltage Side	Minimum	0.3347	0.2854	0.3184	0.3293
	25th quantile	0.4481	0.4455	0.4475	0.4475
	Median	0.4735	0.4720	0.4732	0.4731
	Average	0.4564	0.4538	0.4559	0.4558
	Standard Deviation	0.0427	0.0452	0.0432	0.0432
	75th quantile	0.4859	0.4849	0.4857	0.4856
	95th quantile	0.4967	0.4961	0.4964	0.4964
	99th quantile	0.5010	0.5010	0.5010	0.5010
	Maximum	0.5010	0.5010	0.5010	0.5010
Number of elements of which the limit is violated		0 out of 206	0 out of 206	0 out of 206	0 out of 206
Line Loading	Minimum	0.0000	0.0000	0.0000	0.0000
	25th quantile	0.0004	0.0004	0.0004	0.0004
	Median	0.0056	0.0059	0.0056	0.0056
	Average	0.0395	0.0421	0.0400	0.0401
	Standard Deviation	0.0705	0.0741	0.0712	0.0713
	75th quantile	0.0450	0.0487	0.0459	0.0462
	95th quantile	0.2151	0.2215	0.2162	0.2175
	99th quantile	0.3242	0.3343	0.3262	0.3254
	Maximum	0.4552	0.5625	0.4889	0.4621
Number of elements of which the limit is violated		0 out of 451	0 out of 451	0 out of 451	0 out of 451

4.2 Large integration of EV and PV in the reference Cyprus MV grid

In this section a large integration of EV and PV is simulated in the reference MV grid. In particular, for each previously explained EV charging scenario the voltage regulation methods for PV is also investigated at unity and 0.95 power factor and cosφ(P). This is performed in order to exhibit the effects of voltage regulation alongside with the large integration of EV and PV.

4.2.1 Uncontrolled charging – Full Charging

4.2.1.1 Uncontrolled charging – Full Charging (Unity Power Factor)

The results for the "Uncontrolled charging – Full Charging" scenario in the presence of PV systems operating at unity power factor are shown in the Figures below. In all simulated cases (high amount of PV systems and EVs) there are no voltage level and line loading violations observed. In addition, the results show that the net load reduces as the PV capacity increases.

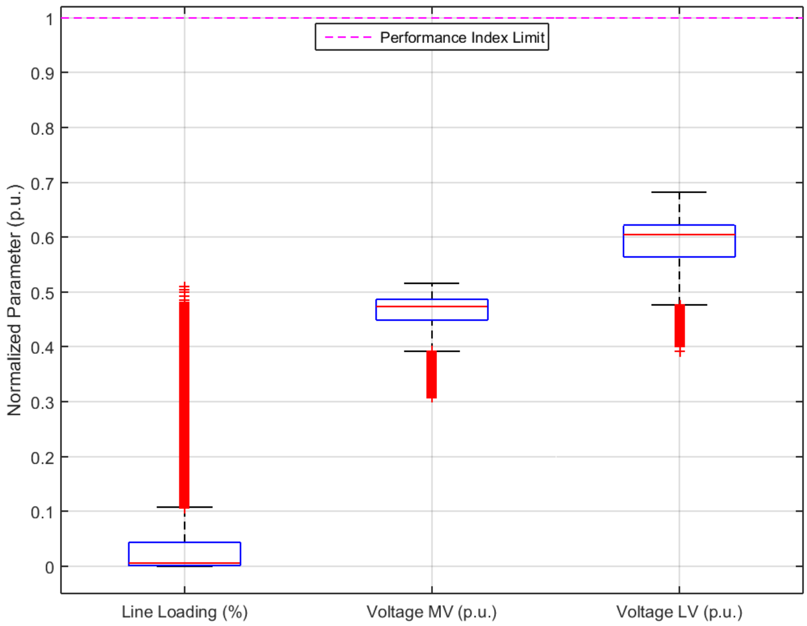

Figure 47. PQ parameters normalized to their limit – EV UC/FC and PV scenario – Unity Power Factor.

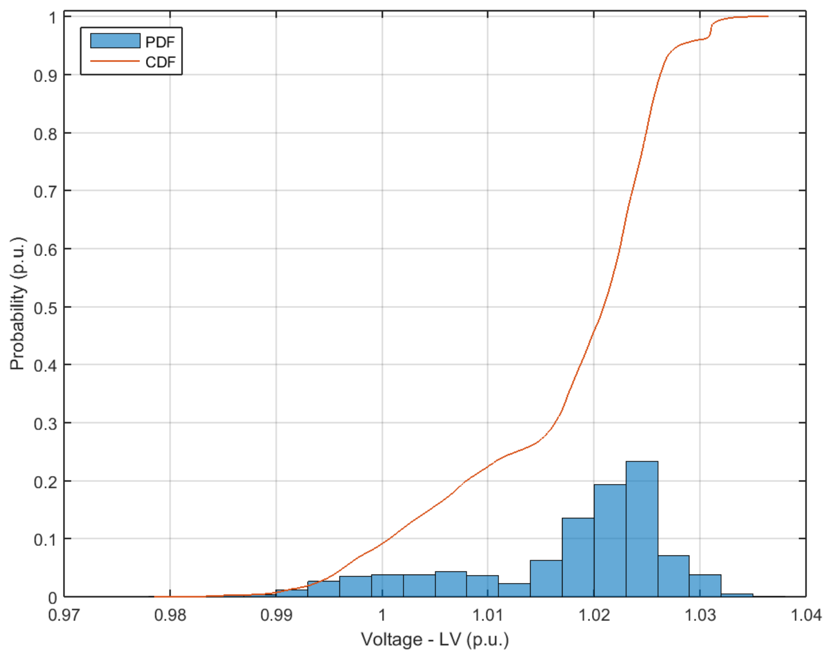

Figure 48. Probability distribution and cumulative probability distribution – Voltage at low voltage side – EV UC/FC and PV scenario – Unity Power Factor.

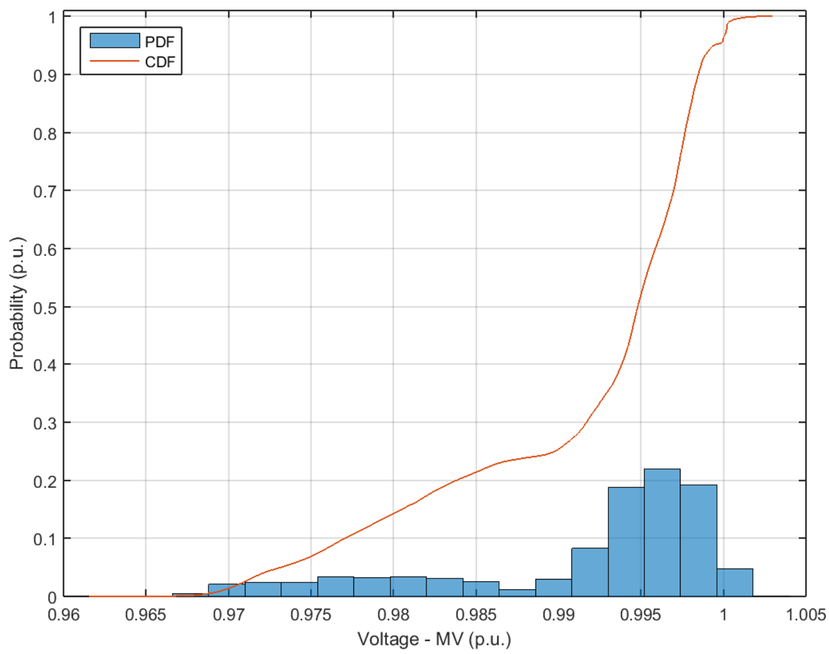

Figure 49. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – EV UC/FC and PV scenario – Unity Power Factor.

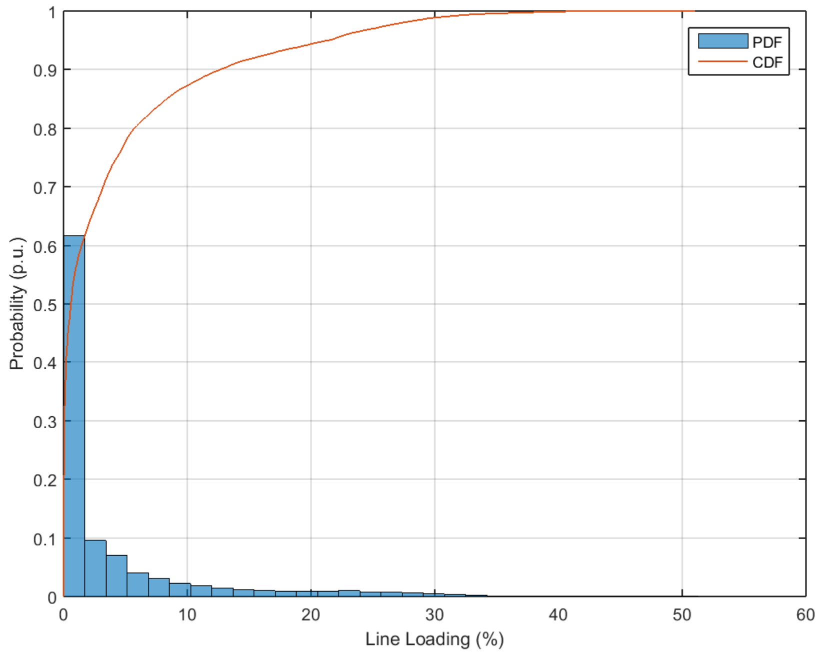

Figure 50. Probability distribution and cumulative probability distribution – Line Loading – EV UC/FC and PV scenario – Unity Power Factor.

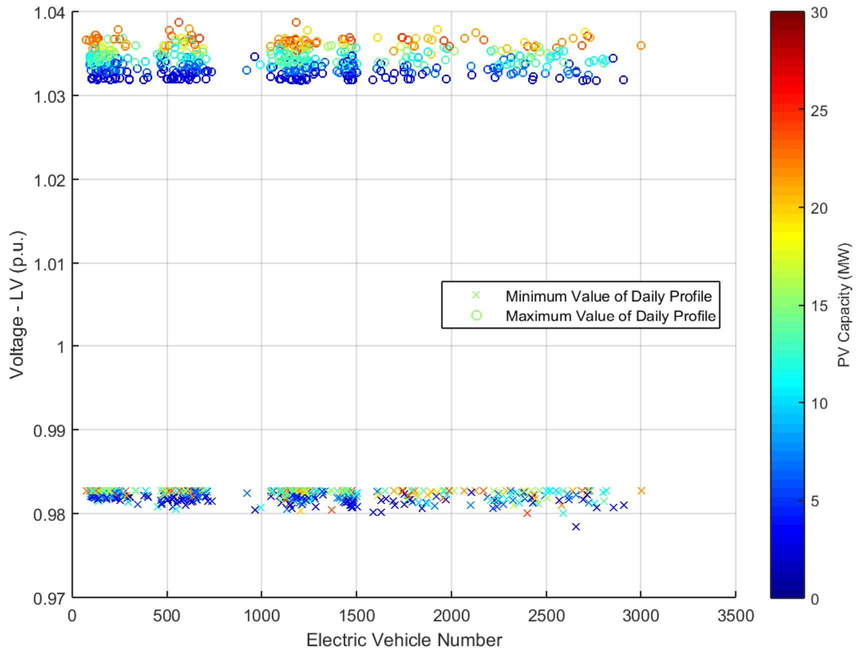

Figure 51. Voltage Variation at Low Voltage Side vs Electric Vehicle Number (including PV Capacity) – UC/FC - Unity Power Factor.

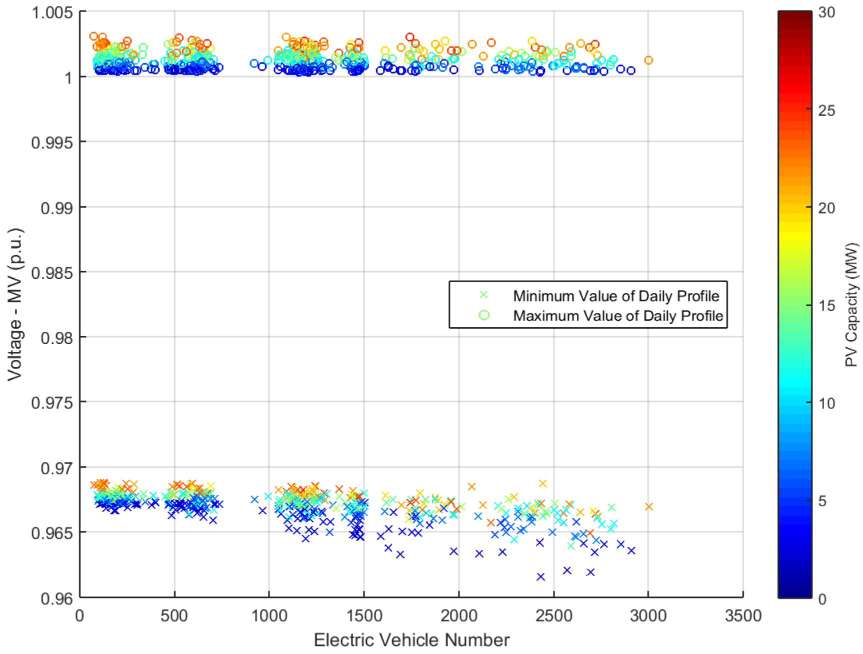

Figure 52. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number (including PV Capacity) – UC/FC - Unity Power Factor.

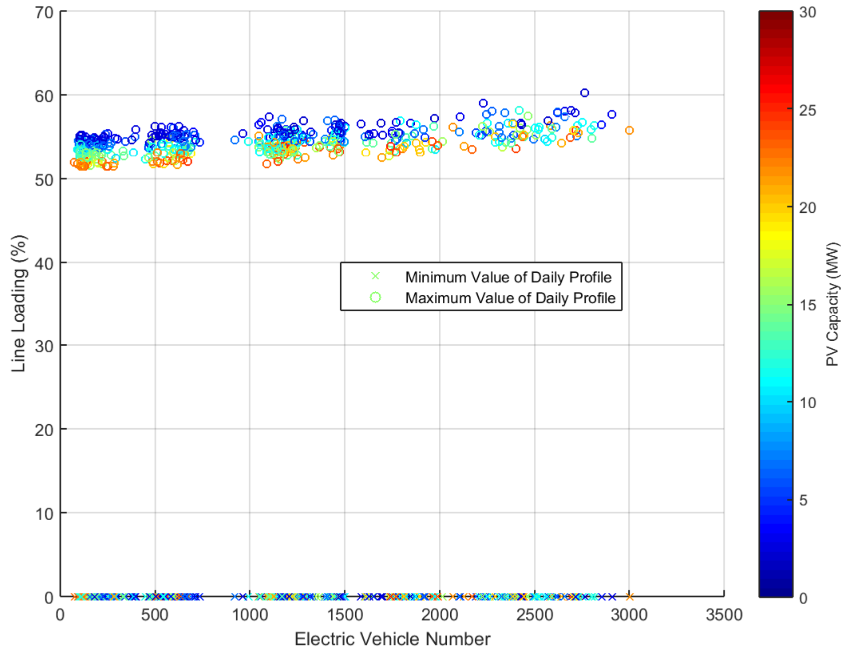

Figure 53. Line Loading vs Electric Vehicle Number (including PV Capacity) – UC/FC - Unity Power Factor.

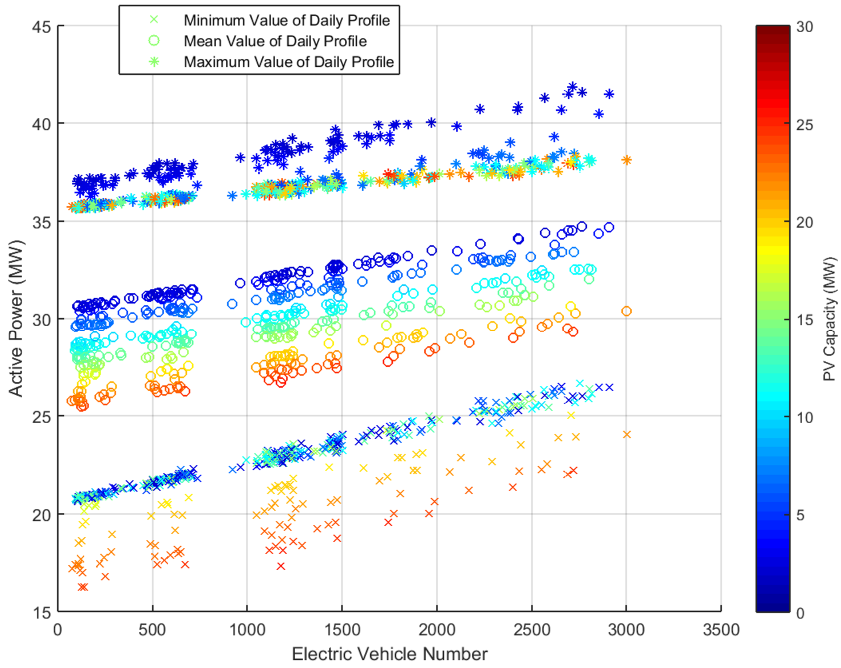

Figure 54. Active Power vs Electric Vehicle Number (including PV Capacity) – UC/FC - Unity Power Factor.

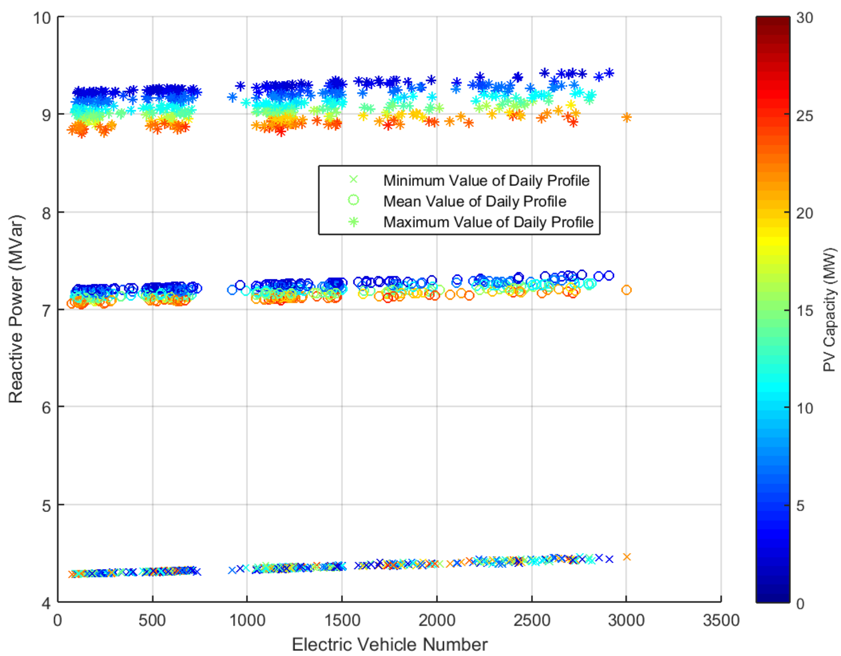

Figure 55. Reactive Power vs Electric Vehicle Number (including PV Capacity) – UC/FC - Unity Power Factor.

4.2.1.2 Uncontrolled charging – Full Charging (Power Factor equal to 0.95)

The results for the "Uncontrolled charging – Full Charging" scenario in the presence of PV systems operating at power factor equal to 0.95 are shown in the Figures below. In all simulated cases (high amount of PV systems and EVs) there are no voltage level and line loading violations observed. In addition, the results show that the net load reduces as the PV capacity increases.

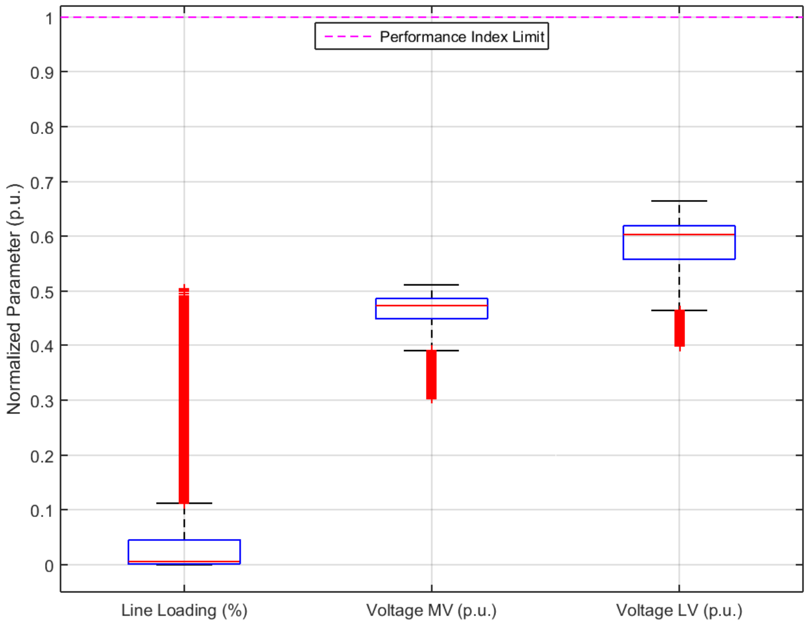

Figure 56. PQ parameters normalized to their limit – EV UC/FC and PV scenario – Power Factor equal to 0.95.

