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# Report Task 3.2.2

*Evaluation of existing grid hosting capacity for Photovoltaics (PV)*

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# Table of Contents

# List of Figures

# List of Tables

# Executive Summary

Overcoming local limitations in distribution grid sections with high photovoltaic (PV) penetration may be a challenging issue if appropriate planning strategies and regulations are not adopted. The installation of PV systems should be done with care and according to local grid capability in order to avoid costly reinforcement measures which at some situations may not be realizable in practice due to land or other restrictions. Considering the PV hosting capacity limits can help significantly in maintaining the secure and reliable operation of the electricity grid and avoid damages caused by violating thermal limits or by exceeding the recommended voltage range during times of high PV power production. The application of alternative measures at distribution grid level such as the local voltage support via reactive power regulation (undertaken by photovoltaic inverters) is an emerging topic which is already utilized in practise by Distribution System Operators (DSO) for increasing the installed PV capacity and for this reason, the aforementioned capability is considered for defining the maximum hosting PV capacity. However, measures of voltage regulation achieved via dedicated equipment like for example distribution transformers with on-load tap changer functionality are not going to be considered at this stage as this can increase considerably the cost of accommodating renewable energy sources into the electricity grid. Last but not least, the aim of the specific study is to assess the capacity of existing grids without undertaking expansion or reinforcement tasks.

The hosting capacity for distributed energy resources and in particular PV defines the acceptable amount of PV systems able to be installed at a specific electricity grid based on local performance constrains which are related to voltage profile, power quality and thermal rating of existing network. The system wide hosting capabilities related to stability and frequency control are not within the scope of this study.

The purpose of the report is to provide information on the methodology and approach followed to define the maximum PV capacity of six typical/common distribution grids of Cyprus. More specifically, the PV hosting capacity was defined according to two major technical categories related to voltage quality and the thermal limits of distribution lines/transformers calculated for steady-state conditions. From the results, it is evident that the PV hosting capacity can considerably increase if proper regulations are formulated and able to guide the DSO in installing the PV systems strategically according to specific spatial relationship of PV generation.

# 1. Introduction

For this work package, a reference subset of Cyprus MV network was constructed based on the subset obtained by the JRC and enhanced with 3 new transmission substations in order to act and form a representative subset for the investigations of high penetration levels of PV. The reference subset used to simulate the integration of high levels of PV using DIgSILENT PowerFactory include substations of urban, urban-touristic and rural categories as follows:

- S/S Alambra (rural)
- S/S Renos Prentzas (urban)
- S/S Ypsonas (rural)
- S/S Hadjipaschalis (urban-touristic)
- S/S Sotira (rural)
- S/S Athienou (rural)

Initially, a deterministic approach is applied to model two scenarios for assessing the maximum PV capacity of the reference grid by using the time series data collected for the reference year 2014.

In the first deterministic scenario, the full year load time series at feeder level is allocated appropriately at each distribution transformer of the reference grid under consideration (more information on the load allocation is provided in the Methodology section). PV capacity is inserted into the reference grid capped to the nominal power of each distribution transformer. More specifically, at each distribution transformer, a PV system is installed having a power times series output which is defined by the multiplication of the normalized per kWp PV time series of the district it is situated in by the distribution transformer nominal power. In this way, possible limit violations because of the combination of load and maximum possible PV production are investigated for each individual distribution substation.

In the second deterministic scenario, analysis using the load time series is performed in order to simulate typical daily profiles related to the maximum and minimum load consumption. A typical clear day PV production profile is used in combination with the load profile having the lowest power consumption at noon hours to assess the PV capacity of each distribution substation busbar. The PV capacity at each individual distribution transformer busbar is increased in steps until a violation in voltage upper limit/upstream line is observed or the transformer rated capacity is reached. The PV capacity under those specific conditions is noted as the maximum possible PV capacity of the specific distribution transformer busbar.

Finally, a probabilistic scenario is performed by using DIgSILENT PowerFactory. The aforementioned approach is carried based on a probabilistic model analysis, by applying the Monte Carlo method, in order to ensure that results for random placement of PV systems will be obtained as well. The Monte Carlo method is carried out by setting the PV capacity at all distributions substations as a random variable. A significant number of simulations is performed (300000 per tested scenario) and all potential problems identified are documented. The Monte Carlo approach further provides useful information for each of the HV/MV substation under investigation while applying voltage regulation as well. Specifically, voltage regulation schemes defined in the standard EN 50438 [1] for PV systems are investigated for different values i.e. fixed power factor and for active power related control mode cosφ(P). During all the investigations, the following quantities are considered:

- Maximum capacity of transformer/lines (thermal limits).
- Voltage quality violations (according to EN 50160 standard [2]).
- Reverse flows.
- Short circuit current levels.
- PV Inverter capability of voltage support via reactive power regulation.

# 2. Methodology

In this section, the methodology followed to calculate the PV hosting capacity of the distribution grids under investigation is described in detail. The hosting PV capacity is defined as the maximum amount of PV that can be accommodated without impacting system operation (reliability, power quality, thermal limits etc.) under existing control and infrastructure configurations [3-5].

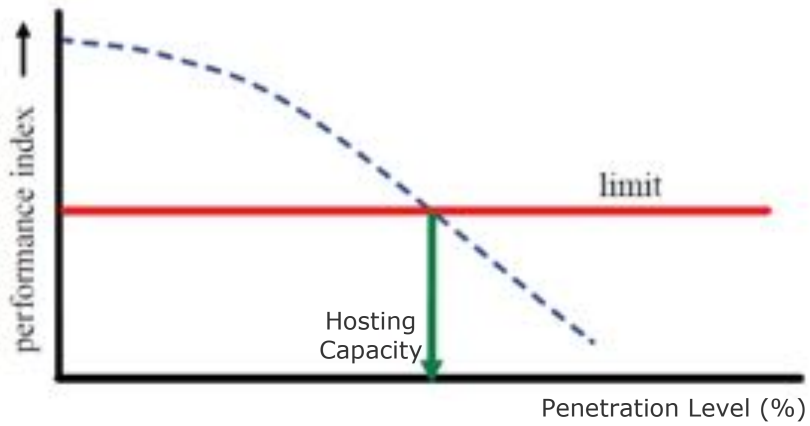


**Figure 1.** Definition of hosting capacity with the help of performance index [3].

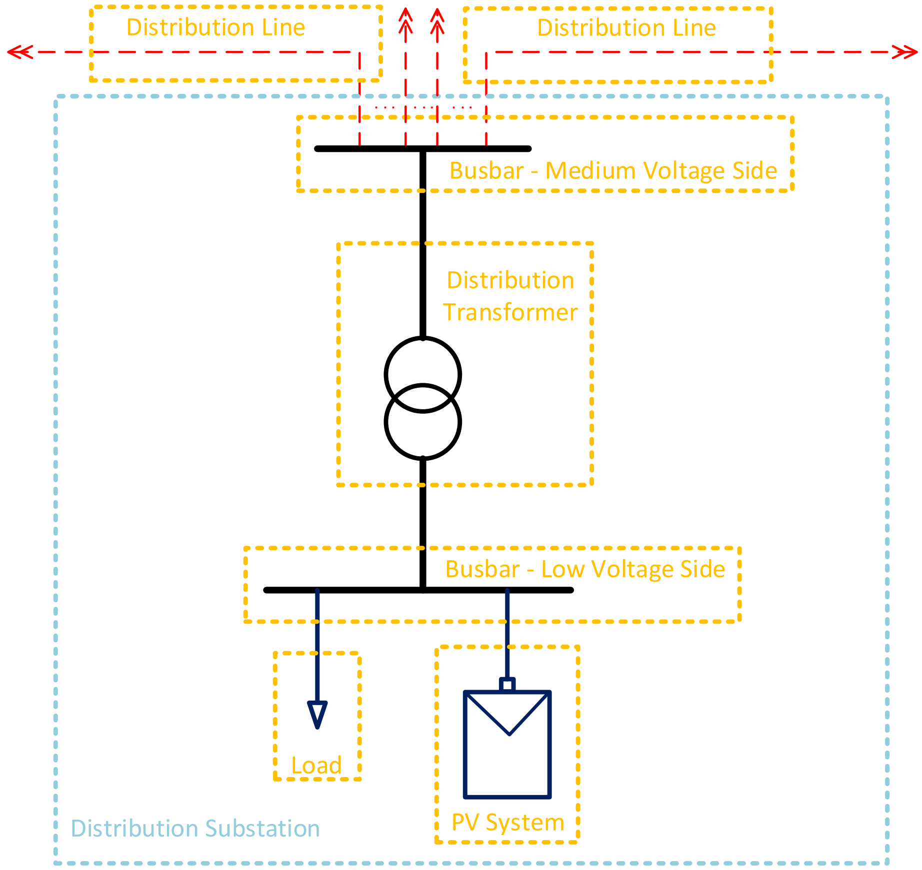


**Figure 2.** Composition of Distribution Substation Model - Notations.

A performance index (PI) is formulated which is composed by three main quantities. The first quantity is the voltage at low voltage level, the second quantity is the voltage at medium voltage level and the third one is the thermal limit of distribution lines. In addition, an important limit taken is that the thermal capacity of distribution transformers is never violated while performing simulations. To summarize, in the event that any of the quantities formulating the PI is violated, then the point of violation is used to determine the hosting PV capacity of the distribution grid under consideration. In this respect, a significantly large number of scenarios is undertaken in order to assess the range and conditions under which the violation of the adopted PI starts to occur. The PI is defined in a graphical way in Fig.1. The distribution substation model (which is the fundamental element of transmission substation) and its element composition with labeling is shown in Fig. 2.