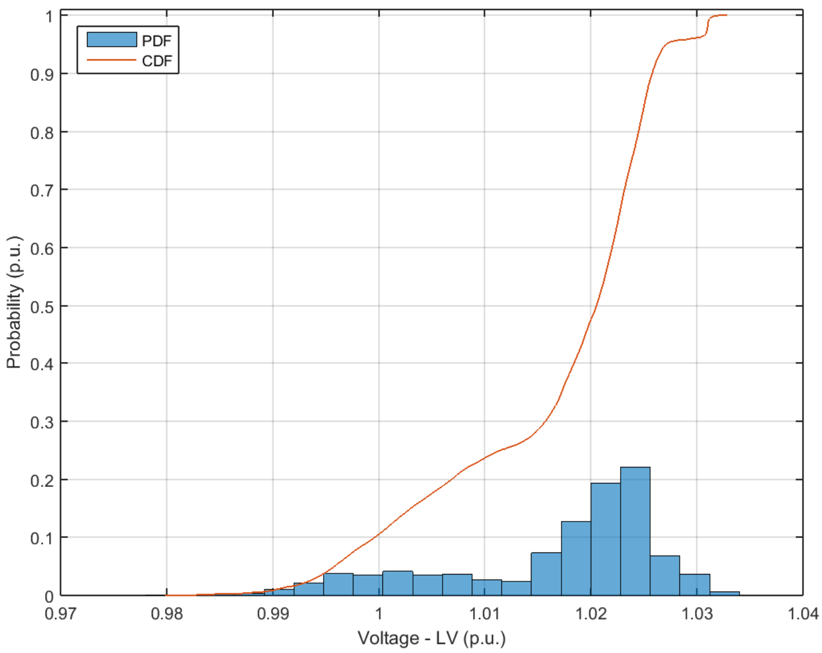

Figure 57. Probability distribution and cumulative probability distribution – Voltage at low voltage side – EV UC/FC and PV scenario – Power Factor equal to 0.95.

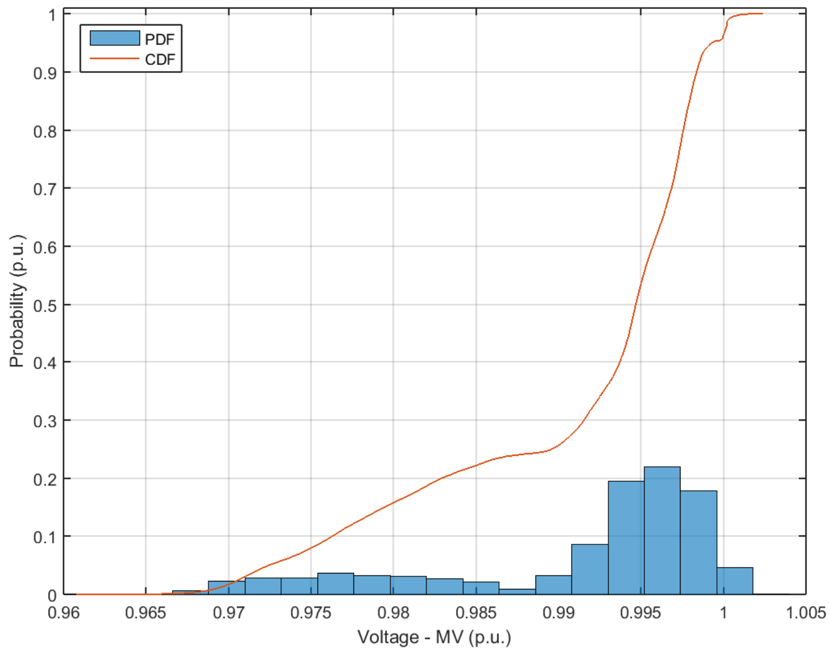

Figure 58. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – EV UC/FC and PV scenario – Power Factor equal to 0.95.

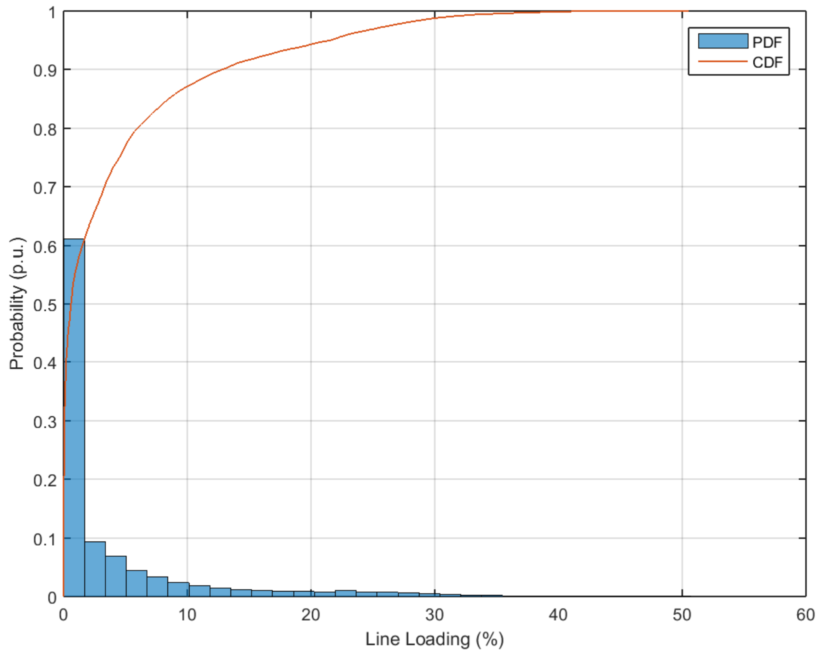

Figure 59. Probability distribution and cumulative probability distribution – Line Loading – EV UC/FC and PV scenario – Power Factor equal to 0.95.

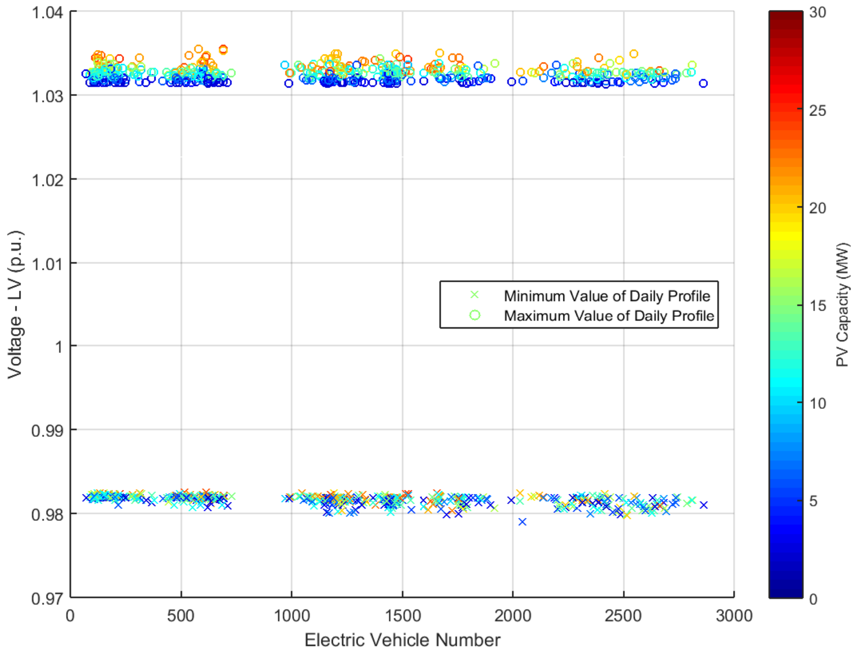

Figure 60. Voltage Variation at Low Voltage Side vs Electric Vehicle Number (including PV Capacity) – UC/FC – Power Factor equal to 0.95.

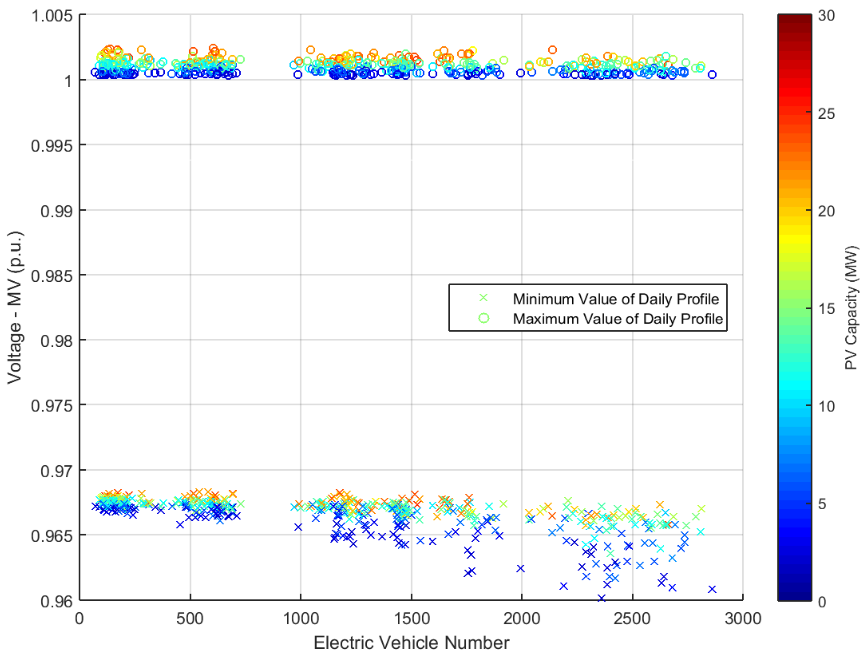

Figure 61. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number (including PV Capacity) – UC/FC – Power Factor equal to 0.95.

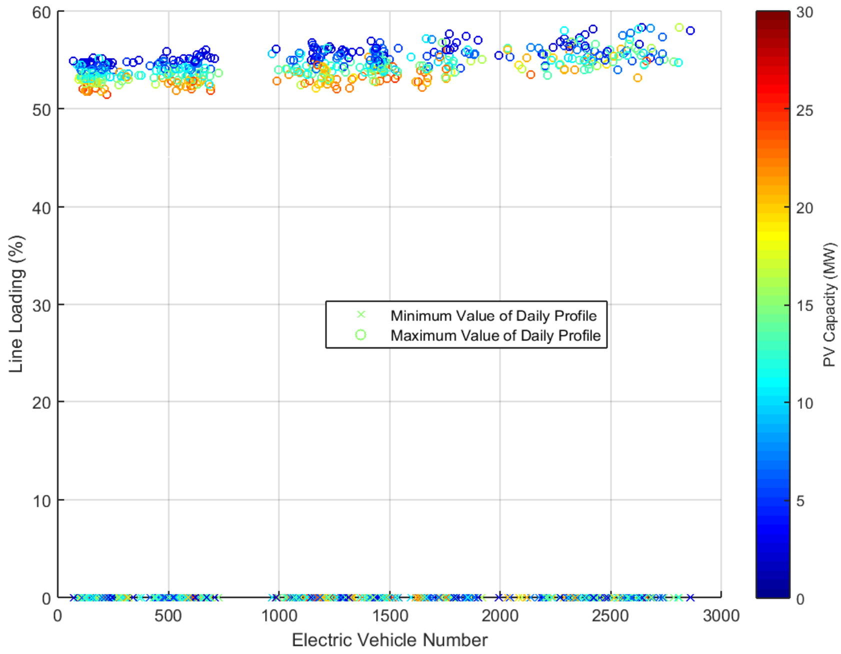

Figure 62. Line Loading vs Electric Vehicle Number (including PV Capacity) – UC/FC – Power Factor equal to 0.95.

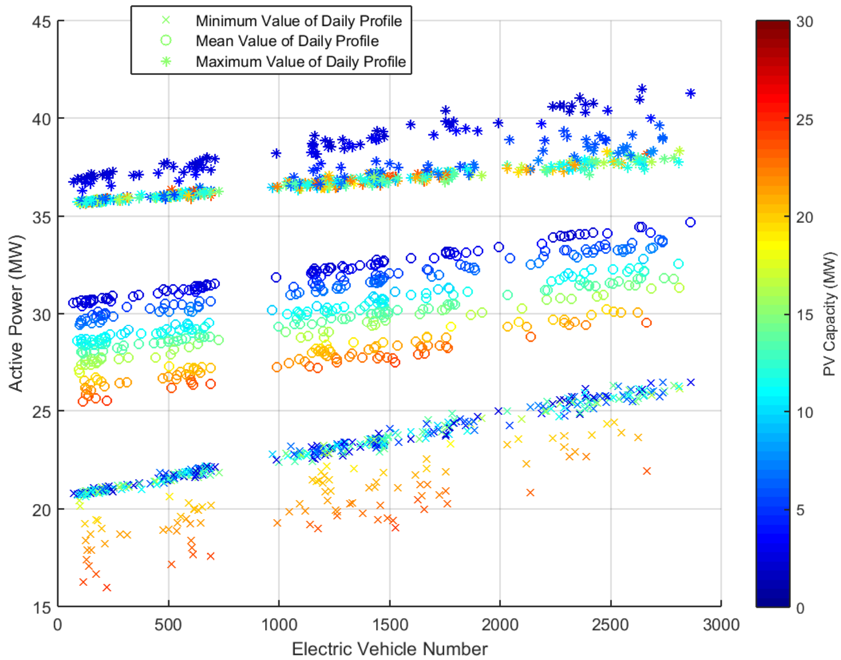

Figure 63. Active Power vs Electric Vehicle Number (including PV Capacity) – UC/FC – Power Factor equal to 0.95.

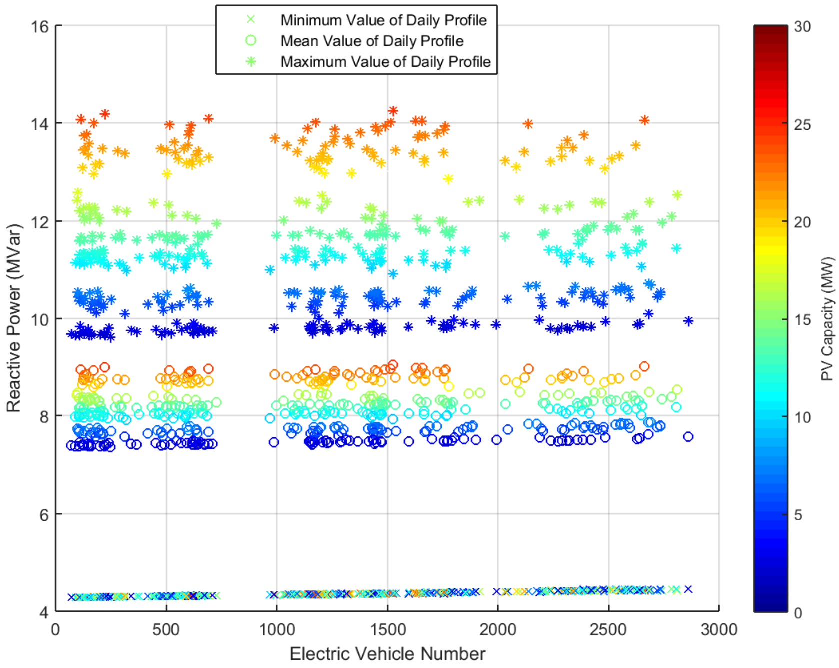

Figure 64. Reactive Power vs Electric Vehicle Number (including PV Capacity) – UC/FC – Power Factor equal to 0.95.

4.2.1.3 Uncontrolled charging – Full Charging (Power Factor cosφ(P))

The results for the "Uncontrolled charging – Full Charging" scenario in the presence of PV systems operating at cosφ(P) power factor scheme are shown in the Figures below. In all simulated cases (high amount of PV systems and EVs) there are no voltage level and line loading violations observed. In addition, the results show that the net load reduces as the PV capacity increases.

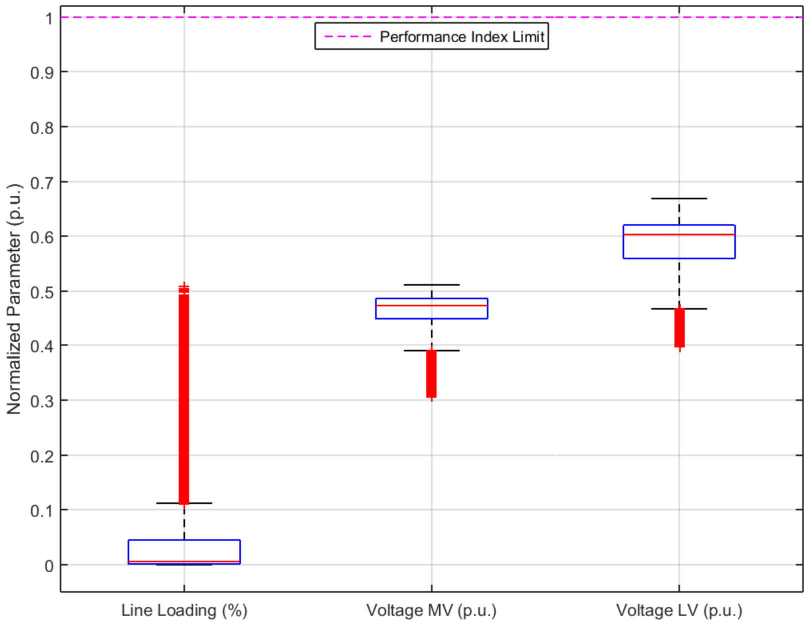

Figure 65. PQ parameters normalized to their limit – EV UC/FC and PV scenario – Power Factor cosφ(P).

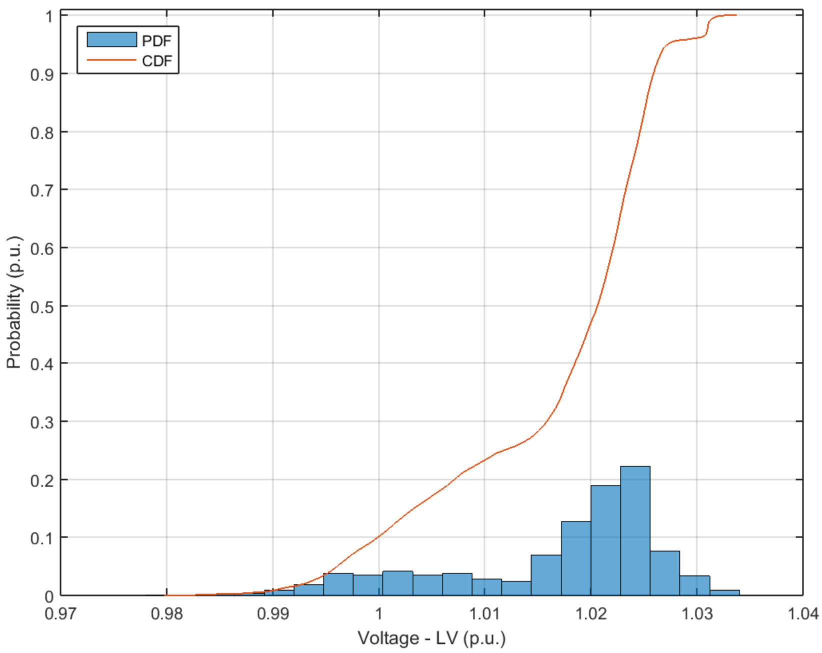

Figure 66. Probability distribution and cumulative probability distribution – Voltage at low voltage side – EV UC/FC and PV scenario – Power Factor cosφ(P).

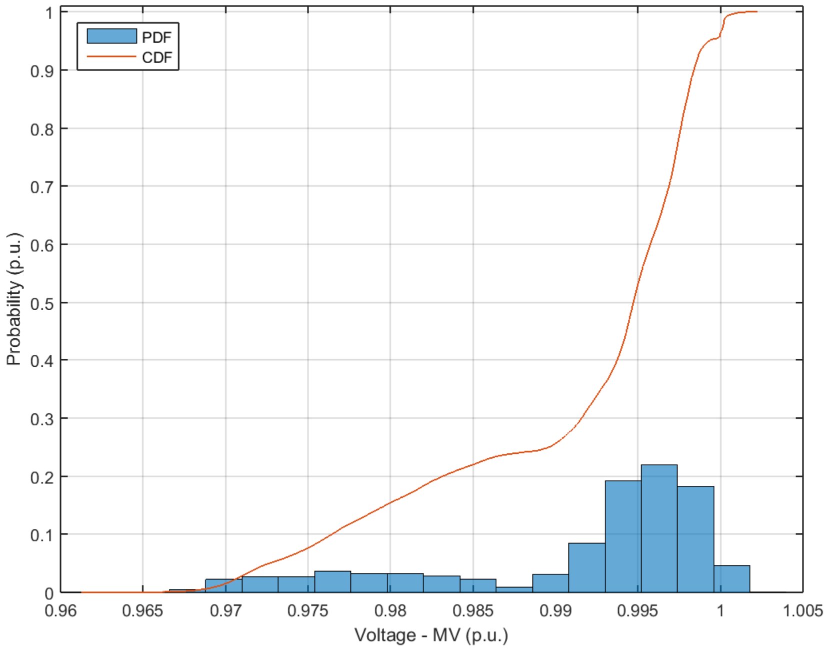

Figure 67. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – EV UC/FC and PV scenario – Power Factor cosφ(P).

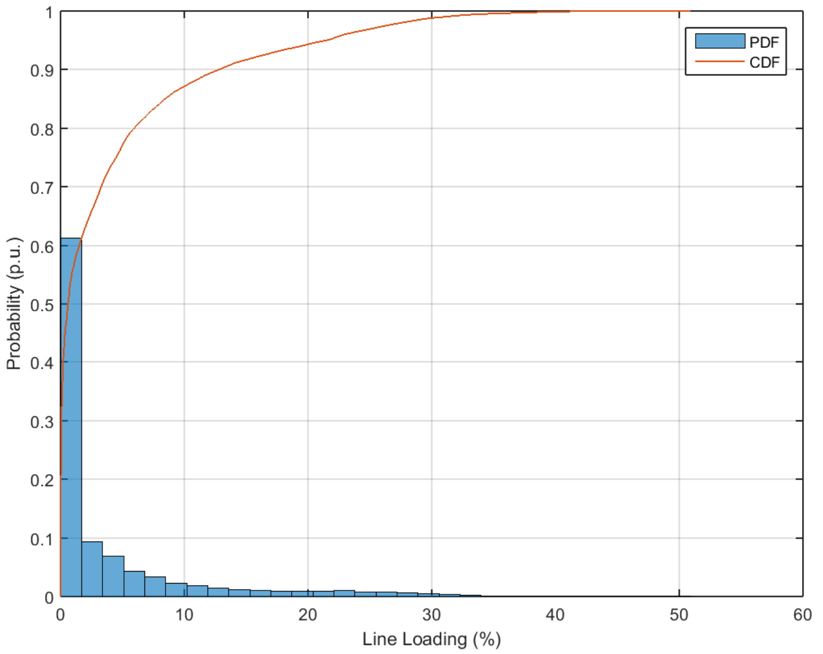

Figure 68. Probability distribution and cumulative probability distribution – Line Loading – EV UC/FC and PV scenario – Power Factor cosφ(P).

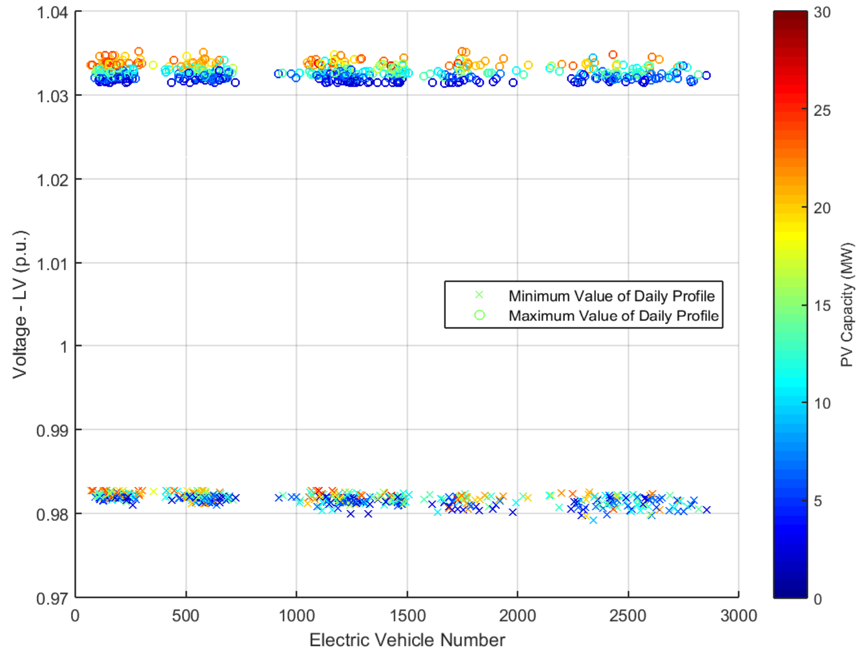

Figure 69. Voltage Variation at Low Voltage Side vs Electric Vehicle Number (including PV Capacity) – UC/FC – Power Factor cosφ(P).

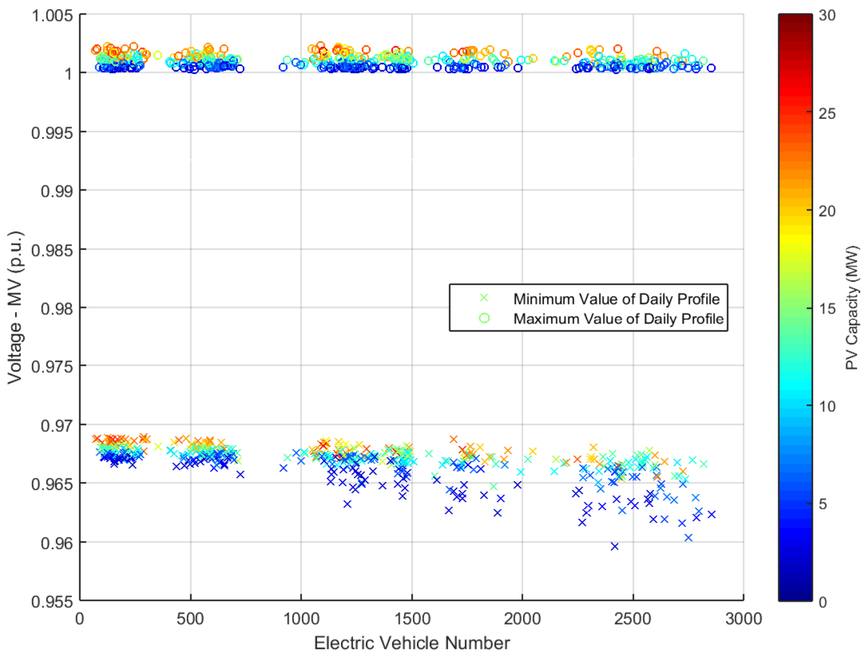

Figure 70. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number (including PV Capacity) – UC/FC – Power Factor cosφ(P).

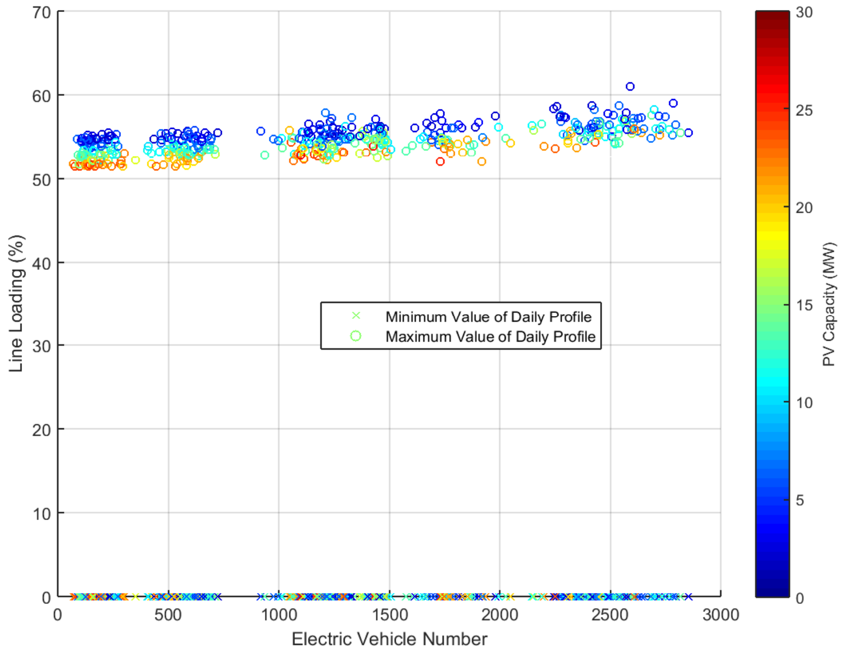

Figure 71. Line Loading vs Electric Vehicle Number (including PV Capacity) – UC/FC – Power Factor cosφ(P).

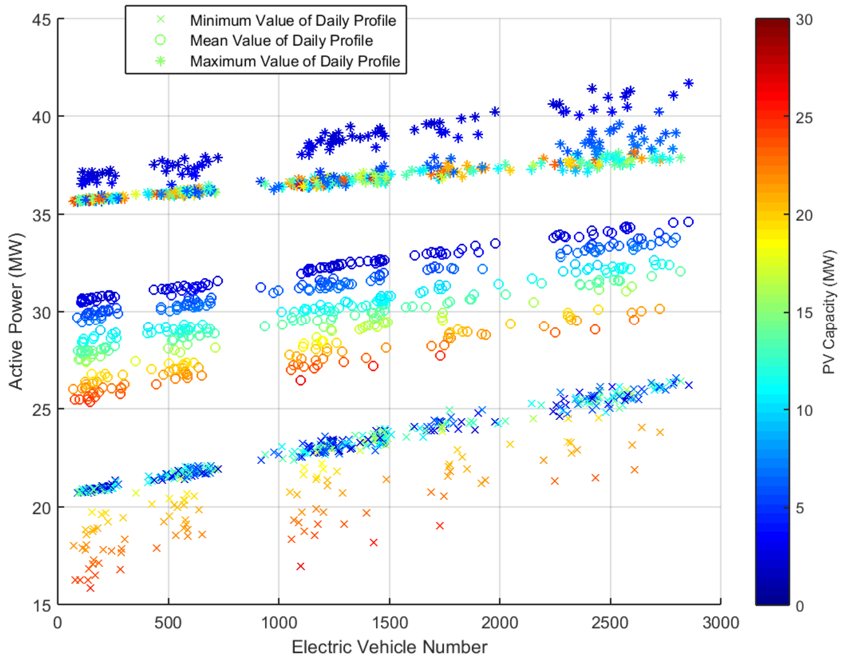

Figure 72. Active Power vs Electric Vehicle Number (including PV Capacity) – UC/FC – Power Factor cosφ(P).

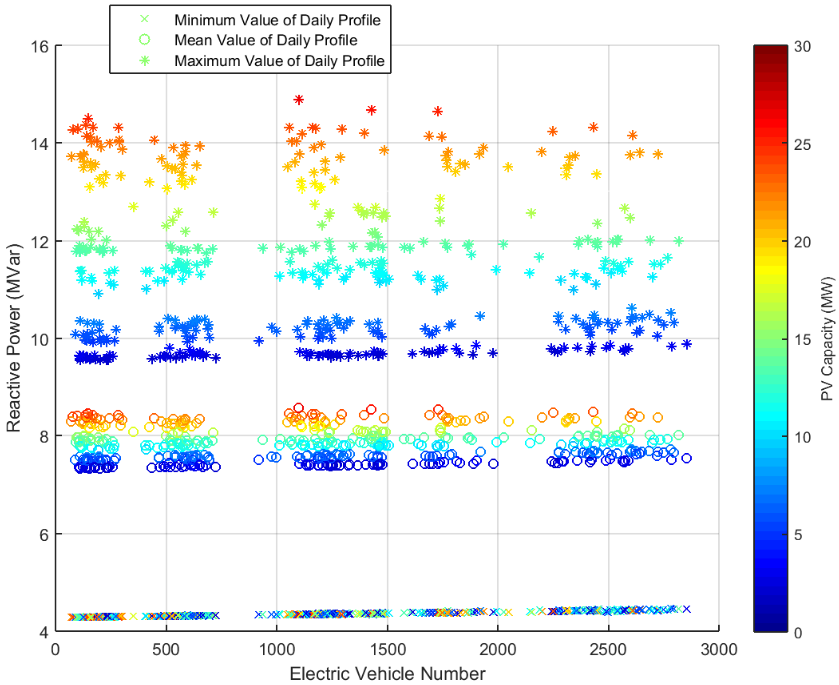

Figure 73. Reactive Power vs Electric Vehicle Number (including PV Capacity) – UC/FC – Power Factor cosφ(P).

4.2.1.4 Uncontrolled Charging – Full Charging and PV

By introducing both the EVs and PV integrated into the MV reference grid, the voltage levels are improved in comparison to the base case simulated when no PV are included. The results, summarized in the Table below, show that the lines are not significantly affected when the surplus energy consumed by EVs charging is covered by the local PV system production.

Table 4. Statistical analysis of PQ parameters – UC/FC in the presence of PV.

		Scenario: Uncontrolled Charging-Full Charging			
Normalized Parameter	Statistical Analysis	No PV	Unity Power Factor	Power Factor equal to 0.95	Power Factor cosφ(P)
Voltage – Low Voltage Side	Minimum	0.3950	0.3975	0.3951	0.3959
	25th quantile	0.5554	0.5635	0.5575	0.5592
	Median	0.6013	0.6046	0.6026	0.6032
	Average	0.5814	0.5868	0.5838	0.5846
	Standard Deviation	0.0532	0.0498	0.0507	0.0505
	75th quantile	0.6181	0.6216	0.6192	0.6199
	95th quantile	0.6350	0.6401	0.6355	0.6362
	99th quantile	0.6551	0.6571	0.6556	0.6559
	Maximum	0.6556	0.6825	0.6644	0.6692
Number of elements of which the limit is violated		0 out of 206	0 out of 206	0 out of 206	0 out of 206
Voltage – Medium Voltage Side	Minimum	0.2854	0.3077	0.3007	0.2980
	25th quantile	0.4455	0.4489	0.4480	0.4481
	Median	0.4720	0.4741	0.4735	0.4736
	Average	0.4538	0.4581	0.4566	0.4570
	Standard Deviation	0.0452	0.0412	0.0424	0.0420
	75th quantile	0.4849	0.4867	0.4862	0.4863
	95th quantile	0.4961	0.4971	0.4965	0.4966
	99th quantile	0.5010	0.5017	0.5014	0.5015
	Maximum	0.5010	0.5155	0.5121	0.5116
Number of elements of which the limit is violated		0 out of 206	0 out of 206	0 out of 206	0 out of 206
Line Loading	Minimum	0.0000	0.0000	0.0000	0.0000
	25th quantile	0.0004	0.0005	0.0005	0.0005
	Median	0.0059	0.0059	0.0060	0.0060
	Average	0.0421	0.0386	0.0393	0.0392
	Standard Deviation	0.0741	0.0689	0.0696	0.0695
	75th quantile	0.0487	0.0432	0.0451	0.0448
	95th quantile	0.2215	0.2140	0.2152	0.2151
	99th quantile	0.3343	0.3060	0.3104	0.3096
	Maximum	0.5625	0.5133	0.5141	0.5313
Number of elements of which the limit is violated		0 out of 451	0 out of 451	0 out of 451	0 out of 451

4.2.2 Uncontrolled charging considering mobility curves

4.2.2.1 Uncontrolled charging considering mobility curves (Unity Power Factor)

The results for the "Uncontrolled charging considering mobility" scenario in the presence of PV systems operating at unity power factor are shown in the Figures below. In all simulated cases (high amount of PV systems and EVs) there are no voltage level and line loading violations observed.

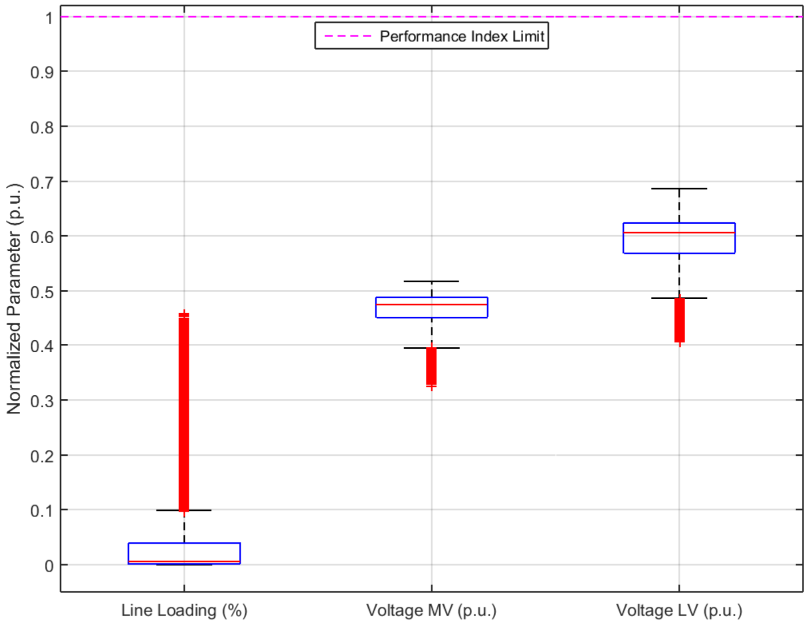

Figure 74. PQ parameters normalized to their limit – EV UCM and PV scenario – Unity Power Factor.

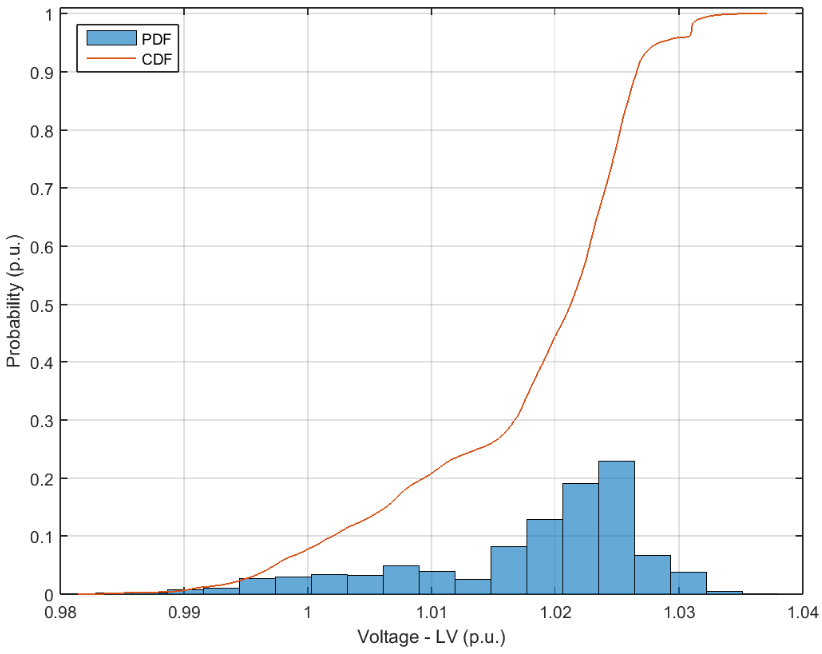

Figure 75. Probability distribution and cumulative probability distribution – Voltage at low voltage side – EV UCM and PV scenario – Unity Power Factor.

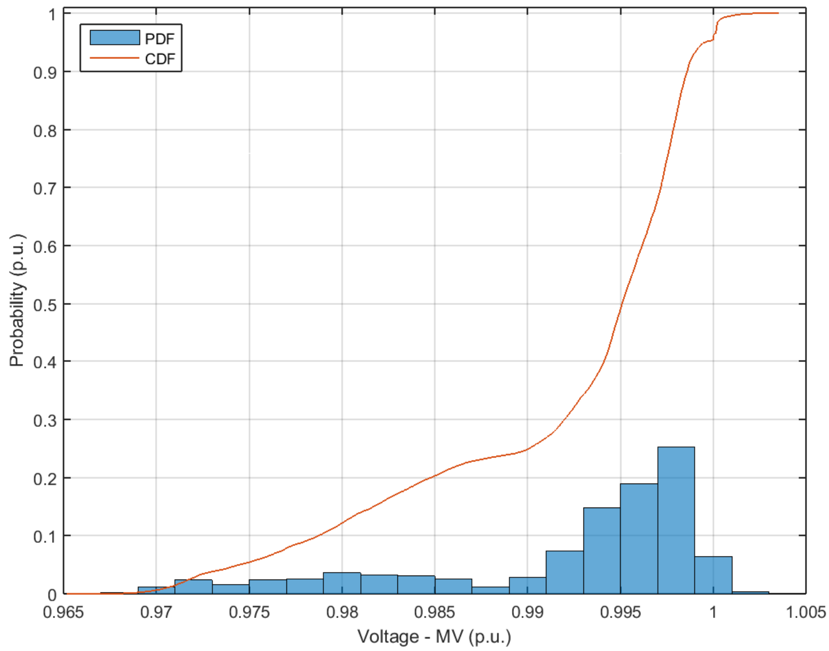

Figure 76. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – EV UCM and PV scenario – Unity Power Factor.