Initially, two deterministic scenarios were simulated. In the first scenario, at each distribution substation, a PV plant having a rating equal to the thermal limit of the distribution transformer is connected at the low voltage side of the distribution transformer as depicted in Fig. 2. The time series power data (active and reactive power measurements) for each feeder obtained from ABB SCADA (provided by the DSO) is allocated to each transformer in such a way as to consider the power losses as well. Specifically, in radial distribution systems the problem arising quite often is that very little information is recorded for the actual loading of distribution lines and load consumption of each distribution substation. The data monitored includes the total active/reactive power flowing into a radial feeder (which is valid for Cyprus). To be able to estimate the voltage variation along a feeder, a load scaling technique is used which is readily available as a tool in PowerFactory DIgSILENT. A good approach is to scale the distribution loads according to the nominal power ratings of the distribution transformers. In Fig. 3, the load scaling technique is described graphically for a single measurement value. In the aforementioned figure, the measured value at the beginning of the feeder is measured to be 50 MW. Throughout the feeder three loads are connected, of which only one of them is precisely known (20 MW). The other two loads are estimated to be around 10 MW each based on transformers thermal limits. The PowerFactory DIgSILENT is then used to perform a load flow analysis via the Feeder Load Scaling tool so that the selected groups of loads are scaled accordingly in order to meet the measured value [4]. The procedure is repeated for each measurement of the feeder time series data in order to acquire a time series profile for each distribution substation. The profile of each distribution substation (both for active and reactive power) is stored in a file and used in the subsequent simulation tasks. The feeder profile is finally unlinked from the simulation case and the (distribution substation) load values are now taken from the created file. In this way, the load profiles are defined by considering power losses and it becomes possible to simulate the different PV concentrations by formulating a base/reference scenario.

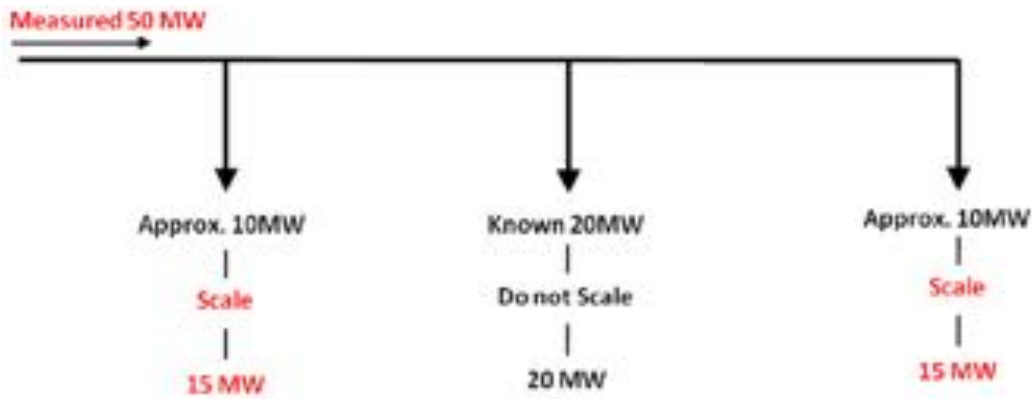


**Figure 3.** Feeder load scaling [5].

The time series for PV of the transmission substation under consideration is normalized per unit capacity (per kWp) and further used in the simulations. A PV system is installed at each substation having a capacity equal to the thermal limit of the transformer (at which the PV system is connected). To achieve this, the normalized PV profile is assigned to the specific PV system element and multiplied with the rated power of the transformer (by setting the scaling factor of the PV system equal to the rated power of the transformer). The aim of this deterministic scenario is to identify the elements of the grid being operated beyond their designed limits when the distribution grid is loaded fully with PV systems. Results for short circuit currents at each substation and the different voltage regulation methods are investigated for this scenario as well.

The flow chart of the aforementioned procedure is shown in Fig. 4.

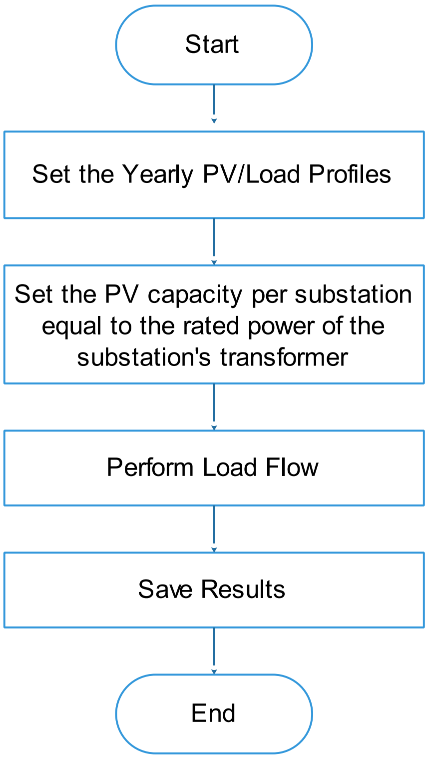


**Figure 4.** Flowchart of maximum installed PV capacity scenario.

In the second deterministic scenario, the capacity of each substation in terms of voltage level and upstream line thermal limit is assessed, by installing PV capacity only at the low voltage side of the (transformer's) substation under consideration and nowhere else. For capacity tests, it is required to undertake a large number of simulations and for this reason it is not practical or feasible to use the whole time series. Also, in many PV system impact studies the effect of PV feed-in power is analysed based on worst-case assumptions for the local load and generation, while neglecting the simultaneity of generation and consumption. Conservative worst-case assumptions, such as no load and 100% PV feed-in, over-estimate the impact of PV production on the operation of the grid and lead to a less efficient utilization of the existing infrastructure. Therefore, the worst daily profile having the lowest but not zero load value at noon hours (10:00 – 14:00) is identified via data analysis (by using the time series of the total substation consumption) as the maximum power production from PV systems is observed during this period of the day [4].

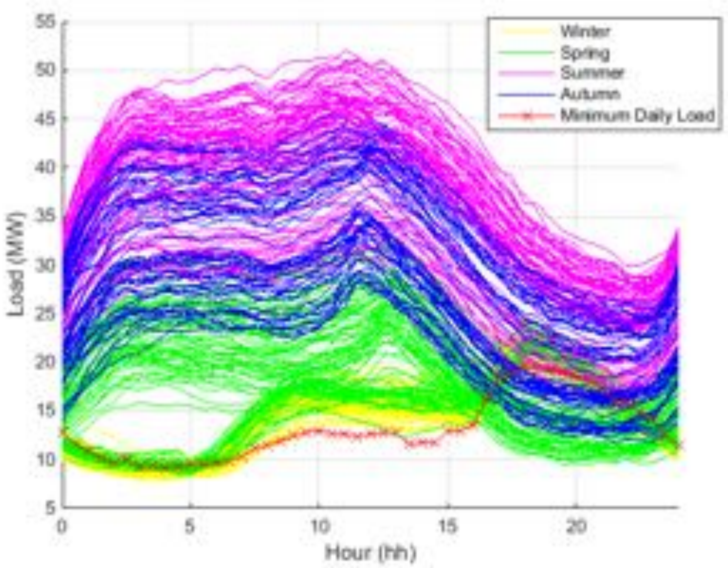


**Figure 5.** Minimum daily load.

Specifically, high feed-in PV produced power during times of low load consumption can cause reverse power flows over the feeder impedances which leads to increased voltage magnitudes within the distribution grid and hence this phenomenon is of great interest for the hosting capacity investigations. The minimum daily load is shown in Fig. 5 and it is determined with the use of the minimum load performance index *ML* given as:

$$ML = \min(x_{t_1} \quad x_{t_2} \quad \ldots \quad x_{t_n})\Big|_{t_n=14:00}^{t_1=10:00} + \mathrm{mean}(x_{t_1} \quad x_{t_2} \quad \ldots \quad x_{t_n})\Big|_{t_n=14:00}^{t_1=10:00} \quad (1)$$

where $ML$ is the Selection Criterion (SCr) for the minimum load determination calculated per day and $x$ the load value per half hour. The daily load profile with the lowest load performance index is chosen.