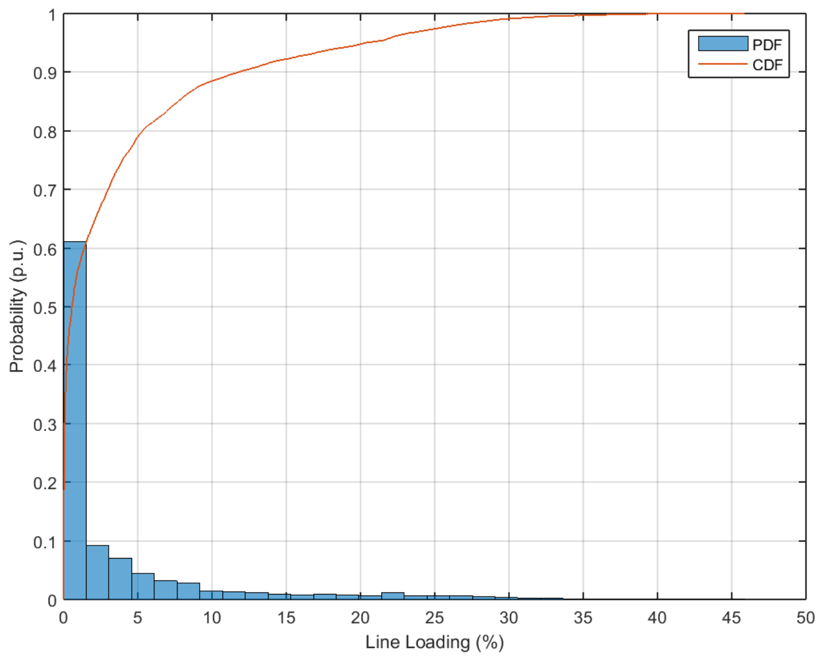

Figure 77. Probability distribution and cumulative probability distribution – Line Loading – EV UCM and PV scenario – Unity Power Factor.

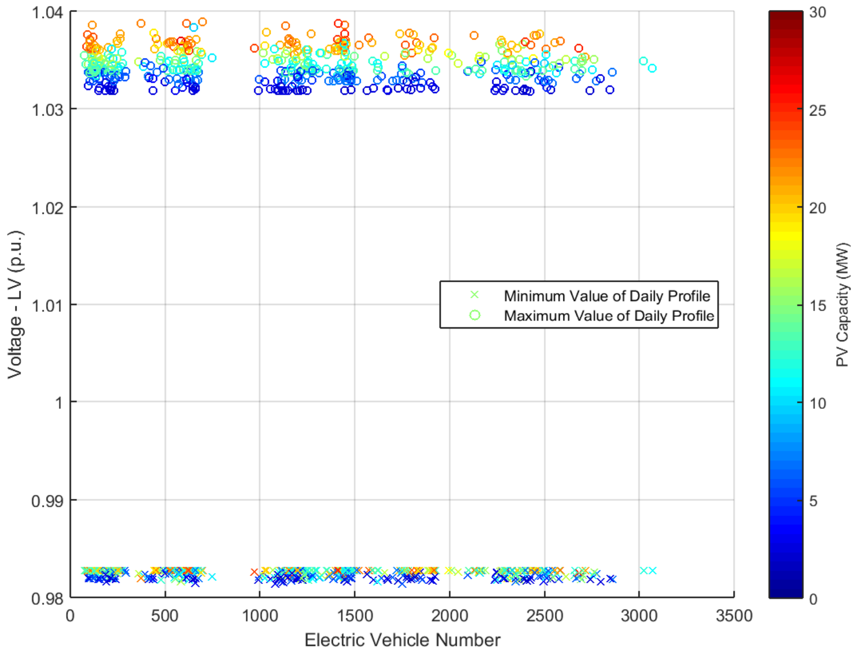

Figure 78. Voltage Variation at Low Voltage Side vs Electric Vehicle Number (including PV Capacity) – UCM - Unity Power Factor.

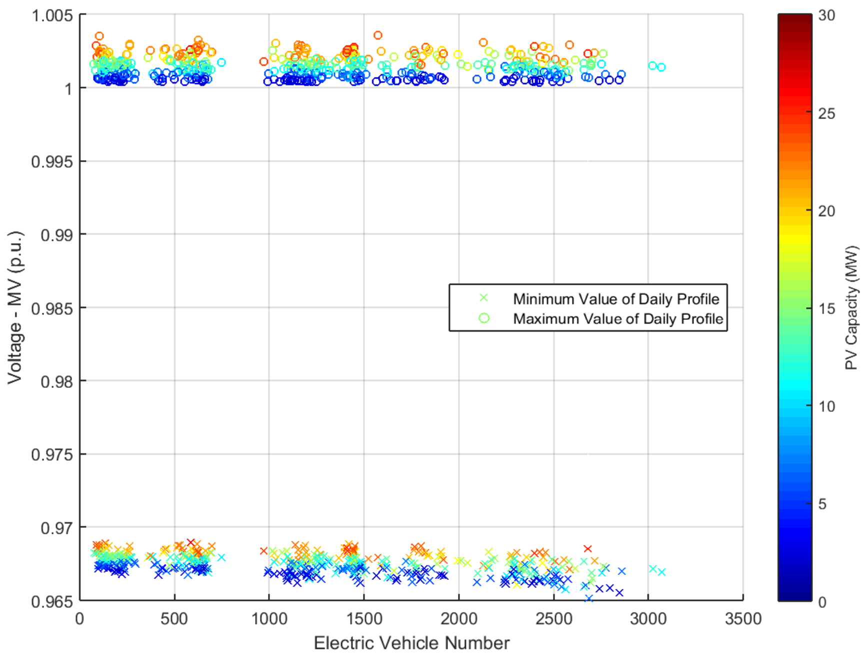

Figure 79. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number (including PV Capacity) – UCM - Unity Power Factor.

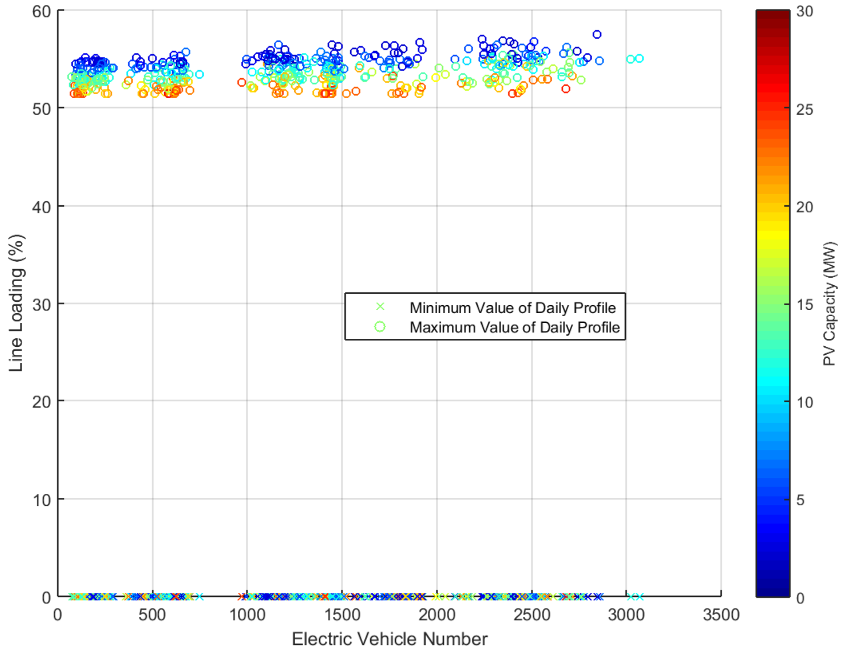

Figure 80. Line Loading vs Electric Vehicle Number (including PV Capacity) – UCM - Unity Power Factor.

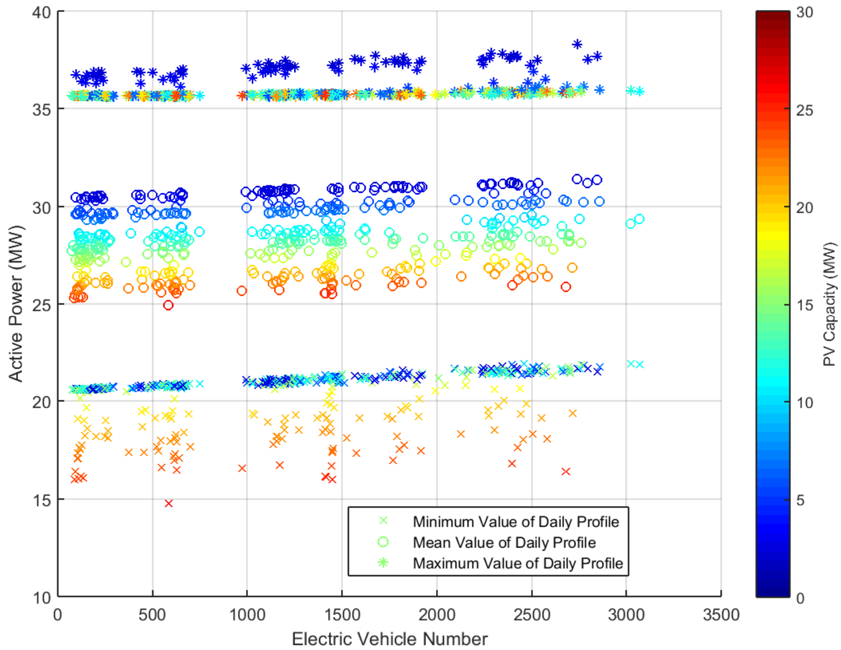

Figure 81. Active Power vs Electric Vehicle Number (including PV Capacity) – UCM - Unity Power Factor.

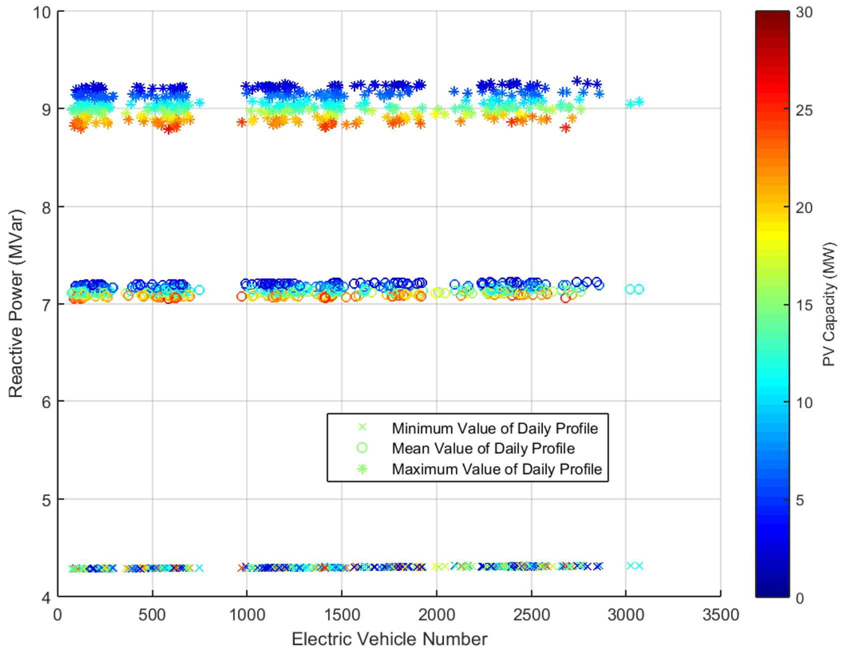

Figure 82. Reactive Power vs Electric Vehicle Number (including PV Capacity) – UCM - Unity Power Factor.

4.2.2.2 Uncontrolled charging considering mobility curves (Power Factor equal to 0.95)

The results for the "Uncontrolled charging considering mobility" scenario in the presence of PV systems operating at power factor 0.95 are shown in the Figures below. In all simulated cases (high amount of PV systems and EVs) there are no voltage level and line loading violations observed.

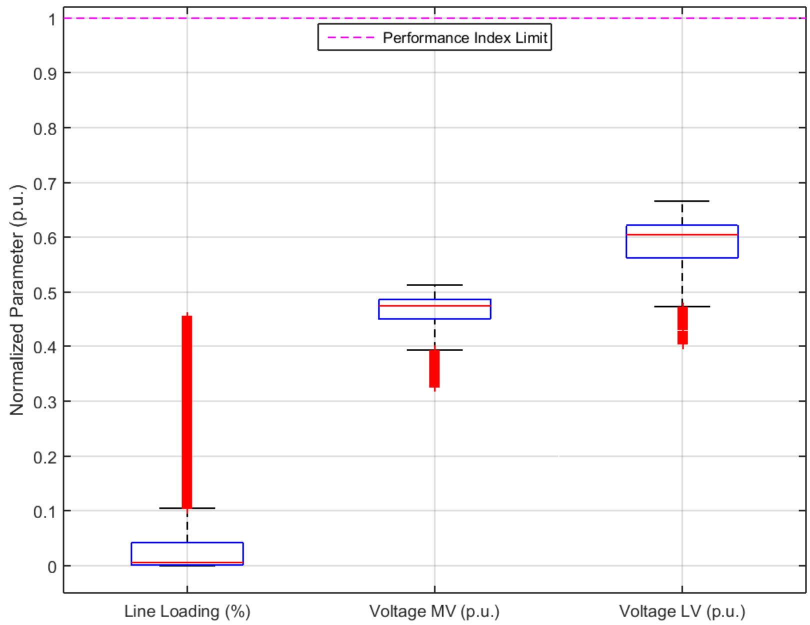

Figure 83. PQ parameters normalized to their limit – EV UCM and PV scenario – Power Factor equal to 0.95.

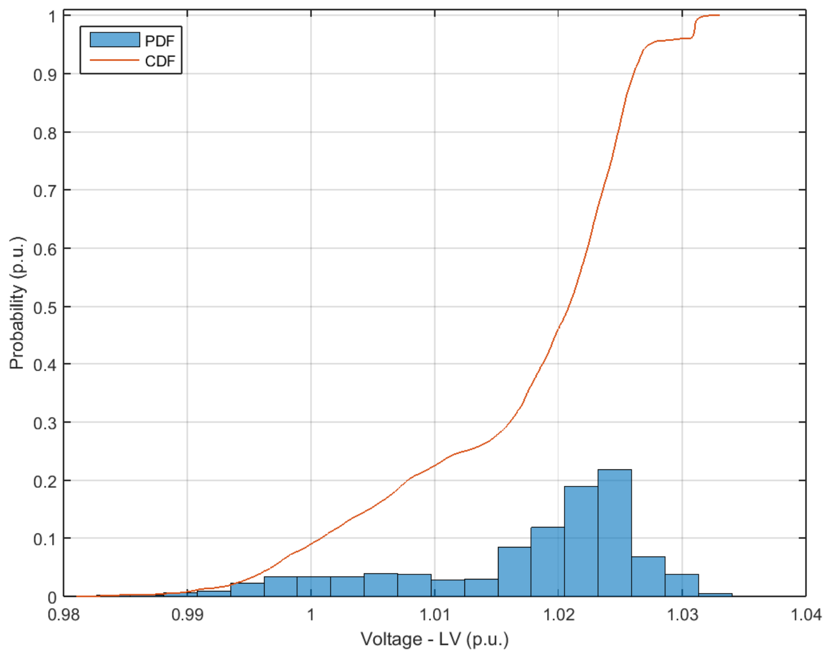

Figure 84. Probability distribution and cumulative probability distribution – Voltage at low voltage side – EV UCM and PV scenario – Power Factor equal to 0.95.

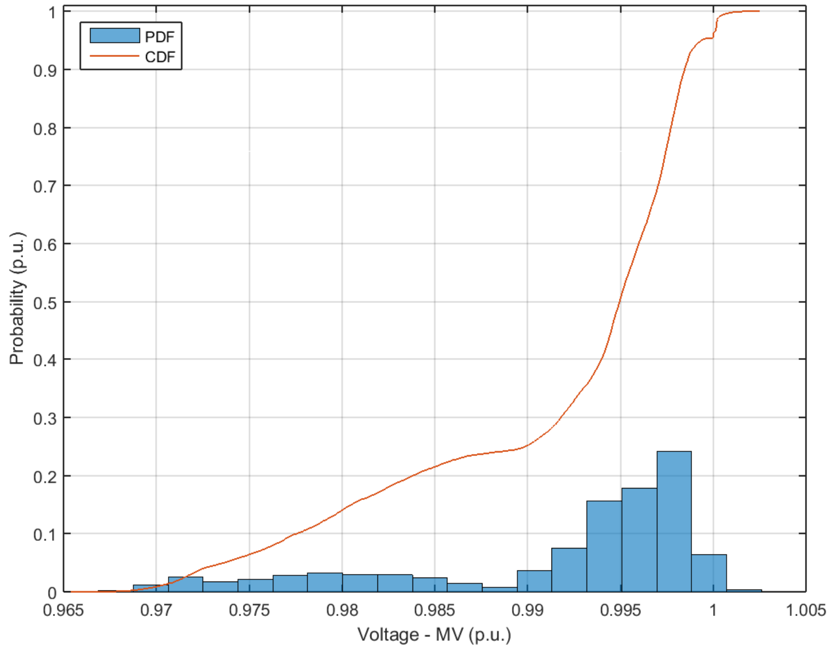

Figure 85. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – EV UCM and PV scenario – Power Factor equal to 0.95.

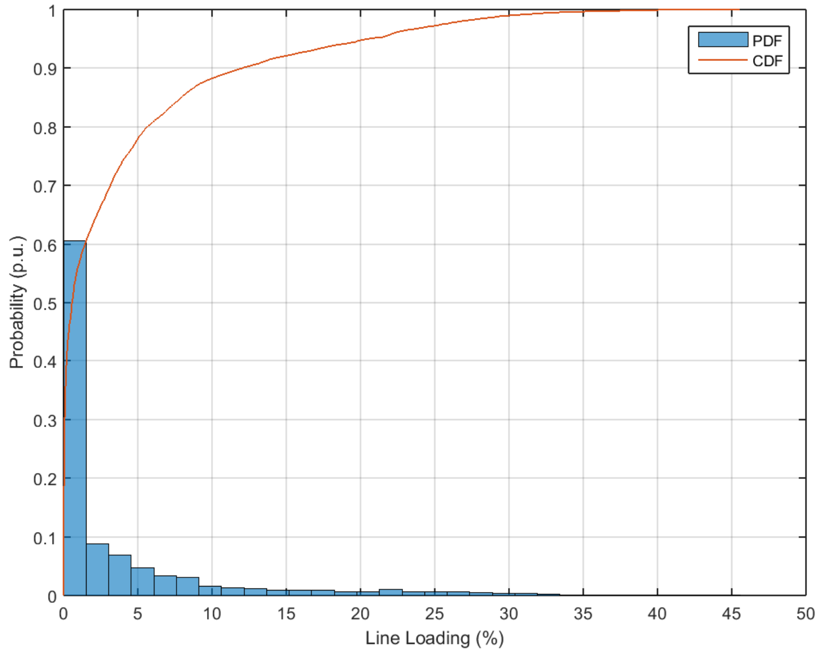

Figure 86. Probability distribution and cumulative probability distribution – Line Loading – EV UCM and PV scenario – Power Factor equal to 0.95.

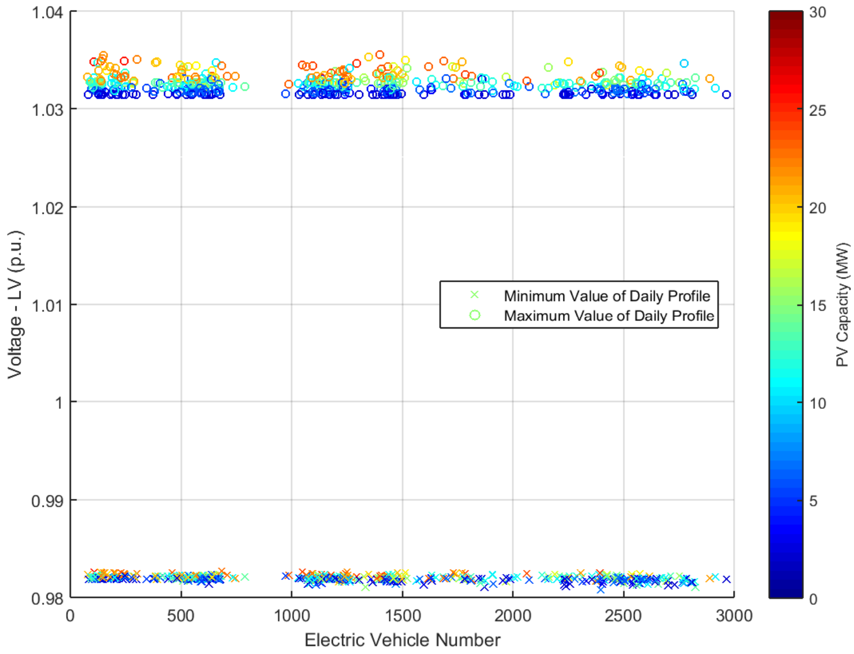

Figure 87. Voltage Variation at Low Voltage Side vs Electric Vehicle Number (including PV Capacity) – UCM – Power Factor equal to 0.95.

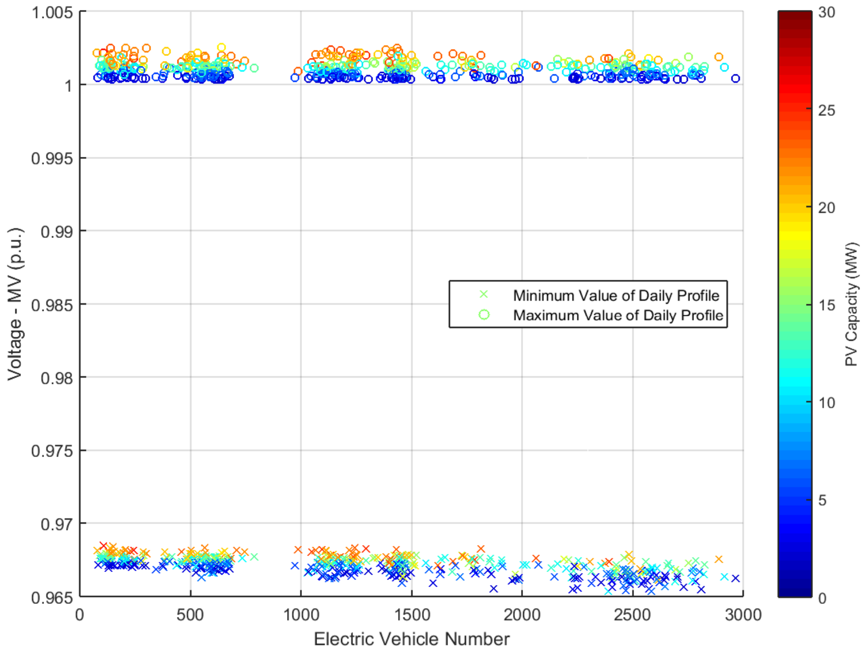

Figure 88. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number (including PV Capacity) – UCM – Power Factor equal to 0.95.

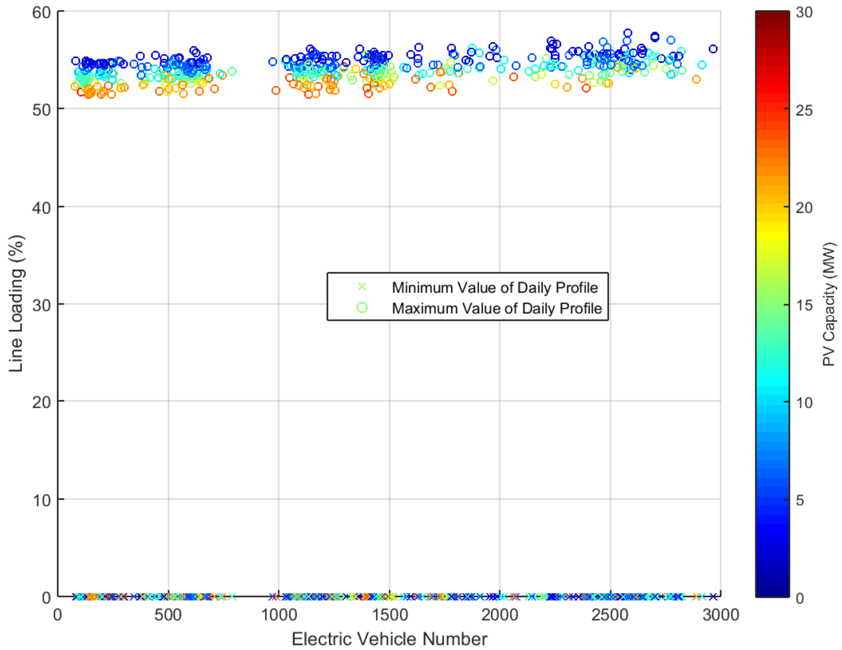

Figure 89. Line Loading vs Electric Vehicle Number (including PV Capacity) – UCM – Power Factor equal to 0.95.

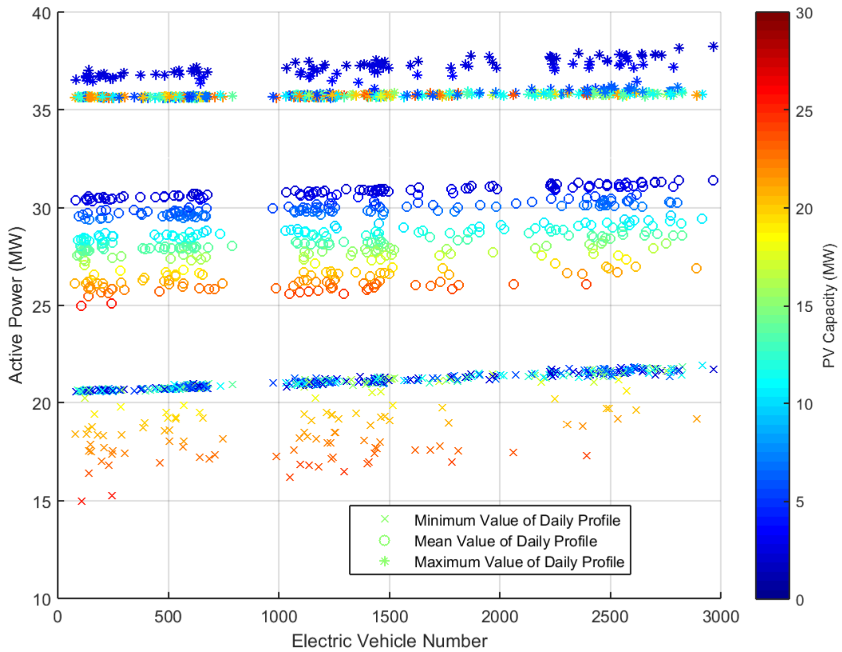

Figure 90. Active Power vs Electric Vehicle Number (including PV Capacity) – UCM – Power Factor equal to 0.95.

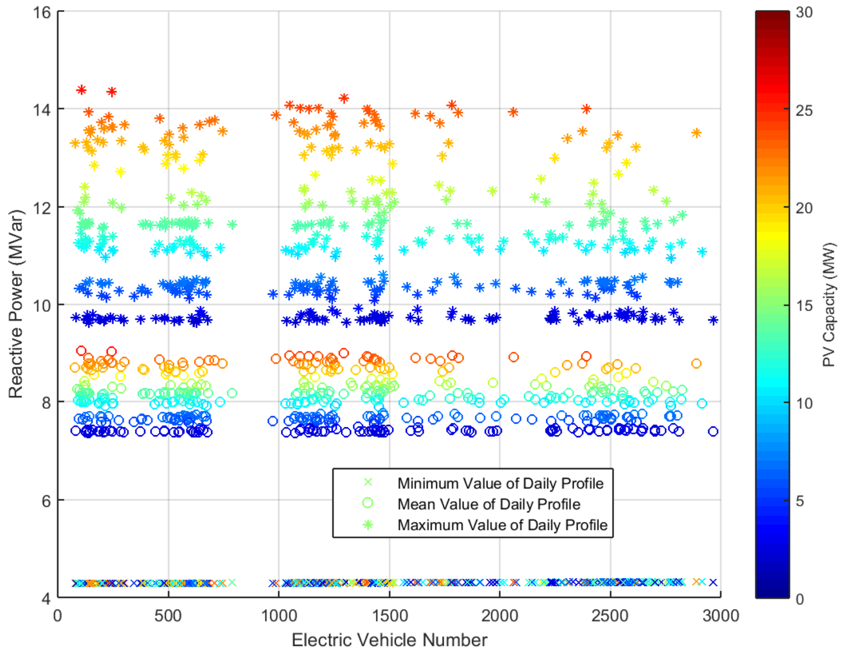

Figure 91. Reactive Power vs Electric Vehicle Number (including PV Capacity) – UCM – Power Factor equal to 0.95.

4.2.2.3 Uncontrolled charging considering mobility curves (Power Factor cosφ(P))

The results for the "Uncontrolled charging considering mobility" scenario in the presence of PV systems operating at cosφ(P) power factor are shown in the Figures below. In all simulated cases (high amount of PV systems and EVs) there are no voltage level and line loading violations observed.

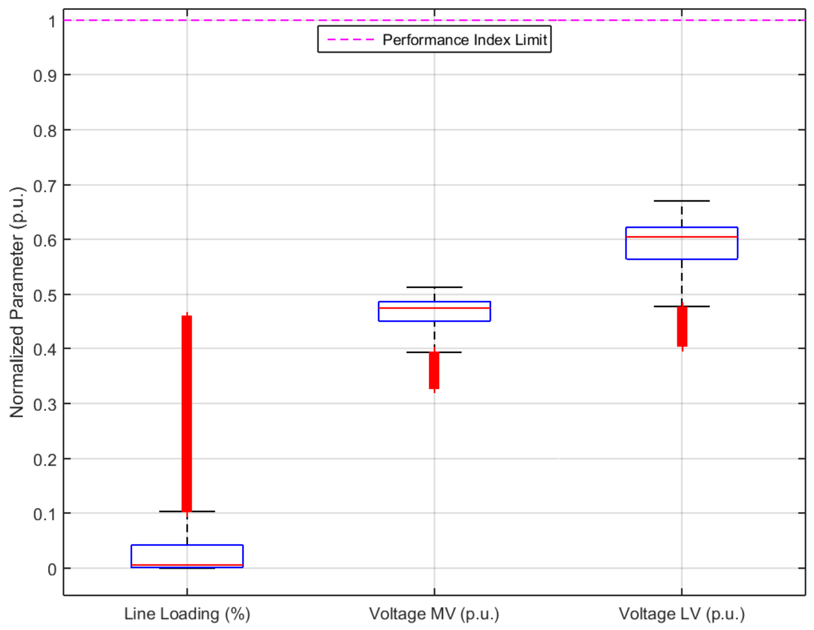

Figure 92. PQ parameters normalized to their limit – EV UCM and PV scenario – Power Factor cosφ(P).

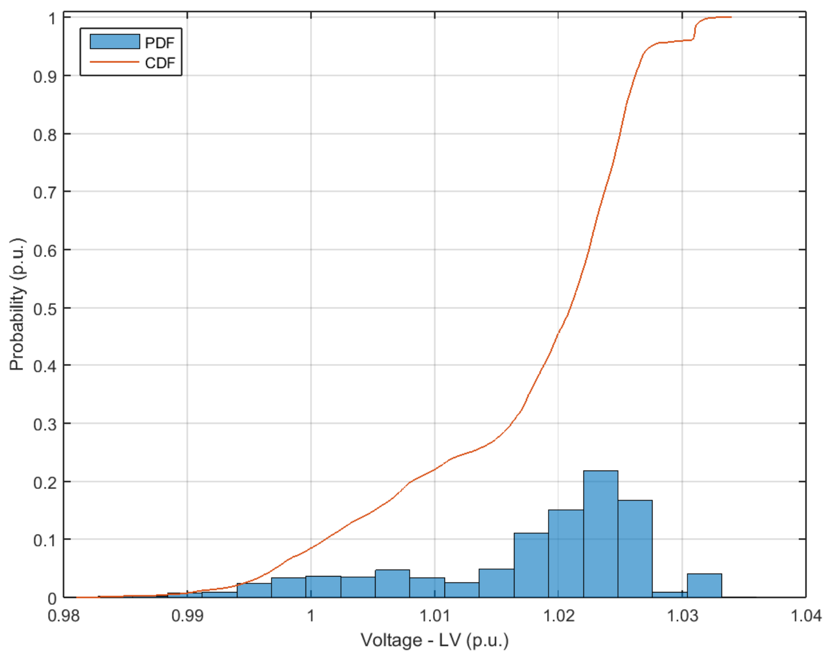

Figure 93. Probability distribution and cumulative probability distribution – Voltage at low voltage side – EV UCM and PV scenario – Power Factor cosφ(P).

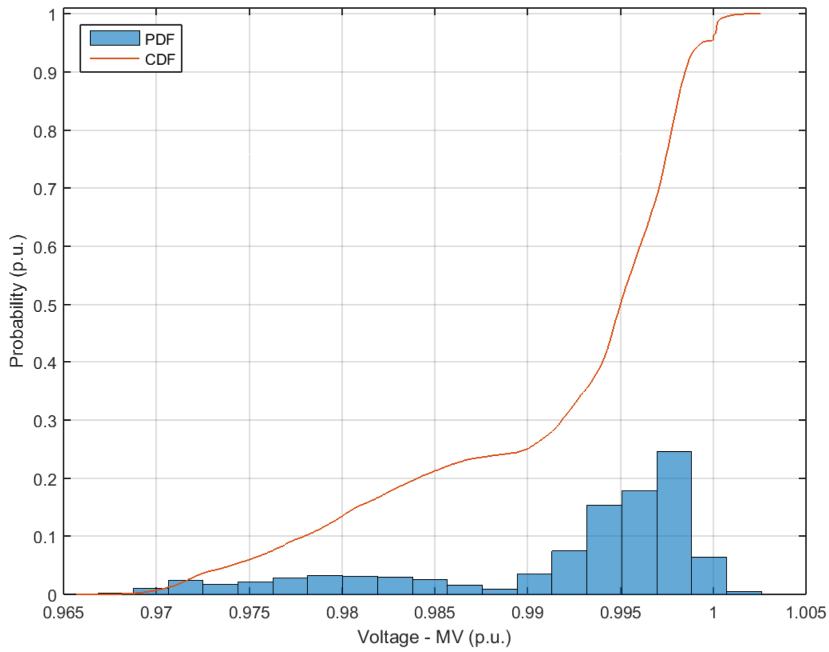

Figure 94. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – EV UCM and PV scenario – Power Factor cosφ(P).

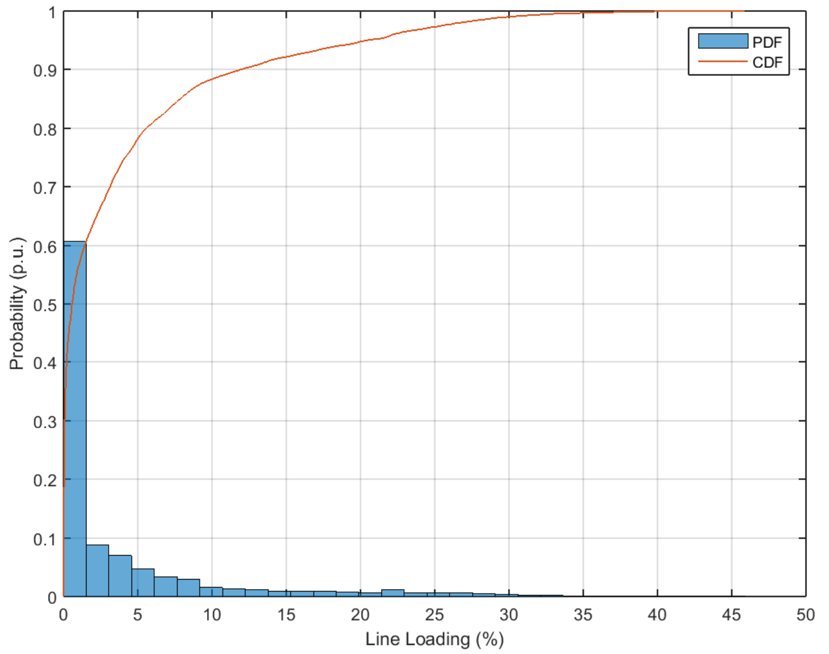

Figure 95. Probability distribution and cumulative probability distribution – Line Loading – EV UCM and PV scenario – Power Factor cosφ(P).

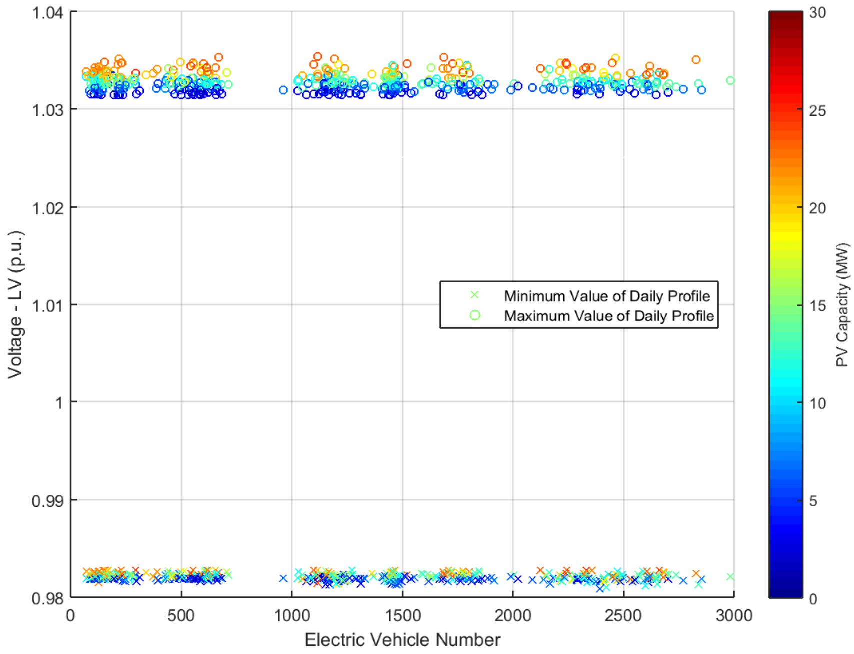

Figure 96. Voltage Variation at Low Voltage Side vs Electric Vehicle Number (including PV Capacity) – UCM – Power Factor cosφ(P).

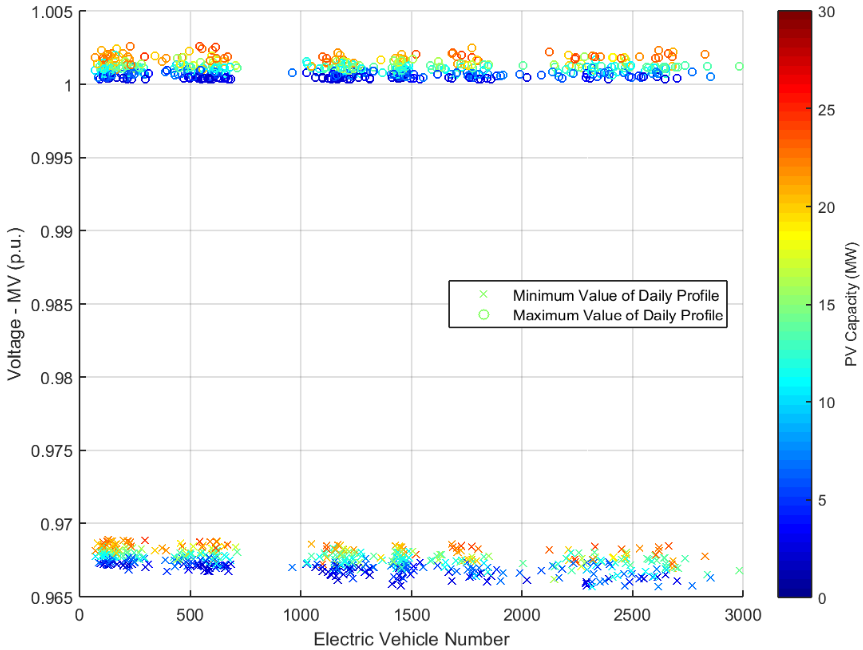

Figure 97. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number (including PV Capacity) – UCM – Power Factor cosφ(P).

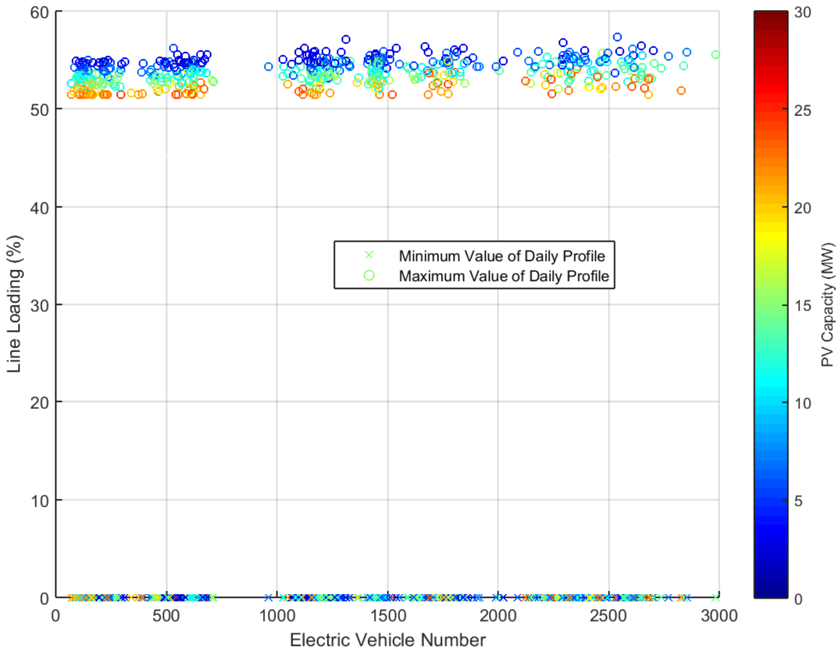

Figure 98. Line Loading vs Electric Vehicle Number (including PV Capacity) – UCM – Power Factor cosφ(P).