In addition, the best PV production profile of the season at which the lowest load profile is lying, is selected for the required simulations. Prior performing capacity tests, it is verified that the tap of the transformer is set at the lowest position possible. The latter is achieved by identifying three worst-case daily load profiles/curves per substation which present the maximum load values in the morning (00:00-10:00), noon (10:00-14:00) and afternoon/night (14:00-24:00) over the whole year and are further used for setting the tap position via testing.

The maximum load for each daily period (morning, noon, and afternoon/night) is shown in Fig. 6 and it is determined with the use of performance index described by equation (2):

$$MX = \max(x_{t_1} \quad x_{t_2} \quad \ldots \quad x_{t_n})\Big|_{t_n}^{t_1} + \mathrm{mean}(x_{t_1} \quad x_{t_2} \quad \ldots \quad x_{t_n})\Big|_{t_n}^{t_1} \quad (2)$$

where *MX* is the SCr for maximum load determination calculated per daily period of interest and $x$ the load value per half hour. The daily load profile with the higher load performance index per period is chosen.

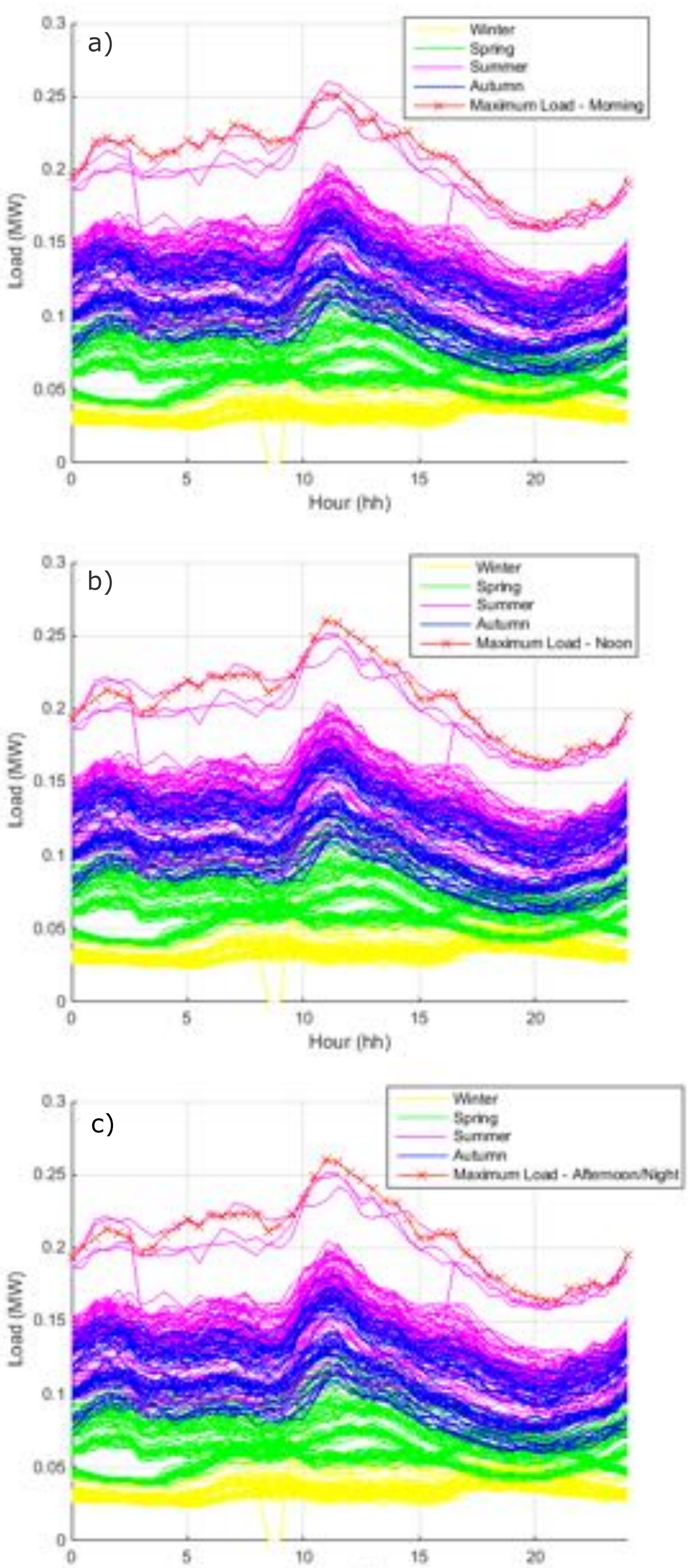


**Figure 6.** Maximum daily load profiles, a) Morning b) Noon and c) Afternoon/Night.

The flow chart for the second deterministic scenario is shown in Fig. 7. The algorithm reduces the tap by one if no voltage violations are observed when testing the three worst-case load profiles. The procedure is repeated and if a violation of voltage limit is observed then the tap position is advanced by one step.

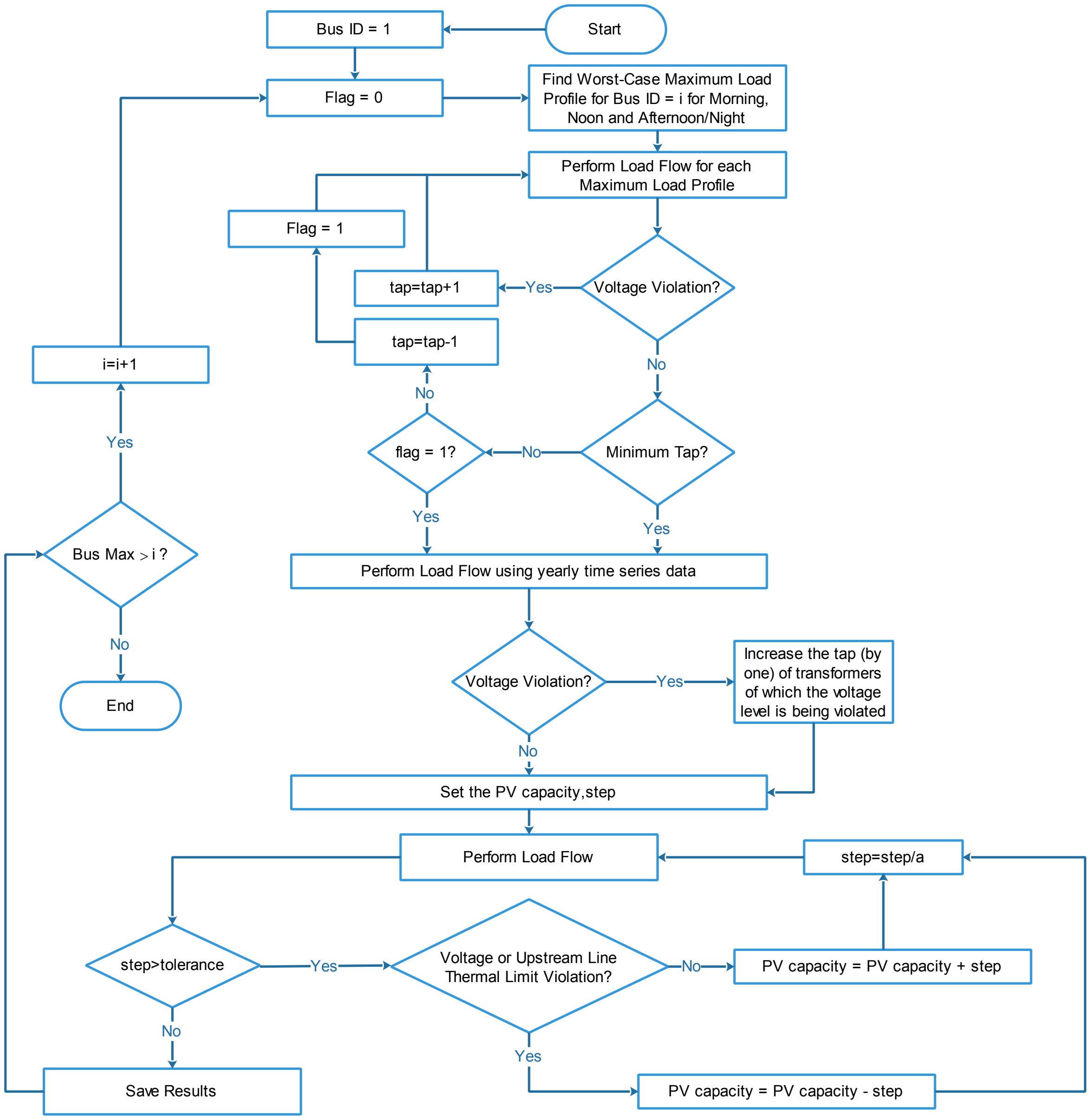


**Figure 7.** Flowchart of maximum PV capacity per substation methodology.

After all the taps are adjusted via the developed algorithm, a simulation of the whole time series is performed to verify that no further violations of voltage are noticed. At the case when a violation of voltage (at low voltage side) is seen at a specific substation, the tap of the substation's transformer is increased by one.