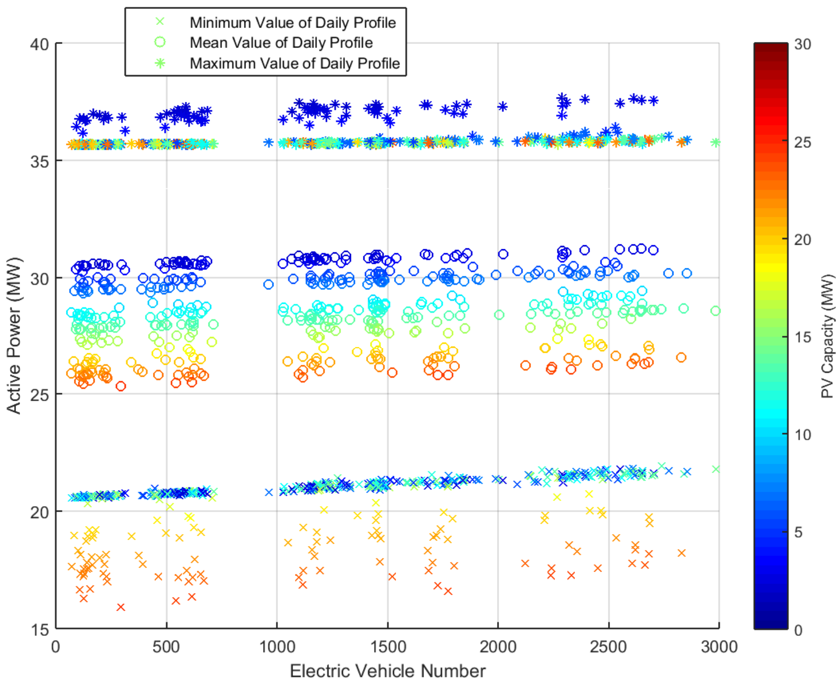

Figure 99. Active Power vs Electric Vehicle Number (including PV Capacity) – UCM – Power Factor cosφ(P).

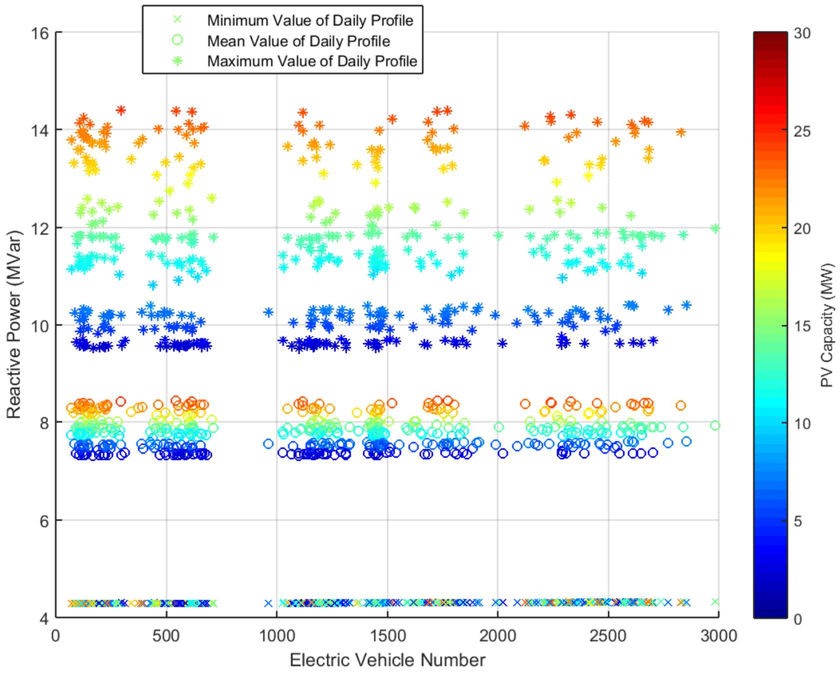

Figure 100. Reactive Power vs Electric Vehicle Number (including PV Capacity) – UCM – Power Factor cosφ(P).

4.2.2.4 Uncontrolled charging considering mobility curves and PV

For the uncontrolled charging considering mobility curves scenario, by introducing both the EVs and PV integrated into the MV reference grid, the voltage levels are improved in comparison to both the base case simulated when no PV are included and the Uncontrolled charging – Full Charging scenario. The results, summarized in the Table below, show that the lines are not significantly affected when the surplus energy consumed by EVs charging is covered by the local PV system production.

Table 5. Statistical analysis of PQ parameters – UC considering mobility.

		Scenario: UC considering mobility			
Normalized Parameter	Statistical Analysis	No PV	Unity Power Factor	Power Factor equal to 0.95	Power Factor cosφ(P)
Voltage – Low Voltage Side	Minimum	0.4043	0.4066	0.4040	0.4042
	25th quantile	0.5599	0.5686	0.5621	0.5642
	Median	0.6030	0.6063	0.6043	0.6048
	Average	0.5841	0.5897	0.5864	0.5874
	Standard Deviation	0.0515	0.0482	0.0493	0.0489
	75th quantile	0.6203	0.6234	0.6214	0.6221
	95th quantile	0.6361	0.6420	0.6367	0.6374
	99th quantile	0.6553	0.6578	0.6556	0.6563
	Maximum	0.6556	0.6858	0.6651	0.6707
Number of elements of which the limit is violated		0 out of 206	0 out of 206	0 out of 206	0 out of 206
Voltage – Medium Voltage Side	Minimum	0.3184	0.3258	0.3267	0.3283
	25th quantile	0.4475	0.4504	0.4494	0.4498
	Median	0.4732	0.4755	0.4748	0.4750
	Average	0.4559	0.4603	0.4587	0.4592
	Standard Deviation	0.0432	0.0393	0.0406	0.0401
	75th quantile	0.4857	0.4876	0.4870	0.4871
	95th quantile	0.4964	0.4978	0.4968	0.4969
	99th quantile	0.5010	0.5020	0.5016	0.5017
	Maximum	0.5010	0.5178	0.5127	0.5129
Number of elements of which the limit is violated		0 out of 206	0 out of 206	0 out of 206	0 out of 206
Line Loading	Minimum	0.0000	0.0000	0.0000	0.0000
	25th quantile	0.0004	0.0005	0.0005	0.0005
	Median	0.0056	0.0056	0.0057	0.0057
	Average	0.0400	0.0366	0.0375	0.0372
	Standard Deviation	0.0712	0.0660	0.0670	0.0666
	75th quantile	0.0459	0.0395	0.0421	0.0415
	95th quantile	0.2162	0.2034	0.2050	0.2039
	99th quantile	0.3262	0.2945	0.3011	0.2987
	Maximum	0.4889	0.4662	0.4699	0.4594
Number of elements of which the limit is violated		0 out of 451	0 out of 451	0 out of 451	0 out of 451

4.2.3 Controlled EV charging (smart charging)

4.2.3.1 Controlled EV charging (Unity Power Factor)

The results for the "Controlled EV charging" scenario in the presence of PV systems operating at unity power factor are shown in the Figures below. In all simulated cases (high amount of PV systems and EVs) there are no voltage level and line loading violations observed.

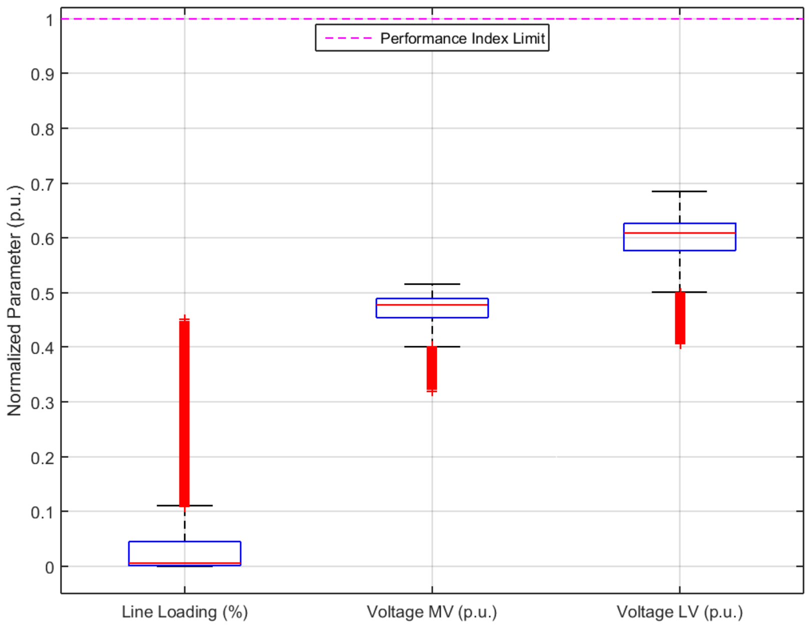

Figure 101. PQ parameters normalized to their limit – EV SC and PV scenario – Unity Power Factor.

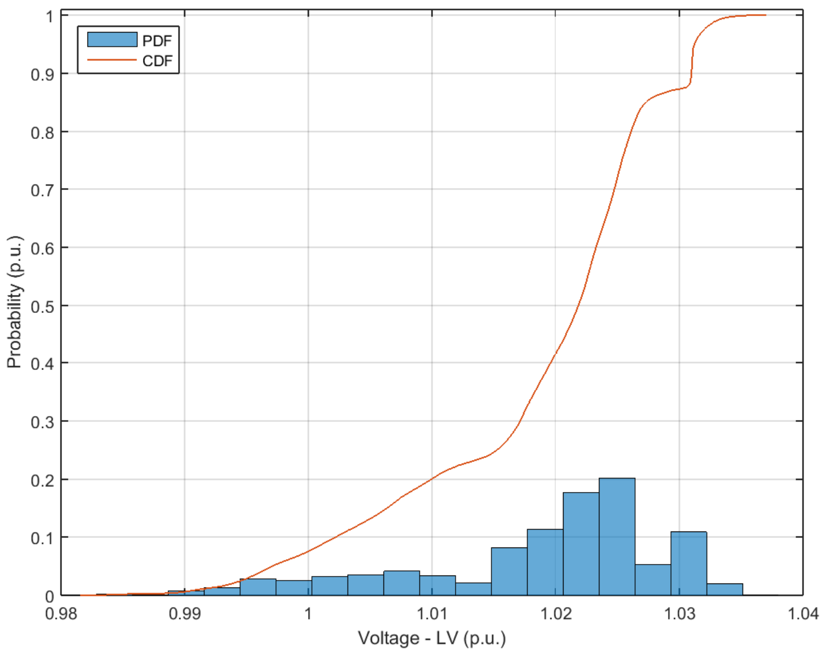

Figure 102. Probability distribution and cumulative probability distribution – Voltage at low voltage side – EV SC and PV scenario – Unity Power Factor.

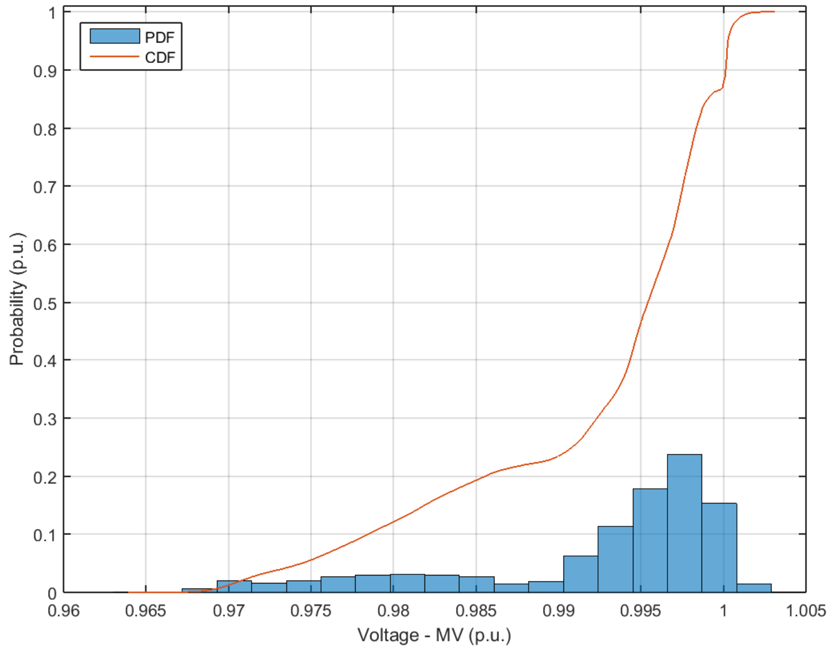

Figure 103. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – EV SC and PV scenario – Unity Power Factor.

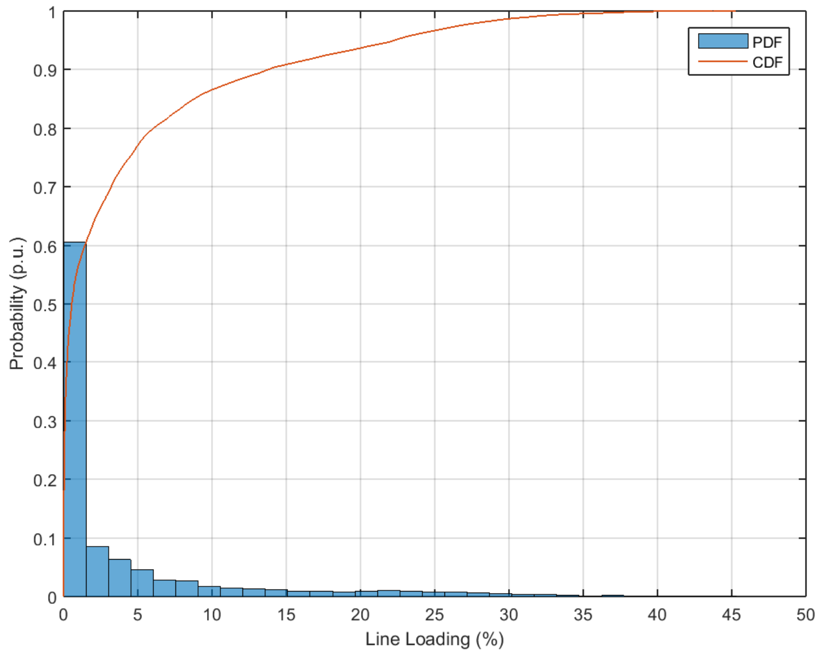

Figure 104. Probability distribution and cumulative probability distribution – Line Loading – EV SC and PV scenario – Unity Power Factor.

Figure 105. Voltage Variation at Low Voltage Side vs Electric Vehicle Number (including PV Capacity) – SC - Unity Power Factor.

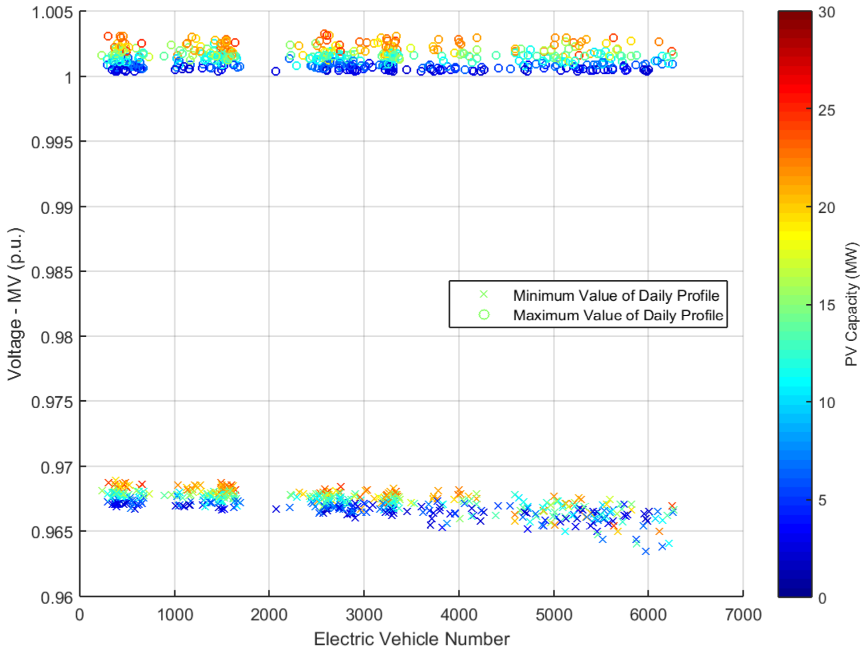

Figure 106. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number (including PV Capacity) – SC - Unity Power Factor.

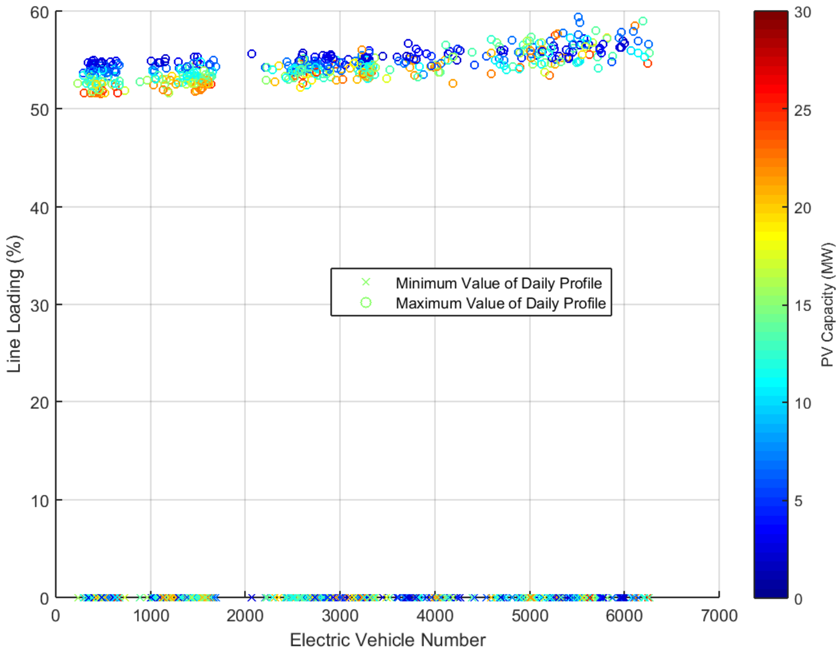

Figure 107. Line Loading vs Electric Vehicle Number (including PV Capacity) – SC - Unity Power Factor.

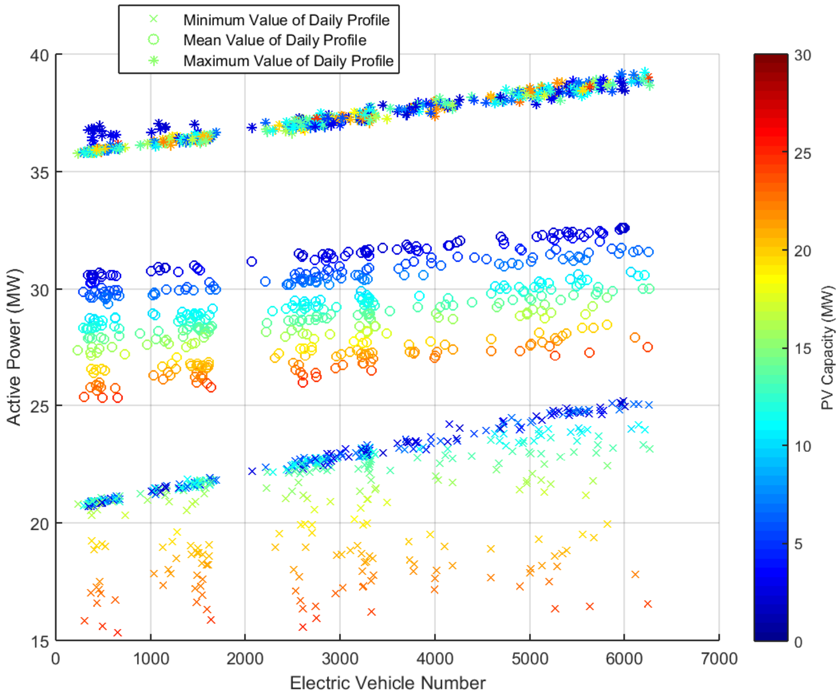

Figure 108. Active Power vs Electric Vehicle Number (including PV Capacity) – SC - Unity Power Factor.

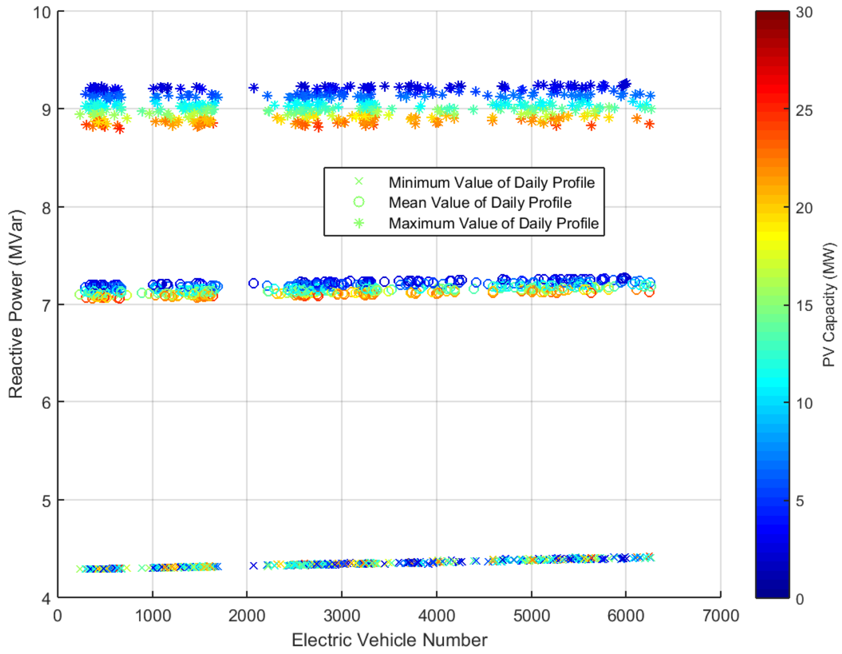

Figure 109. Reactive Power vs Electric Vehicle Number (including PV Capacity) – SC - Unity Power Factor.