In order to assess the hosting PV capacity in a general way, Monte Carlo simulations were also performed by testing the distribution grid at the lowest load conditions while varying the PV capacity. The flow chart of the applied Monte Carlo method is depicted in Fig. 8.

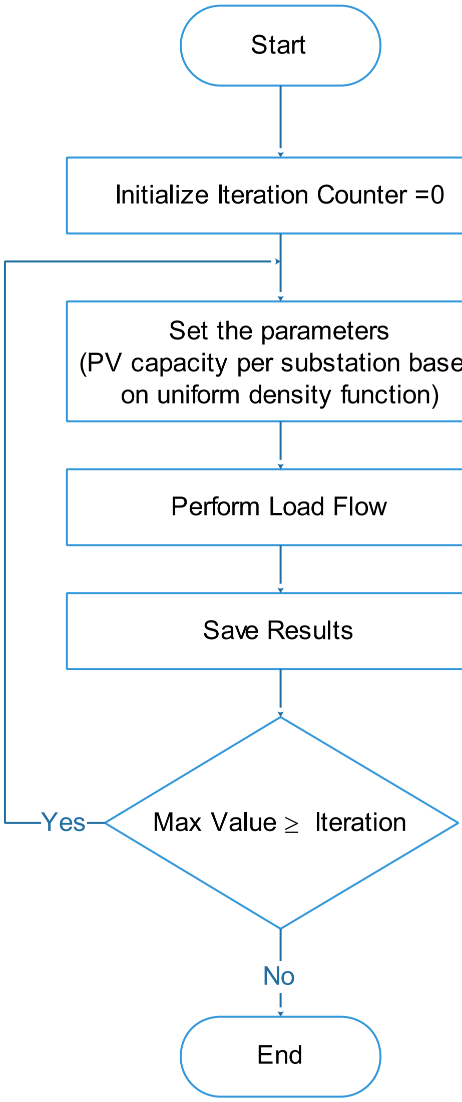


**Figure 8.** Flowchart of Monte Carlo simulation [6].

The parameters of the PI are normalized according to their range by using the following formulas:

$$V_{rorm}^{LV} = \frac{V_{LV}^{p.u.} - V_{\text{EN50160 Limit}}^{\text{Low Limit}}}{V_{\text{EN50160 Limit}}^{\text{Upper Limit}} - V_{\text{EN50160 Limit}}^{\text{Lower Limit}}} = \frac{\mathrm{V}^{LV} - 0.9}{0.2} \tag{3}$$

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.)

$$V_{rorm}^{MV} = \frac{V_{MV}^{p.u.} - V_{\text{EN50160 Limit}}^{\text{Low Limit}}}{V_{\text{EN50160 Limit}}^{\text{Upper Limit}} - V_{\text{EN50160 Limit}}^{\text{Lower Limit}}} = \frac{\mathrm{V}^{MV} - 0.9}{0.2} \tag{4}$$

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.)

$$L_{norm} = \frac{L_{\%}^{sim}}{L_{\%}^{\text{Upper Limit}} - L_{\%}^{\text{Lower Limit}}} = \frac{L_{\%}^{sim}}{100} \tag{5}$$

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.

By adopting the formulas (3), (4) and (5), it becomes possible to set the same upper limit for all the parameters of the PI. Herein, a single/unified limit is defined (equal to unity) that can be used in assessing the maximum PV hosting capacity (and to enable possible comparison between the parameters included in the PI group).

In general, the investigation studies performed for the hosting PV capacity can be distinguished in two categories which are adopted in this report; the deterministic (simulation of specific scenarios) [7], [8], [9] and the probabilistic approaches (using Monte-Carlo techniques) [10], [11], [12].

Properties, such as the individual installed capacity per substation and the characteristics of the point of common coupling (PCC), can have a significant impact on the hosting capacity of a particular distribution grid. Due to this, probabilistic assessment approaches are of utmost importance for the analysis of PV hosting capacity for distribution grids and hence can be considered as state-of-the-art [4]. The methods applied for assessing the PV hosting capacity are shown in Fig. 9.

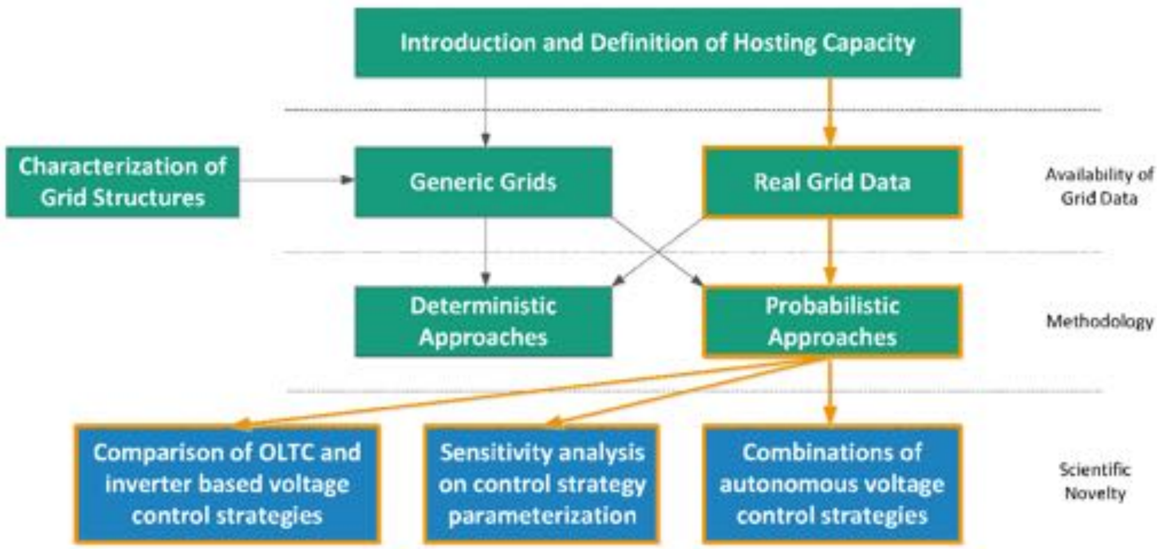


**Figure 9.** Overview of research methods used for assessing the hosting PV capacity [4].

It must be noted that the PI can include other parameters as well like the short circuit current, the unbalance, the total harmonic distortion (THD), individual harmonics etc [13]. Despite this, the PI is chosen to include only three parameters due to lack of required information. In particular, the short circuit current is not considered as part of the PI as no information is available for the settings of protection relays or other protection related equipment. Furthermore, the total harmonic distortion and the unbalance indices are not included in the PI due unavailability of necessary measurements which will help in defining a base scenario. In addition, very little information is available for the harmonic footprint and/or type of inverters found currently in the market. Also, the variation of harmonic angles is not exactly known (even at the case when the amplitude of individual harmonics is found in datasheets of inverter manufacturers) making the problem more complex and undefined. At this point, it must be said that if the angle of individual current harmonics is not set properly or the range variation is not modelled properly then a misleading outcome will be obtained. Last but not least, in [14] it is observed that EN 61727 compatible inverters do not cause noticeable voltage distortion in distribution grids therefore there is no justifiable evidence that harmonic distortion will be a limiting factor against the deployment of PV. To the contrary, as the inverter technology progress, the harmonic currents produced by the PV inverters are being reduced considerably causing less voltage distortion. This trend is justified via measurements undertaken by FOSS power quality team in various PV park installations [14], [15].

# 3. Summary of Results

Following the methodology as described above all the six typical substations of Cyprus were analysed delivering the attached 6 complementary sets of results. More details are given covering the various steps for the conducted analysis.

Through the analysis undertaken, the PV hosting capacity of the reference grid subset is addressed. The electrical characteristics of the analysed substations are summarized in Table 1.

**Table 1.** Substations under investigation and their electrical characteristics.

| Substation Name | Substation type | Substation Capacity MVA (SC) | Firm Capacity MVA (FC) | Feeders | Number of Distribution Substations | Number of Distribution Lines | Distribution Transformer Capacity (MVA) |
|---|---|---|---|---|---|---|---|
| Alambra S/S | Rural | 46 | 31 | 10 | 736 | 1293 | 121.48 |
| Renos Prentzas S/S | Urban | 120 | 80 | 24 | 155 | 252 | 126.1 |
| Ypsonas S/S | Rural | 20 | 10 | 7 | 251 | 443 | 52.85 |
| Hadjipaschalis S/S | Urban/ Touristic | 120 | 80 | 22 | 206 | 451 | 150.12 |
| Sotera S/S | Rural | 63 | 31.5 | 11 | 369 | 688 | 88.13 |
| **Athienou S/S** | Rural | 32 | 16 | 4 | 138 | 255 | 24.51 |

From the investigation, it has been found that the PV hosting capacity of transmission S/S is approaching their firm capacity. Above this limit, violations of PI index start to occur and therefore possible deployment of PV above this capacity needs to be done with caution and by undertaking proper planning/expansion studies.

Before applying voltage regulation techniques both voltage and line loading violations were occurring above a certain PV capacity value. After applying voltage regulation, the voltage violations were eliminated but the thermal limit of lines was the governing factor. This is an important issue which limits the PV hosting capacity even when applying voltage regulation. Higher penetration can only be achieved under specific operational practices and such specificities should be evaluated case by case.

The short circuit currents are not affected by the installed PV capacity neither by voltage regulation but they are mostly depended on grid topology and transformer rated power.

As no information is available for low voltage circuits connected at each distribution transformer it was not feasible to undertake any relative studies. Despite this, it must be highlighted though that the main busbar (transformer low voltage side) of low voltage circuits is included in the investigations undertaken. Furthermore, in low voltage circuits, modifications are allowed/feasible to be undertaken without significant and costly reinforcements therefore they are not expected to be a limiting factor for PV deployment. These modifications are aligned with the load requirements of prosumers and hence are not additional to the PV hosting requirements.

Harmonic distortion is not expected to be a limiting factor in the deployment of PV as it is well known that new generation inverters produce low harmonic currents and their contribution cannot cause high voltage distortion at the low voltage side of the distribution transformer. When more information is to be made available via a GIS database (about the type/technology of inverters etc.) or via systematic measurements (about unbalancing and harmonics for example) it will be possible to undertake a more detailed study about all the aspects of power quality that can affect the PV hosting capacity.

From these results the following hosting capacities have been evaluated through the Monte Carlo detailed analysis:

### A. Hadjipaschalis S/S

The PV hosting capacity results for Hadjipasxalis substation with three 40 MVA transmission transformers, 22 feeders, 206 distribution substations/transformers/ busbars and 451 distribution lines either underground or overhead) located in Paphos district area (in a touristic/urban area), are presented in Table 2. More specifically, Table 2 depicts the uncontrolled deployment limit (which is the maximum capacity limit of PV without any spatial based regulations/restrictions) and the controlled deployment limit (which is the maximum capacity limit of PV only when spatial based regulations/restrictions are considered) of different voltage regulation schemes for the parameters of the PI.

**Table 2.** Hadjipaschalis S/S - Uncontrolled/Controlled PV Deployment Limits.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| **Unity Power Factor** | 33.4 | 91.1 | above 92.5 | above 92.5 | 32.7 | 85.6 |
| **Power Factor equal to 0.95** | above 90.9 | above 90.9 | above 90.9 | above 90.9 | 34.9 | 84.3 |
| **Power Factor cosφ(P)** | above 90.7 | above 90.7 | above 90.7 | above 90.7 | 32.0 | 85.1 |

### B. Athienou S/S

The PV hosting capacity results for Athienou substation with two 16 MVA transmission transformers (with a total distribution transformer capacity of 24.511 MVA), 4 feeders, 138 distribution substations/transformers/busbars and 255 distribution lines either underground or overhead located in Larnaca district area, are presented in Table 3.

**Table 3.** Athienou S/S - Uncontrolled/Controlled PV Deployment Limits.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| **Unity Power Factor** | 3.22 | 9.17 | 7.77 | 14.20 | 3.81 | 8.85 |
| **Power Factor equal to 0.95** | 6.23 | 13.02 | 12.01 | 15.81 | 3.31 | 8.16 |
| **Power Factor cosφ(P)** | 8.82 | 14.68 | above 15.50 | above 15.50 | 3.10 | 8.09 |

### C. Ypsonas S/S

The PV hosting capacity results for Ypsonas substation with two 10 MVA transmission transformers (with a total distribution transformer capacity of 52.850 MVA), 7 feeders, 251 distribution substations/transformers/busbars and 443 distribution lines either underground or overhead located in Nicosia district area, are presented in Table 4.

**Table 4.** Ipsonas S/S - Uncontrolled/Controlled PV Deployment Limits.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| **Unity Power Factor** | 3.31 | 11.13 | 6.07 | 16.79 | 11.37 | 24.50 |
| **Power Factor equal to 0.95** | 6.30 | 16.40 | 10.48 | 23.27 | 10.14 | 21.36 |
| **Power Factor cosφ(P)** | 8.49 | 19.48 | 16.88 | 31.13 | 9.44 | 19.09 |

### D. Renos Prentzas S/S

The PV hosting capacity results for Renos Prentzas substation with three 40 MVA transmission transformers (with a total distribution transformer capacity of 126.100 MVA), 24 feeders, 155 distribution substations/transformers/busbars and 252 distribution lines either underground or overhead located in Nicosia district area, are presented in Table 5.

**Table 5.** Renos Prentzas S/S - Uncontrolled/Controlled PV Deployment Limits.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| **Unity Power Factor** | above 76.2 | above 76.2 | above 76.2 | above 76.2 | above 76.2 | above 76.2 |
| **Power Factor equal to 0.95** | above 75.9 | above 75.9 | above 75.9 | above 75.9 | above 75.9 | above 75.9 |
| **Power Factor cosφ(P)** | above 76.17 | above 76.17 | above 76.17 | above 76.17 | 58.12 | 71.38 |

### E. Alambra S/S

The PV hosting capacity results for Alambra substation with two 15 MVA and one 16 MVA transmission transformers (with a total distribution transformer capacity of 121.475 MVA), 10 feeders, 736 distribution substations/transformers/busbars and 1293 distribution lines either underground or overhead located in Nicosia district area, are presented in Table 6.

**Table 6.** Alambra S/S - Uncontrolled/Controlled PV Deployment Limits.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| **Unity Power Factor** | 4.84 | 10.36 | 5.68 | 21.00 | 12.72 | 37.79 |
| **Power Factor equal to 0.95** | 4.90 | 13.96 | 6.30 | 27.63 | 9.98 | 35.88 |
| **Power Factor cosφ(P)** | 5.00 | 16.37 | 6.89 | 29.99 | 9.50 | 32.46 |

### F. Sotera S/S

The PV hosting capacity results for Sotera substation with two 31.5 MVA transmission transformers (with a total distribution transformer capacity of 88.126 MVA), 11 feeders, 369 distribution substations/transformers/busbars and 688 distribution lines either underground or overhead located in Larnaca district area, are presented in Table 7.

**Table 7.** Sotera S/S - Uncontrolled/Controlled PV Deployment Limits.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| **Unity Power Factor** | 9.59 | 28.87 | 22.70 | 46.22 | 22.47 | 42.60 |
| **Power Factor equal to 0.95** | 32.07 | 50.86 | above 50.91 | above 50.91 | 19.48 | 37.40 |
| **Power Factor cosφ(P)** | above 50.92 | above 50.92 | above 50.92 | above 50.92 | 16.97 | 34.80 |

The terms shown in the Tables above are taken from reference [13]. The following figure (Fig. 10) explains in a graphical way the different PV hosting capacity zones and depicts their importance. The terms "Uncontrolled"/"Controlled" are defined above.

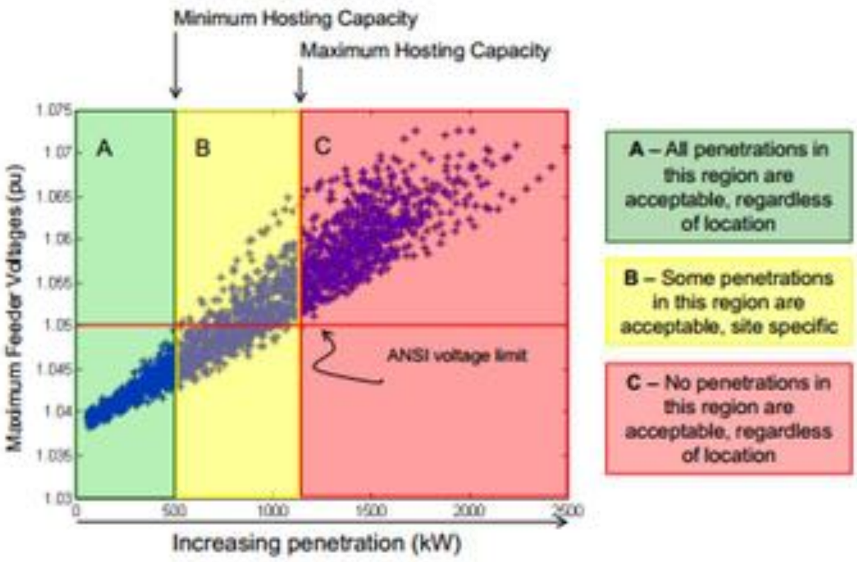


**Figure 10.** Graphical representation of PV hosting capacity zones [13].

Table 8 summarizes the percentage of PV hosting capacity compared to the total capacity of the substation under investigation.