4.2.3.2 Controlled EV charging (Power Factor equal to 0.95)

The results for the "Controlled EV charging" scenario in the presence of PV systems operating at power factor 0.95 are shown in the Figures below. In all simulated cases (high amount of PV systems and EVs) there are no voltage level and line loading violations observed.

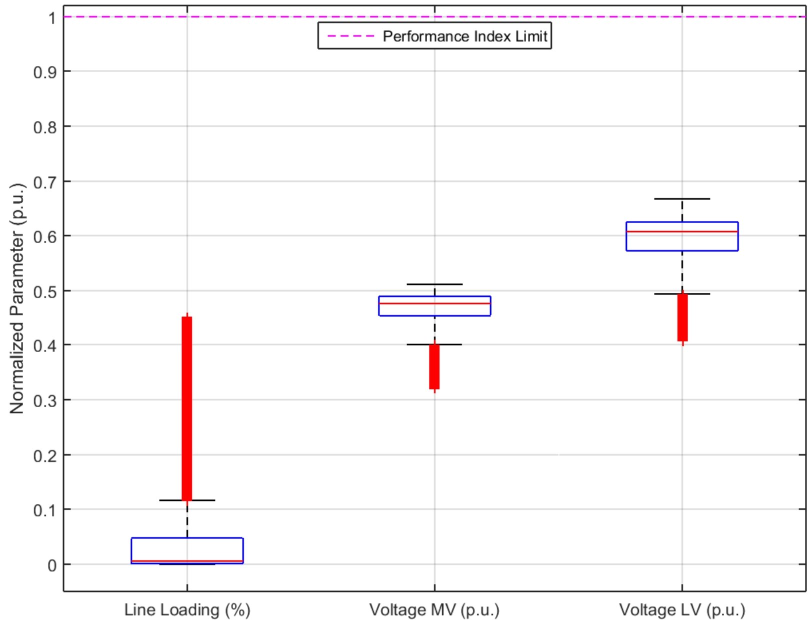

Figure 110. PQ parameters normalized to their limit – EV SC and PV scenario – Power Factor equal to 0.95.

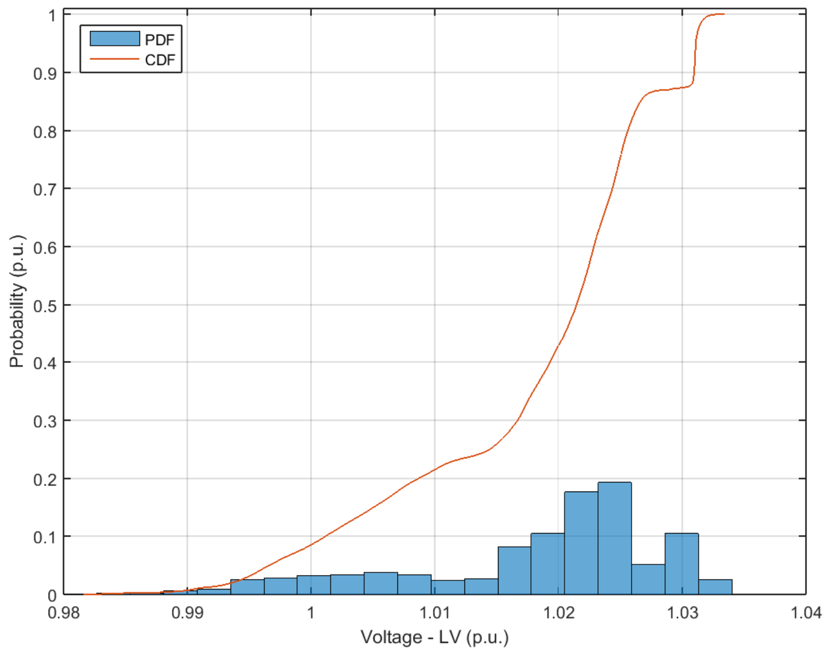

Figure 111. Probability distribution and cumulative probability distribution – Voltage at low voltage side – EV SC and PV scenario – Power Factor equal to 0.95.

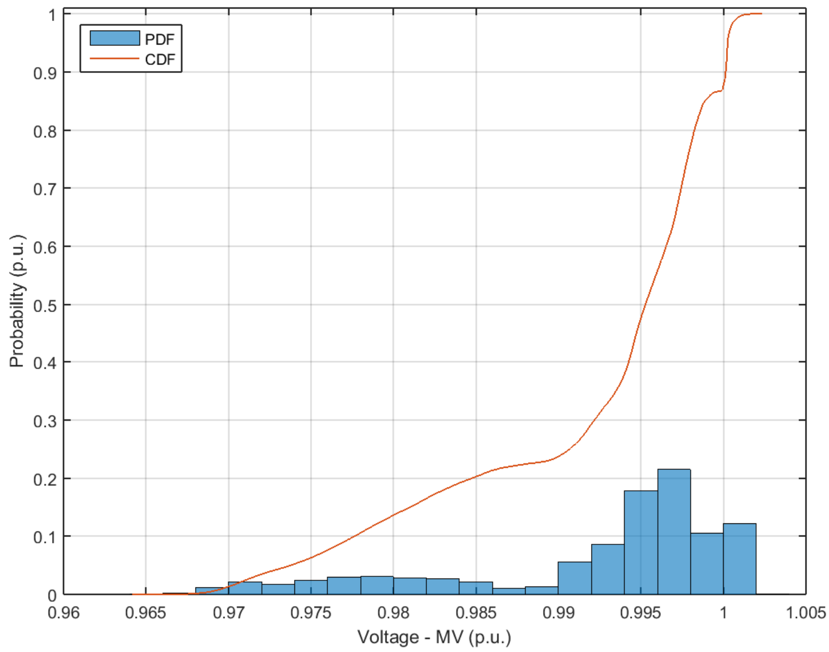

Figure 112. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – EV SC and PV scenario – Power Factor equal to 0.95.

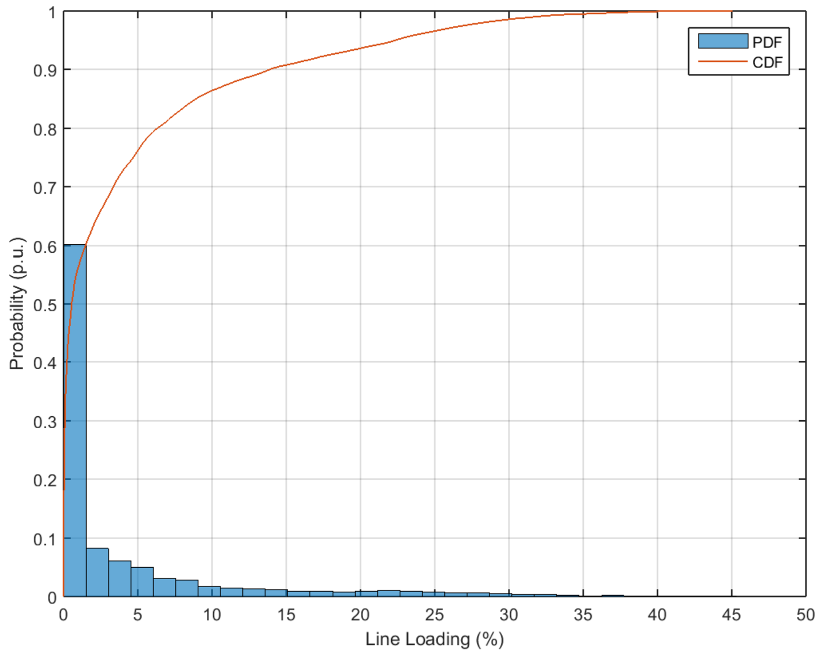

Figure 113. Probability distribution and cumulative probability distribution – Line Loading – EV SC and PV scenario – Power Factor equal to 0.95.

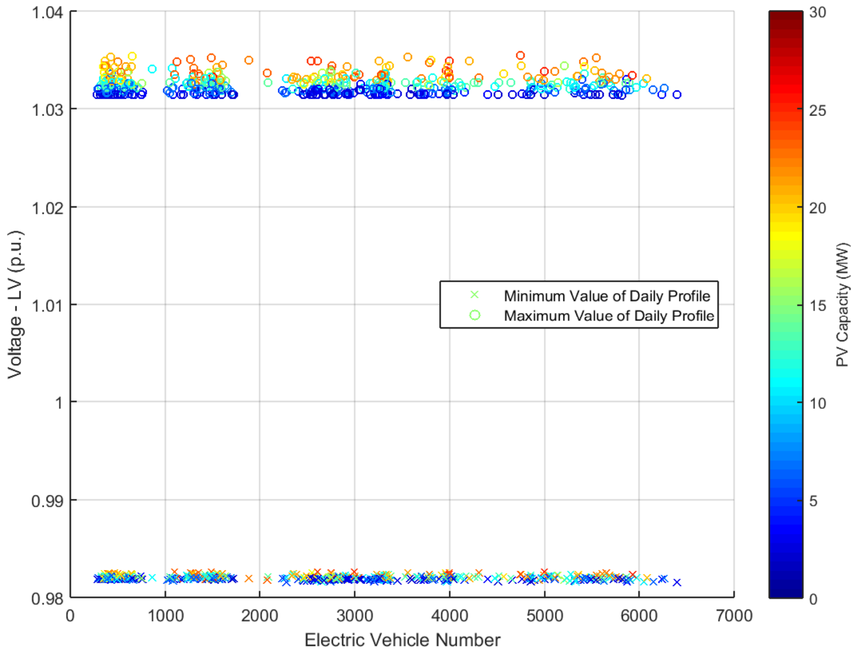

Figure 114. Voltage Variation at Low Voltage Side vs Electric Vehicle Number (including PV Capacity) – SC – Power Factor equal to 0.95.

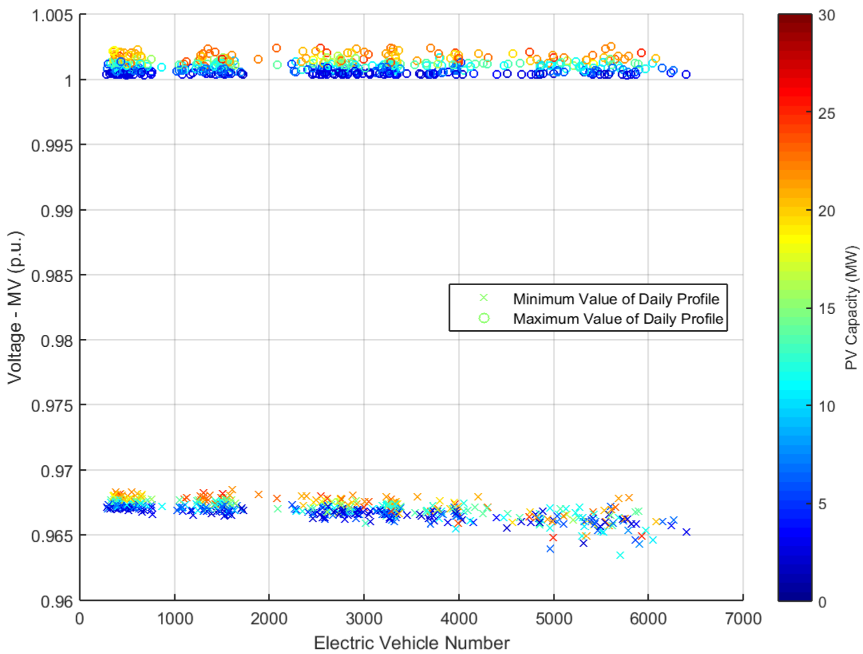

Figure 115. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number (including PV Capacity) – SC – Power Factor equal to 0.95.

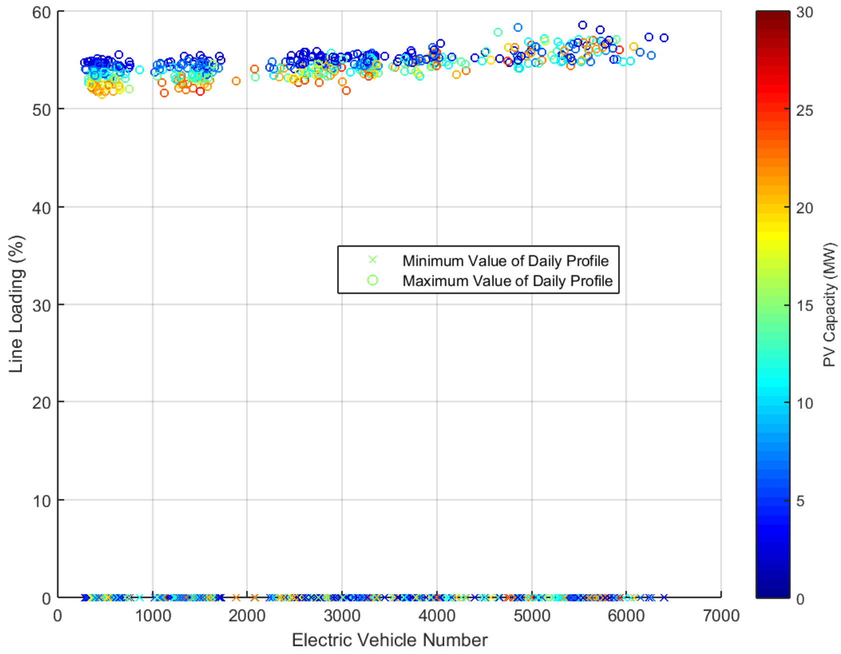

Figure 116. Line Loading vs Electric Vehicle Number (including PV Capacity) – SC – Power Factor equal to 0.95.

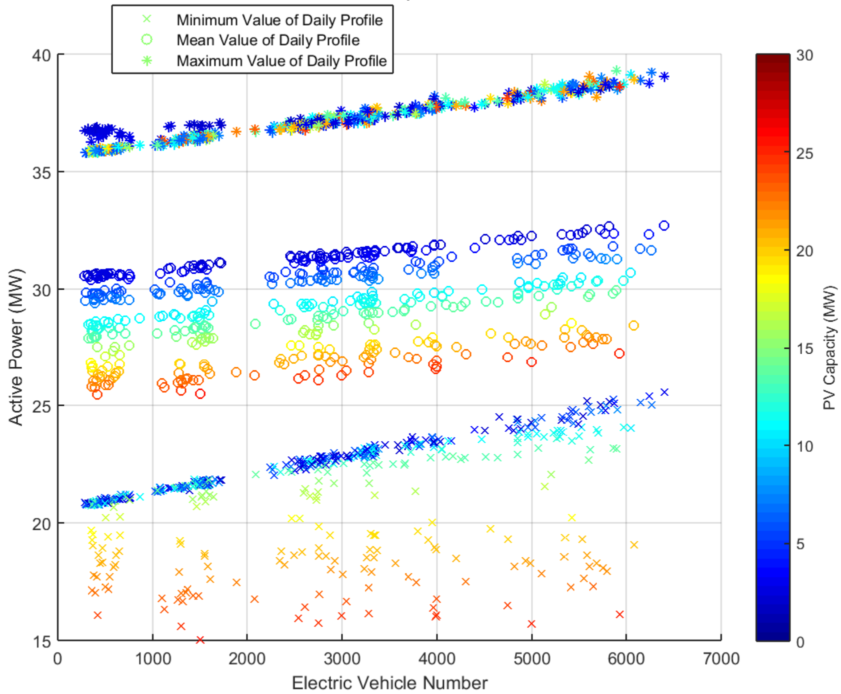

Figure 117. Active Power vs Electric Vehicle Number (including PV Capacity) – SC – Power Factor equal to 0.95.

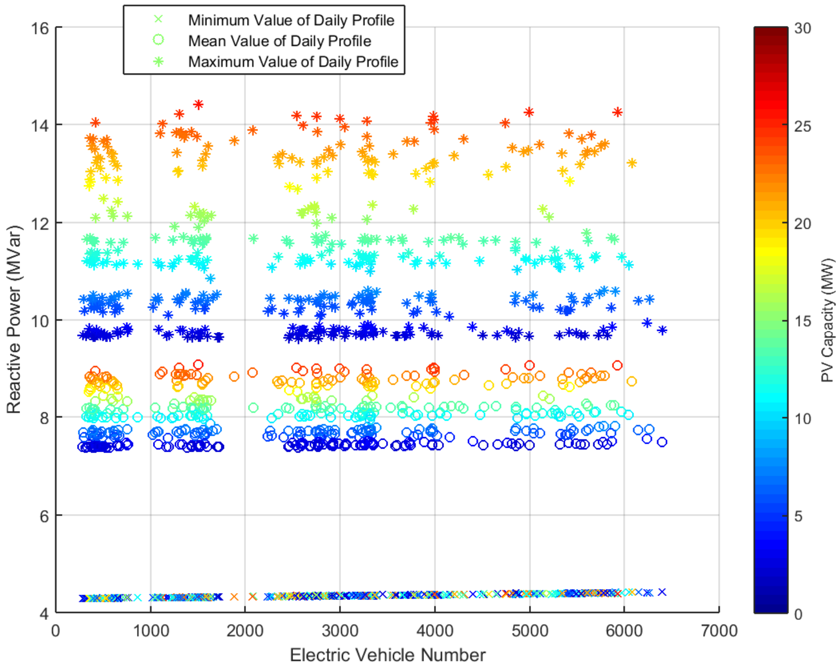

Figure 118. Reactive Power vs Electric Vehicle Number (including PV Capacity) – SC – Power Factor equal to 0.95.

4.2.3.3 Controlled EV charging (Power Factor cosφ(P))

The results for the "Controlled EV charging" scenario in the presence of PV systems operating at cosφ(P) power factor are shown in the Figures below. In all simulated cases (high amount of PV systems and EVs) there are no voltage level and line loading violations observed.

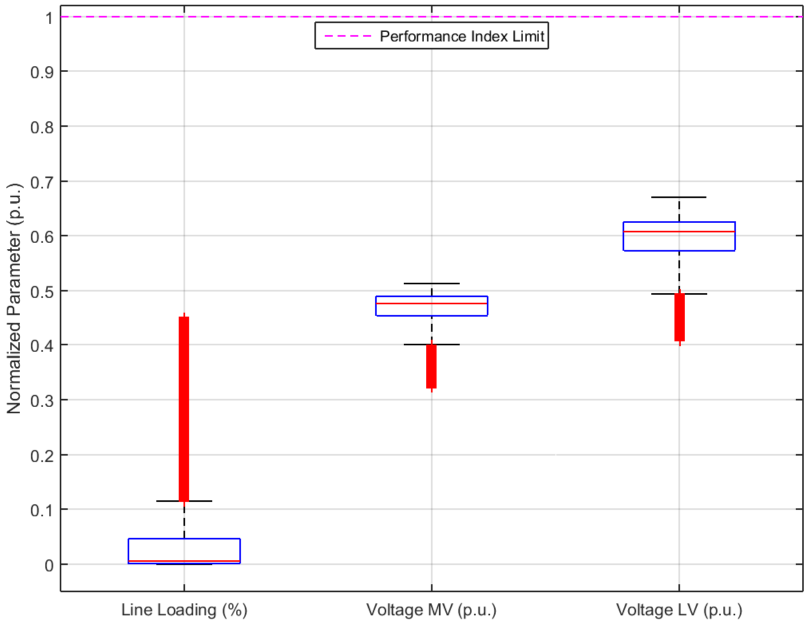

Figure 119. PQ parameters normalized to their limit – EV SC and PV scenario – Power Factor cosφ(P).

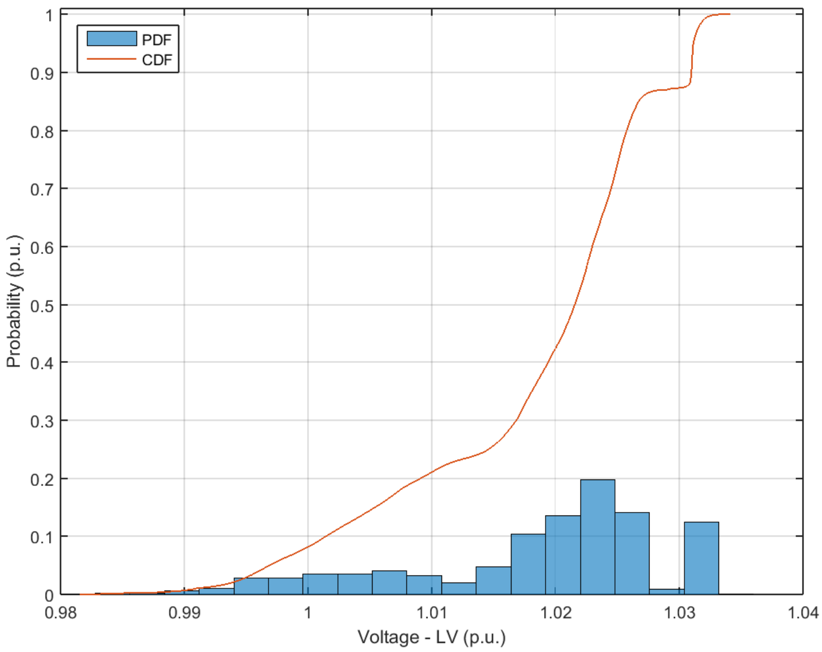

Figure 120. Probability distribution and cumulative probability distribution – Voltage at low voltage side – EV SC and PV scenario – Power Factor cosφ(P).