**Table 8.** PV hosting capacity results in comparison to total substation capacity.

| Substation Name | Substation Capacity MVA (SC) | Minimum PV Hosting Capacity MW (miPHC) | Maximum PV Hosting Capacity MW (maPHC) | Minimum Percentage of miPHC/SC (%) | Maximum Percentage of maPHC/SC (%) |
|---|---|---|---|---|---|
| Alambra S/S (rural) | 46 | 10.36 | 16.37 | 22.52 | 35.59 |
| Renos Prentzas S/S (urban) | 120 | 71.38 | 76.2 | 59.48 | 63.50 |
| Ypsonas S/S (rural) | 20 | 11.13 | 19.09 | 55.65 | 95.45 |
| Hadjipaschalis S/S (urban-touristic) | 120 | 84.3 | 85.6 | 70.25 | 71.33 |
| Sotera S/S (rural) | 63 | 28.87 | 37.4 | 45.83 | 59.37 |
| Athienou S/S (rural) | 32 | 8.09 | 8.85 | 25.28 | 27.66 |

In addition, Table 9 shows the percentage of PV hosting capacity compared to the firm capacity. The maximum and minimum PV hosting capacity in both Tables 8 and 9 are set by taking into account the results for three voltage regulation methods.

**Table 9.** PV hosting capacity results in comparison to firm substation capacity.

| Substation Name | Firm Capacity MVA (FC) | Minimum PV Hosting Capacity MW (miPHC) | Maximum PV Hosting Capacity MW (maPHC) | Minimum Percentage of miPHC/FC (%) | Maximum Percentage of maPHC/FC (%) |
|---|---|---|---|---|---|
| Alambra S/S (rural) | 31 | 10.36 | 16.37 | 33.42 | 52.81 |
| Renos Prentzas S/S (urban) | 80 | 71.38 | 76.2 | 89.23 | 95.25 |
| Ypsonas S/S (rural) | 10 | 11.13 | 19.09 | 111.30 | 190.09 |
| Hadjipaschalis S/S (urban-touristic) | 80 | 84.3 | 85.6 | 105.38 | 107.00 |
| Sotera S/S (rural) | 31.5 | 28.87 | 37.4 | 91.65 | 118.73 |
| Athienou S/S (rural) | 16 | 8.09 | 8.85 | 50.56 | 55.31 |

**Table 10.** Postcodes in each administrative district of Cyprus

| Administrative District | Range of postcode number |
|---|---|
| **Nicosia (Urban area)** | 1000-2499 |
| **Nicosia (Rural area)** | 2500-2999 |
| **Limassol (Urban area)** | 3000-3449 |
| **Limassol (Rural area)** | 3500-4999 |
| **Larnaca (Urban area)** | 6000-7449 |
| **Larnaca (Rural area)** | 5000-5999 & 7500-7999 |
| **Paphos (Urban area)** | 8000-8239 |
| **Paphos (Rural area)** | 8240-8999 |
| **Nicosia (Urban area)** | 1000-2499 |
| **Nicosia (Rural area)** | 2500-2999 |

By considering the energy consumption per postcode, the supplied energy percentage to each postcode from each substation both found in Appendix G and the categorization into urban and rural areas according to postcode seen in Table 10, it is possible to categorize the substations into urban and rural based on the flowchart of Figure 11. The logic for extrapolating the PV hosting capacity to all the substations, the minimum and maximum percentage of permissible PV capacity (in relation to the firm capacity) of the substation type was evaluated from the typical substations analysed. For the urban substation category, the minimum limit of all urban substations investigated was 89.23% while the maximum limit was 107.00%. For the rural substation category, the minimum limit of all rural substations investigated was 33.42% while the maximum limit of PV capacity, (excluding the results of Ypsonas S/S since they are not considered a common case. Ypsonas substation supplies an industrial estate with highly oversized network to cover future loads. This has led through the Monte Carlo simulations to much higher PV penetration levels than normally expected, hence considered an outlier) 118.73%. By using the aforementioned limits, it is possible to extrapolate the PV hosting capacity range for the remaining substations. The PV capacity extrapolation results are shown in Table 10.

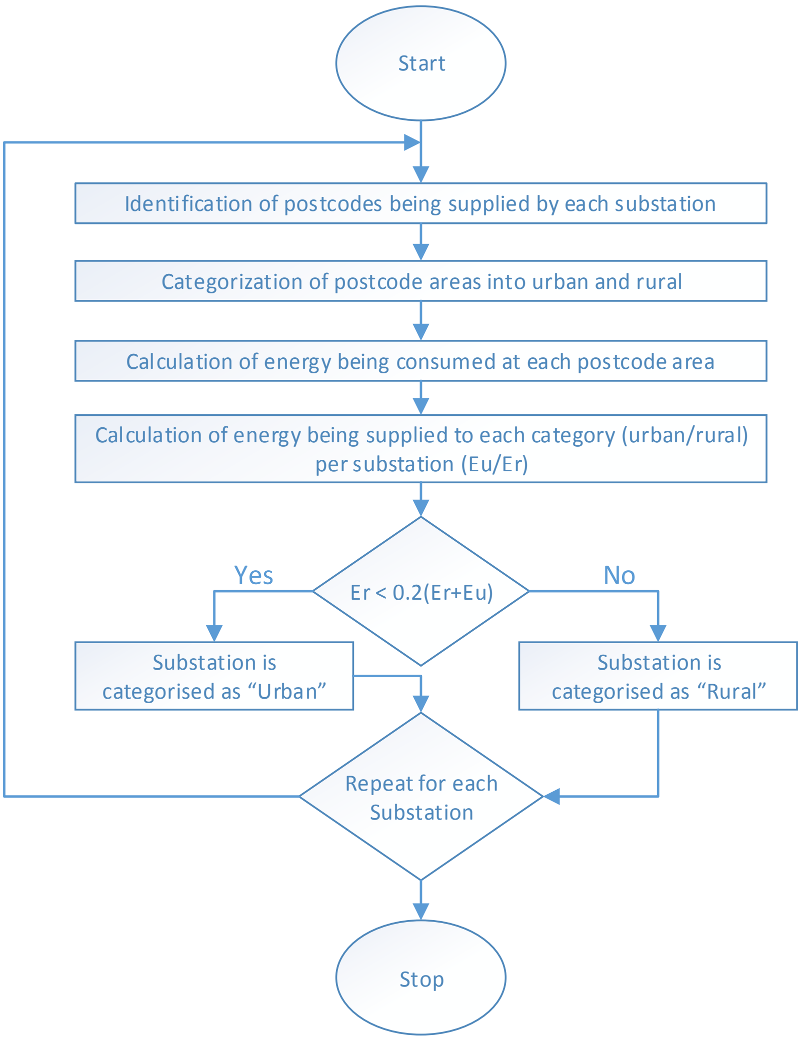


**Figure 11.** Flowchart of the methodology for the categorization of substation into urban and rural

**Table 11.** Extrapolation results of PV hosting capacity for All Cyprus Substations.

| Substation Name | Category | Substation Firm Capacity (SFC) | Minimum Percentage of miPHC/FC (%) | Maximum Percentage of miPHC/FC (%) | Minimum PV Capacity (MWp) | Maximum PV Capacity (MWp) |
|---|---|---|---|---|---|---|
| Akoursos S/S | Rural | 32 | 33.42 | 118.73 | 10.69 | 37.99 |
| Alambra S/S | Rural | 31 | 33.42 | 52.81 | 10.36 | 16.37 |
| Amathous S/S | Rural | 40 | 33.42 | 118.73 | 13.37 | 47.49 |
| Anatoliko S/S | Rural | 16 | 33.42 | 118.73 | 5.35 | 19.00 |
| Aphrodite S/S | Rural | 16 | 33.42 | 118.73 | 5.35 | 19.00 |
| Ayios Athanasios S/S | Rural | 40 | 33.42 | 118.73 | 13.37 | 47.49 |
| Athienou S/S | Rural | 16 | 50.56 | 55.31 | 8.09 | 8.85 |
| Athalassa S/S | Rural | 32 | 33.42 | 118.73 | 10.69 | 37.99 |
| Ayia Napa S/S | Rural | 40 | 33.42 | 118.73 | 13.37 | 47.49 |
| Ayios Nikolaos S/S | Rural | 32 | 33.42 | 118.73 | 10.69 | 37.99 |
| Ayia Phyla S/S | Rural | 60 | 33.42 | 118.73 | 20.05 | 71.24 |
| Commercial Centre S/S | Urban | 69 | 89.23 | 107.00 | 61.57 | 73.83 |
| Dhasoupolis S/S | Urban | 80 | 89.23 | 107.00 | 71.38 | 85.60 |
| District Office S/S | Urban | 80 | 89.23 | 107.00 | 71.38 | 85.60 |
| Dhekelia GIS S/S | Rural | 40 | 33.42 | 118.73 | 13.37 | 47.49 |
| Episkopi S/S | Rural | 16 | 33.42 | 118.73 | 5.35 | 19.00 |
| Ergates S/S | Rural | 32 | 33.42 | 118.73 | 10.69 | 37.99 |
| F.I.Z. S/S | Rural | 40 | 33.42 | 118.73 | 13.37 | 47.49 |
| Hadjipaschalis S/S | Urban | 80 | 105.38 | 107.00 | 84.30 | 85.60 |
| Internation Airport S/S | Rural | 80 | 33.42 | 118.73 | 26.74 | 94.98 |
| Karvounas S/S | Rural | 16 | 33.42 | 118.73 | 5.35 | 19.00 |
| Kokkinotrimithia S/S | Rural | 32 | 33.42 | 118.73 | 10.69 | 37.99 |
| Kolossi S/S | Rural | 40 | 33.42 | 118.73 | 13.37 | 47.49 |
| Kophinou S/S | Rural | 32 | 33.42 | 118.73 | 10.69 | 37.99 |
| Lakatamia S/S | Urban | 40 | 89.23 | 107.00 | 35.69 | 42.80 |
| Larnaka S/S | Urban | 63 | 89.23 | 107.00 | 56.21 | 67.41 |
| Latsia S/S | Rural | 40 | 33.42 | 118.73 | 13.37 | 47.49 |
| Mari S/S | Rural | 30 | 33.42 | 118.73 | 10.03 | 35.62 |
| Melizona S/S | Rural | 40 | 33.42 | 118.73 | 13.37 | 47.49 |
| Old Power Station S/S | Urban | 63 | 89.23 | 107.00 | 56.21 | 67.41 |
| Omonia S/S | Urban | 40 | 89.23 | 107.00 | 35.69 | 42.80 |
| Orounda S/S | Rural | 16 | 33.42 | 118.73 | 5.35 | 19.00 |
| Papacostas S/S | Urban | 63 | 89.23 | 107.00 | 56.21 | 67.41 |
| Paphos S/S | Rural | 80 | 33.42 | 118.73 | 26.74 | 94.98 |
| Pissouri S/S | Rural | 16 | 33.42 | 118.73 | 5.35 | 19.00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Polis S/S** | Rural | 20 | 33.42 | 118.73 | 6.68 | 23.75 |
| **Polemidhia S/S** | Rural | 40 | 33.42 | 118.73 | 13.37 | 47.49 |
| **Prentzas S/S** | Urban | 80 | 89.23 | 95.25 | 71.38 | 76.20 |
| **Protaras S/S** | Rural | 63 | 33.42 | 118.73 | 21.05 | 74.80 |
| **Pyla GIS S/S** | Urban | 40 | 89.23 | 107.00 | 35.69 | 42.80 |
| **Pyrgos S/S** | Rural | 15 | 33.42 | 118.73 | 5.01 | 17.81 |
| **Seminary S/S** | Urban | 69 | 89.23 | 107.00 | 61.57 | 73.83 |
| **Sotera S/S** | Rural | 31.5 | 91.65 | 118.73 | 28.87 | 37.40 |
| **Stroumbi S/S** | Rural | 16 | 33.42 | 118.73 | 5.35 | 19.00 |
| **Strovolos S/S** | Urban | 63 | 89.23 | 107.00 | 56.21 | 67.41 |
| **Tembria S/S** | Rural | 20 | 33.42 | 118.73 | 6.68 | 23.75 |
| **Trimiklini S/S** | Rural | 16 | 33.42 | 118.73 | 5.35 | 19.00 |
| **Xeropotamos S/S** | Rural | 16 | 33.42 | 118.73 | 5.35 | 19.00 |
| **Yermasoyia S/S** | Rural | 32 | 33.42 | 118.73 | 10.69 | 37.99 |
| **Ypsonas S/S** | Rural | 10 | 111.30 | 202.70 | 11.13 | 20.27 |
| **Total Firm Capacity:** | | 2014.50 | PV Capacity Hosting Range: | | 1178.26 | 2262.87 |

It is to be noted that the classification of the substations was done in relation to the degree they physically supply consumers outside the urban areas of cities, irrespective of the fact that they may be physically within the boundaries of cities. Substations such as Amathous, Ayios Athanasios, Ayia Phyla, Paphos, Polemidhia and Yermasoyia have a mix urban and rural load but have been classified under the above criterion as rural loads. This does not limit the correctness of the extrapolation exercise since the selection criteria shown in Figure 11 are met, meaning that these substations supply to a larger extent rural networks with lower PV penetration capabilities.

# 4. General Conclusions - PV Hosting capacity of Distribution network in Cyprus

From the detailed results in the attached reports and the summary of results referred to above, the following conclusions can be drawn:

i. The hosting capacity of the suitably selected transmission substations (a reflection of typical transmission substations in Cyprus) has been evaluated by using a minimum load as defined in the separate reports, aiming through that, to get the worst possible operational scenarios, hence results reached are the minimum expected allowable penetration of PV systems without violating system requirements and quality of supply.

ii. From the extrapolation figures of Table 11, the distribution network is suitably developed in most cases, to integrate PV systems of adequate size to supply the full annual energy needs of connected users with no violation of quality characteristics of supply and / or network thermal capacity. This conclusion is drawn from the fact that the evaluated penetration levels are in the range of the firm capacity of Transmission substations, hence the maximum intended load to be supplied from the specific Transmission substation. From detailed load analysis on the distribution grid of Cyprus, the DSO of Cyprus is using an after diversity factor of 4 kVA per average domestic consumer for the development of the grid (the DSO can confirm this internal development policy when consulted). Hence, a penetration level of PV systems equivalent to the firm capacity of transmission substations reflects an annual yield equal or above the energy needs of the connected consumers.

iii. Substations supplying rural network with overhead lines that have low capacity overhead lines and long feeders (Athienou and Alambra s/s) exhibit a lower PV penetration capacity (33 to 55% of firm capacity instead of 89 to 118% which is found to be valid for the urban substations) than the average, meaning that those circuits (long and low capacity) might require reinforcements to allow the penetration to rise to the expected average. However, through a controlled deployment of the PV systems the referred to reinforcements might not be required at all or to be effected in very extreme cases.

iv. The detailed Monte Carlo analysis has revealed that in general the distribution system in Cyprus is ready to accommodate a high penetration of PV systems capable of rising to the very high figure equivalent to the firm capacity of transmission substations without violating the operational system requirements and quality of supply. This high figure can be reached with enhanced voltage control through the advanced features of inverters by enforcing them to operate in an under-excited state as indicated in Fig. 11 of this report. The results have shown that penetration levels are not higher with power factor less than 0,95.

The PV hosting capacity investigated in this report is strictly relevant to the Distribution network only and it does not address system wide operational limitations. These are beyond the scope of this study but despite this, an extrapolation for all the Transmission substations is conducted giving an estimation of the range of PV possible to be installed utilizing the capabilities of the Distribution network and the advanced features of inverters. The aforementioned range is found to be from 1178 to 2263 MWp, according to Table 11. It should be made clear that these penetration levels are possible with the Distribution infrastructure as is currently developed and it does not include any possible reinforcements and / or extensions that will be implemented by the DSO from now to 2030.

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# 6. Appendices

## Appendix A

## A. Hadjipaschalis s/s - Executive Summary

The results of the PV hosting capacity for Hadjipaschalis substation (with three 40 MVA transmission transformers, 22 feeders, 206 distribution substations /transformers/busbars and 451 distribution lines either underground or overhead) located in Paphos district area (in a touristic/urban area), are presented and analysed in this Appendix. More specifically, the PV hosting capacity was defined according to two major technical categories related to voltage quality and the thermal limits of distribution lines/transformers calculated for steady-state conditions. From the results, it is evident that the PV hosting capacity can considerably increase if proper regulations are formulated and able to guide the DSO in installing the PV systems strategically according to specific spatial relationship of PV generation.

### A.1 Results

The single-line drawing of Hadjipaschalis S/S of which the results are presented in this report is shown in Fig. 12.