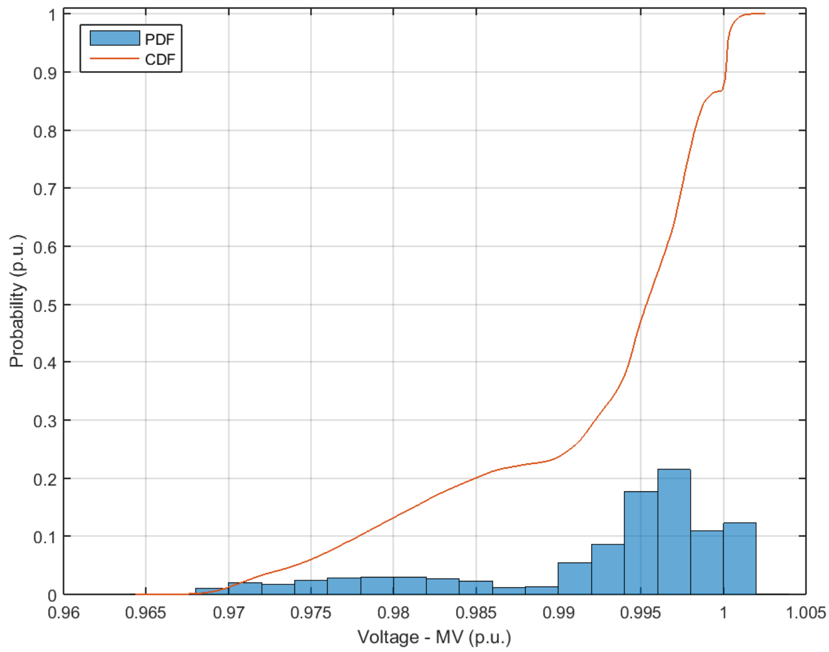

Figure 121. Probability distribution and cumulative probability distribution – Voltage at medium voltage side – EV SC and PV scenario – Power Factor cosφ(P).

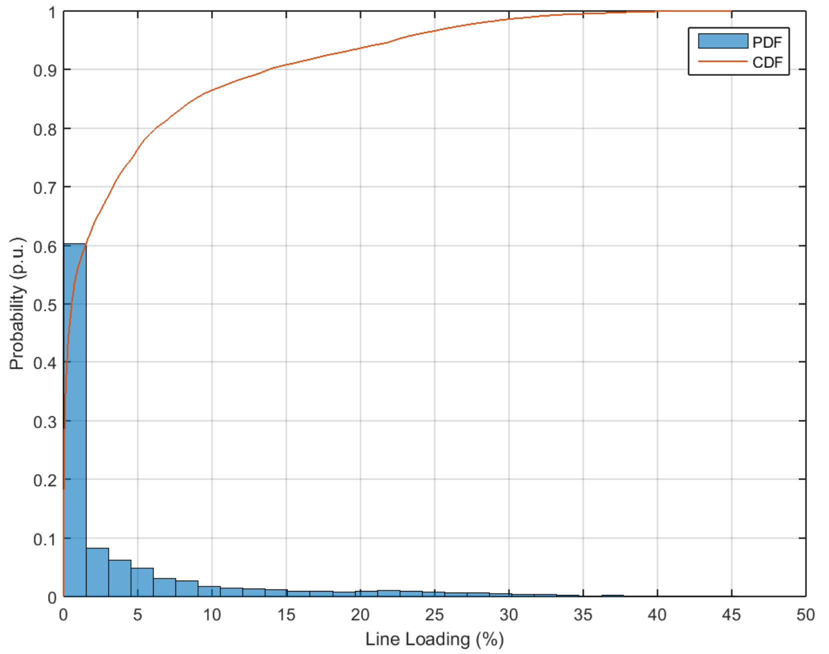

Figure 122. Probability distribution and cumulative probability distribution – Line Loading – EV SC and PV scenario – Power Factor cosφ(P).

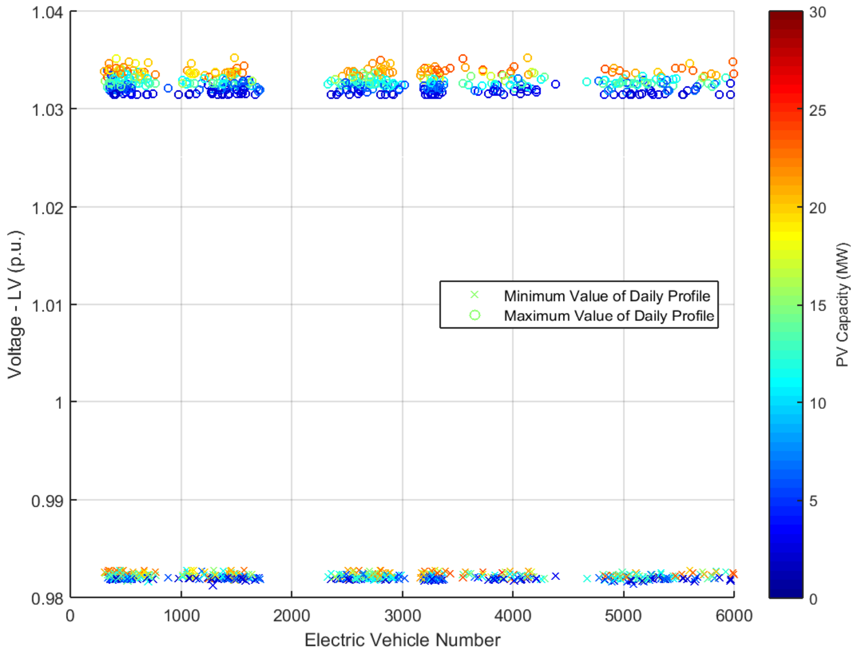

Figure 123. Voltage Variation at Low Voltage Side vs Electric Vehicle Number (including PV Capacity) – SC – Power Factor cosφ(P).

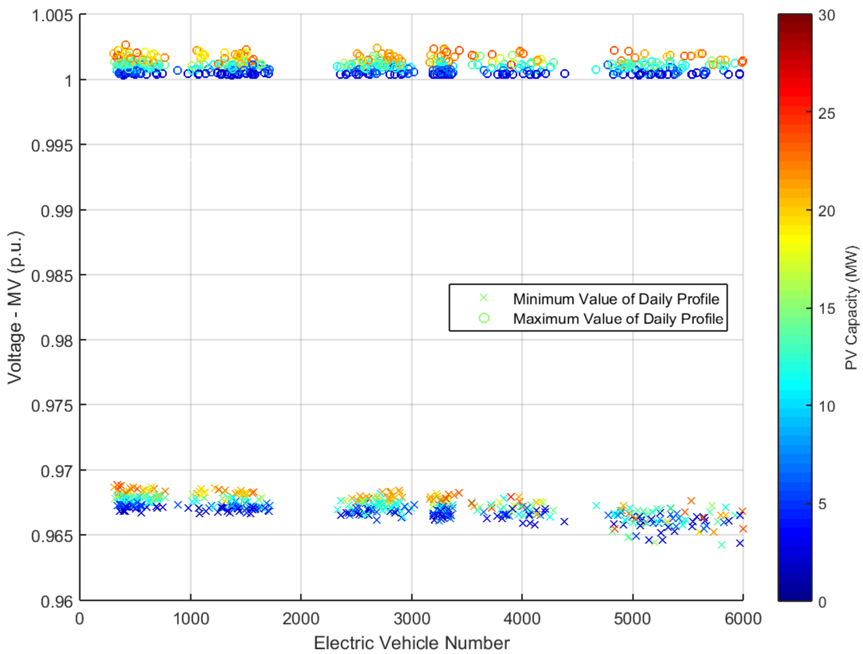

Figure 124. Voltage Variation at Medium Voltage Side vs Electric Vehicle Number (including PV Capacity) – SC – Power Factor cosφ(P).

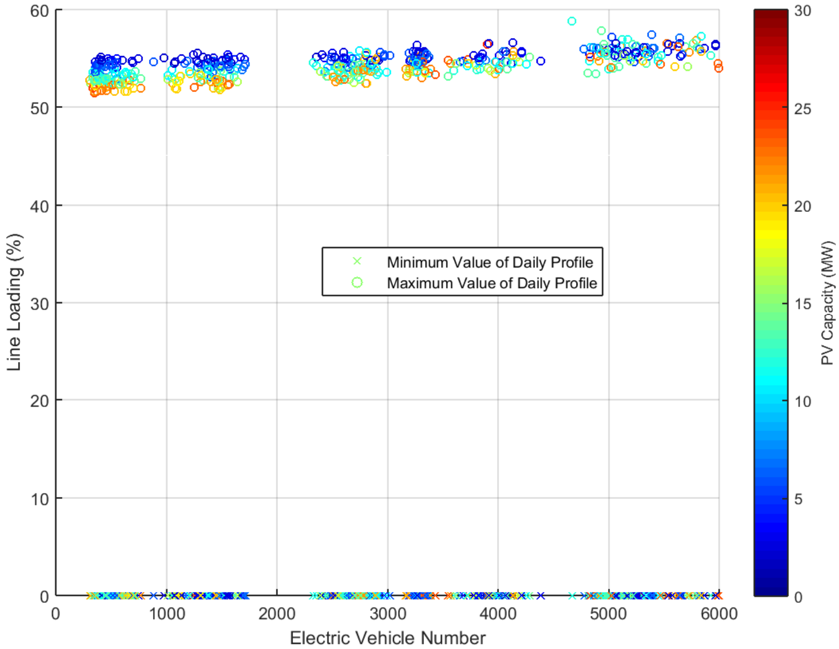

Figure 125. Line Loading vs Electric Vehicle Number (including PV Capacity) – SC – Power Factor cosφ(P).

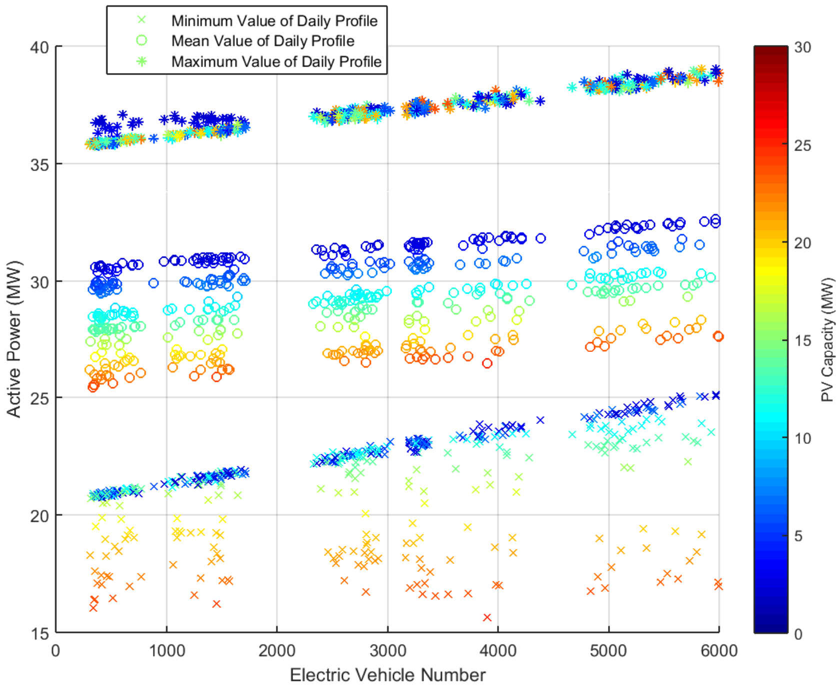

Figure 126. Active Power vs Electric Vehicle Number (including PV Capacity) – SC – Power Factor cosφ(P).

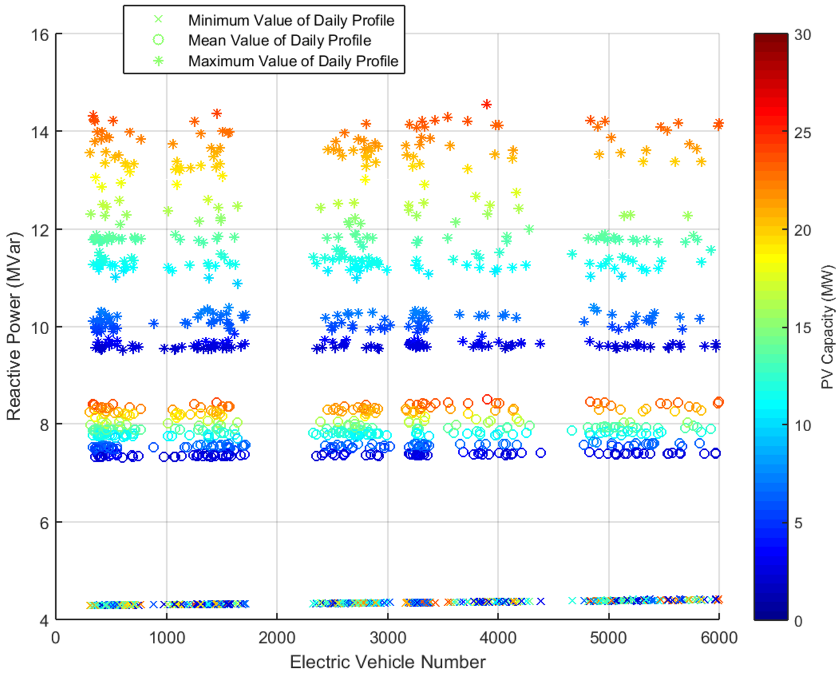

Figure 127. Reactive Power vs Electric Vehicle Number (including PV Capacity) – SC – Power Factor cosφ(P).

4.2.3.4 Controlled EV charging and PV

For the controlled EV charging scenario, by introducing both the EVs and PV integrated into the MV reference grid, the voltage levels are improved in comparison to both the base case simulated when no PV are included, the Uncontrolled charging – Full Charging scenario and the Uncontrolled charging considering mobility curves. The results, summarized in the Table below, show that the lines are not significantly affected when the surplus energy consumed by EVs charging is covered by the local PV system production.

Table 6. Statistical analysis of PQ parameters – Controlled EV charging.

		Scenario: Controlled EV charging			
Normalized Parameter	Statistical Analysis	No PV	Unity Power Factor	Power Factor equal to 0.95	Power Factor cosφ(P)
Voltage – Low Voltage Side	Minimum	0.4077	0.4082	0.4076	0.4059
	25th quantile	0.5589	0.5775	0.5729	0.5736
	Median	0.6030	0.6100	0.6078	0.6083
	Average	0.5839	0.5954	0.5922	0.5930
	Standard Deviation	0.0515	0.0502	0.0512	0.0508
	75th quantile	0.6202	0.6275	0.6253	0.6260
	95th quantile	0.6359	0.6564	0.6555	0.6558
	99th quantile	0.6551	0.6651	0.6583	0.6599
	Maximum	0.6556	0.6844	0.6660	0.6707
Number of elements of which the limit is violated		0 out of 206	0 out of 206	0 out of 206	0 out of 206
Voltage – Medium Voltage Side	Minimum	0.3293	0.3321	0.3310	0.3307
	25th quantile	0.4475	0.4549	0.4537	0.4540
	Median	0.4731	0.4778	0.4768	0.4771
	Average	0.4558	0.4635	0.4619	0.4624
	Standard Deviation	0.0432	0.0396	0.0409	0.0405
	75th quantile	0.4856	0.4900	0.4893	0.4895
	95th quantile	0.4964	0.5014	0.5013	0.5013
	99th quantile	0.5010	0.5051	0.5036	0.5039
	Maximum	0.5010	0.5163	0.5121	0.5131
Number of elements of which the limit is violated		0 out of 206	0 out of 206	0 out of 206	0 out of 206
Line Loading	Minimum	0.0000	0.0000	0.0000	0.0000
	25th quantile	0.0004	0.0005	0.0005	0.0005
	Median	0.0056	0.0055	0.0054	0.0054
	Average	0.0401	0.0394	0.0402	0.0400
	Standard Deviation	0.0713	0.0703	0.0713	0.0710
	75th quantile	0.0462	0.0429	0.0460	0.0454
	95th quantile	0.2175	0.2194	0.2207	0.2202
	99th quantile	0.3254	0.3098	0.3146	0.3132
	Maximum	0.4621	0.4463	0.4525	0.4501
Number of elements of which the limit is violated		0 out of 451	0 out of 451	0 out of 451	0 out of 451

5. Conclusions

In this report information on the methodology and approach followed to analyse the impact of EVs penetration on the distribution system of Cyprus is explicitly described. More specifically, three charging scenarios were examined. The first scenario investigates uncontrolled charging in which the EVs are charged based on a charge start time probability profile, emulating the case when most charging occurs at households and workplaces. In this scenario the mobility curves are not considered and a constant semi-fast charge is used for the simulations. Secondly, an uncontrolled charging scenario considering mobility curves is examined, in which the shape of the EV charging load curve is consistent with people's driving patterns. Lastly, a controlled EV charging (smart charging) scenario is investigated, in which the charging of EVs is controlled by the grid operator, in order to optimise generation and grid capacity. All three scenarios were simulated initially without PV systems connected to the grid (baseline scenario) and then with a large integration of PV within the investigated grid.

The results obtained by simulating the most load demanding case (Uncontrolled charging - Full charging scenario) showed no rating violations of grid assets and / or voltage operational limits for the investigated HV substation. The operation of the investigated feeders with a high level of EVs is found to be within the nominal range and within the system limits. More specifically, the voltage levels at low and medium voltage (MV) buses, are slightly reduced and the lines are slightly loaded in comparison with the base scenario with no EVs. Finally, the results obtained when simulating the "Controlled EV charging" scenario, demonstrated that there is only minor change on the operation of the investigated feeders/substation in comparison to the base scenario with no EVs. This further signifies the importance of controlled charging (smart charging).

By introducing both the EVs and PV integrated into the MV reference grid, the voltage levels are improved in comparison to the base case simulated when no PV are included. The results showed that the lines are not significantly affected when the surplus energy consumed by EVs charging is covered by the local PV system production.

Amongst the simulated voltage regulation methods investigated for the inverter settings of PV (operating at power factor 1, 0.95 and cosφ(P)), the operation at power factor equal to 0.95 showed better performance in terms of voltage levels compared to the other voltage regulatory methods. This voltage regulatory scheme can therefore contribute in the improvement of the voltage levels at both low and medium voltage side.

Finally, the results showed that the introduction of PV offered positive results capable of counterbalancing the effect of large scale EV integration.

6. References

[1] JRC, *Individual mobility: From conventional to electric cars*. 2015.

[2] Eurelectric, "Smart charging : steering the charge, driving the change.," no. March, p. 57, 2015.

[3] C. H. Stephan and J. Sullivan, "Environmental and energy implications of plug-in hybrid-electric vehicles," *Environ. Sci. Technol.*, vol. 42, no. 4, pp. 1185–1190, 2008.

[4] A. Ipakchi and F. Albuyeh, "Grid of the future," *IEEE Power Energy Mag.*, vol. 7, no. 2, pp. 52–62, 2009.

[5] H. Lund and W. Kempton, "Integration of renewable energy into the transport and electricity sectors through V2G," *Energy Policy*, vol. 36, no. 9, pp. 3578–3587, 2008.

[6] S. Lukic, S. Bhattacharya, and a. Huang, "Multi-function bi-directional battery charger for plug-in hybrid electric vehicle application," *2009 IEEE Energy Convers. Congr. Expo.*, pp. 3930–3936, 2009.

[7] EK8-3, "Electric vehicle conductive charging system," vol. 2007, 2009.

[8] "'IEC61851 Part 1: Charging of electric vehicles up to 250 A a.c. and 400 A d.c.', Table 1 "Modes and permissible connections specified in 61851-1, First Edition 2003-04, IEC."

[9] P. Van den Bossche, "'Defining and Developing Standards,'" *Erasums Univ. Coll. Brussels*.

[10] B. University, "http://batteryuniversity.com/learn/article/electric_vehicle_ev." .

[11] A. R. Ofoli, "Impact of Plug in Electric Vehicle Battery Charging on a Distribution System," pp. 409–414, 2013.

[12] DIAVLOS, "Creation and evaluation of a unified design methodology and development of Intelligent Transport Systems (ITS) for medium sized ISLAND cities."

[13] M. Aunedi, "Grid Impact studies of electric vehicles Future Distribution Network Planning Tools : Functional Specifications," pp. 1–85, 2014.

[14] M. J. Bradley, "Electric Vehicle Grid Integration in the U . S ., Europe , and China," no. July, 2013.

[15] EN50438:2013, "Requirements for micro-generating plants to be connected in parallel with public low-voltage distribution networks," 2013.

[16] EN50160, "Voltage Characteristics of Electricity Supplied by Public Distribution Systems," 2010.

7. Appendix

Appendix 1: EV charging profiles aggregated per transmission level substation for the future year 2030 (Uncontrolled charging considering mobility curves and Controlled charging)