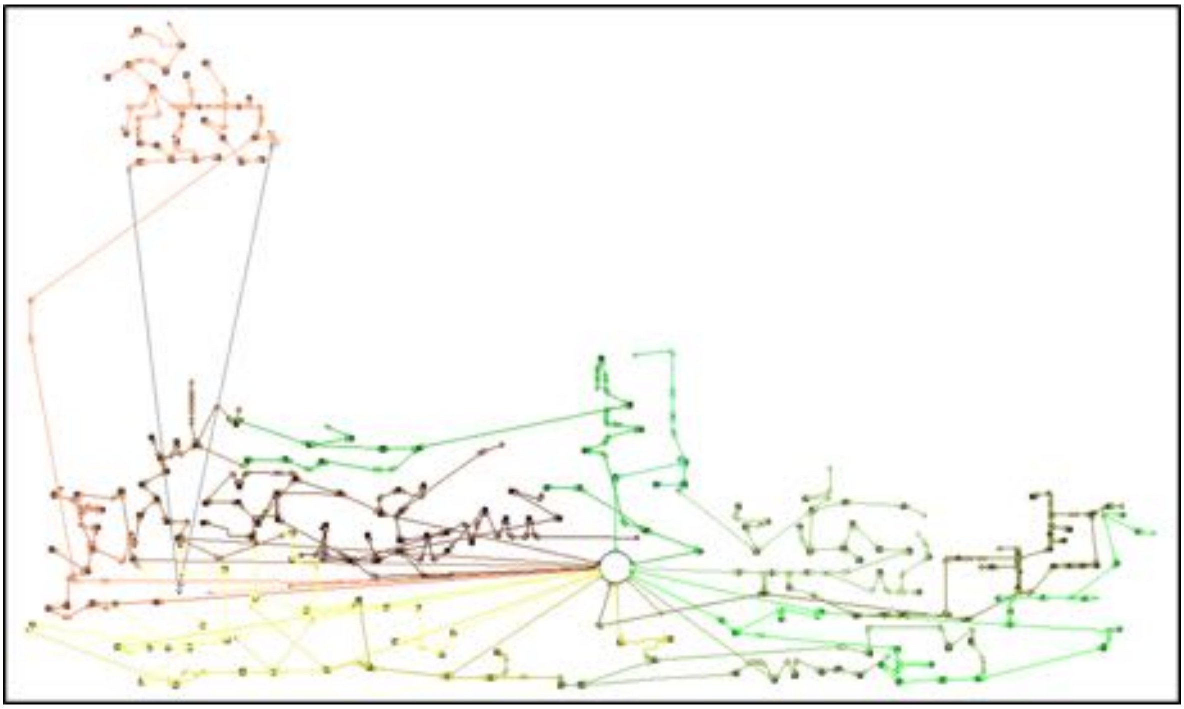

**Figure 12.** Single-line drawing of Hadjipaschalis S/S.

## A1.1 Maximum Installed PV Capacity scenario

### A1.1.1 Unity Power Factor Operation

In the first deterministic scenario, a PV system was installed at each distribution substation equal to the nominal power of the substation's transformer. It is assumed at this point that the inverter of the PV system is not oversized (in respect to the PV array). The total possible capacity that can be installed in the distribution grid under consideration is 150 MVA which can be found by summing up the rated power of all distribution transformers located inside the reference grid. It must be mentioned that the total capacity supported by transmission transformers (which is 120 MVA - 3 x 40 MVA) is disregarded in this scenario. After simulating the full year time series, the parameters of the PI chosen to define the hosting PV capacity are evaluated while considering no voltage regulation schemes (power factor equal to unity).

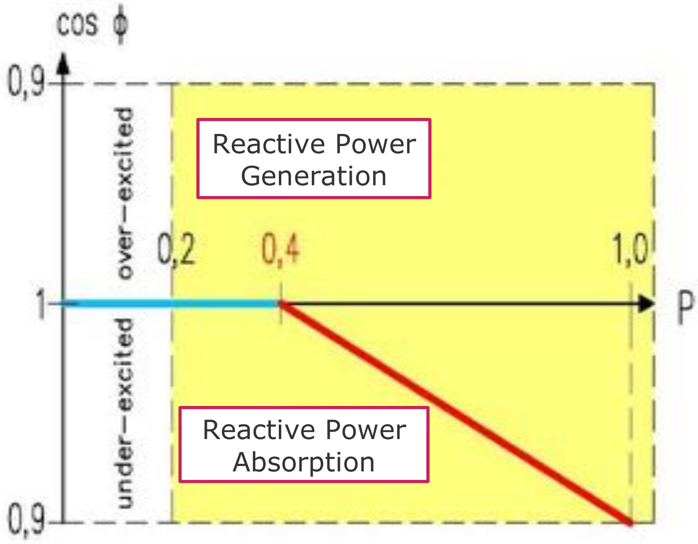


**Figure 13.** Characteristic curve cosφ (P) of power factor in relation to the generated power.

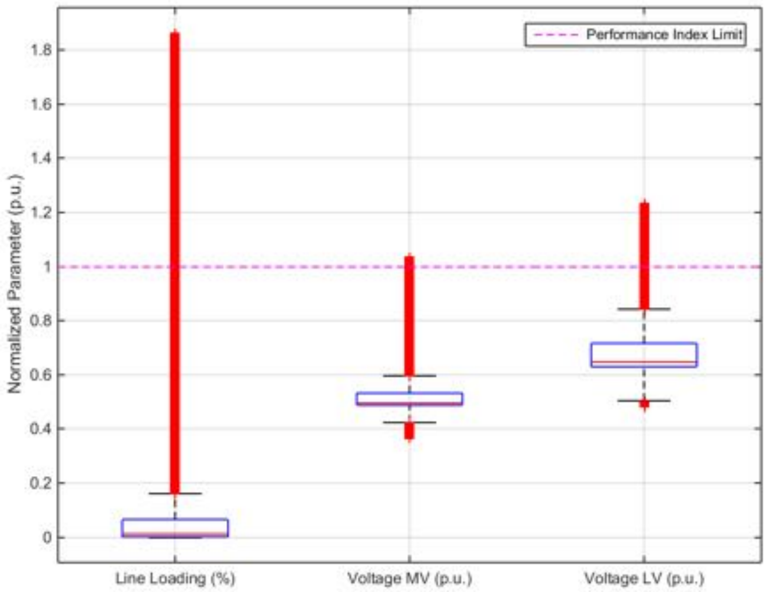


**Figure 14.** Performance Index parameters normalized to their limit – Unity Power Factor.

The specific simulation case was then repeated for two voltage regulation methods; the fixed power factor adjusted to 0.95 and the cosφ(P) method as depicted in

EN50438 [1] with curve characteristics shown in Fig. 13. The results for all buses/lines for each performance quantity are inserted into single data vectors and then statistically analysed. Also, the PI parameters are normalized according to their limit as stated in EN50160 [2]. The statistical analysis of the PI parameters is depicted in Fig. 14. The results of Fig. 14 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 (PDF) and cumulative probability distribution (CDF) for the aforementioned parameters are shown in Fig. 15 to Fig. 17, respectively. It is evident that at full PV deployment conditions, both violations of line loading and voltage limit on the low voltage network are observed (when voltage regulation techniques are not utilized).

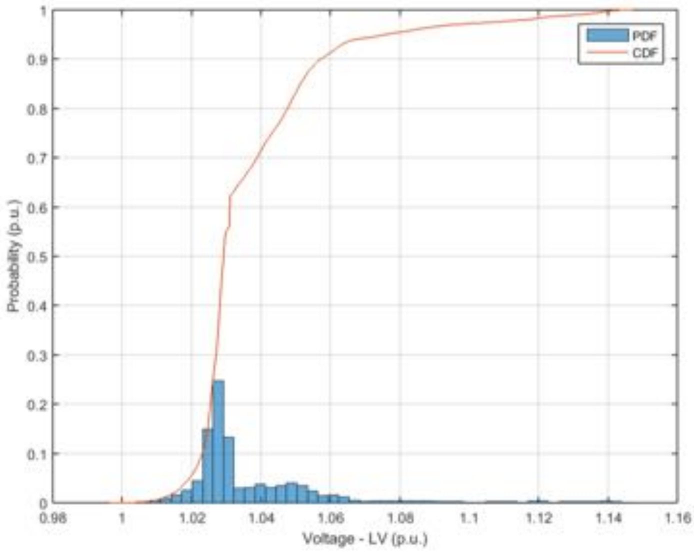


**Figure 15.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity power factor.

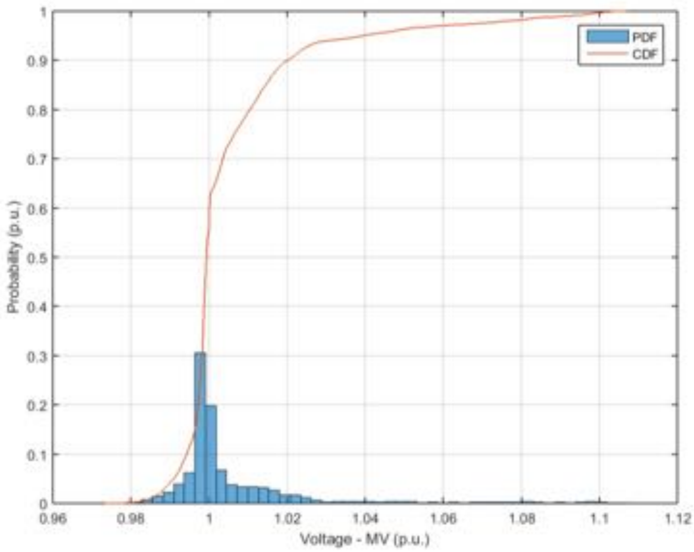


**Figure 16.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Unity power factor.

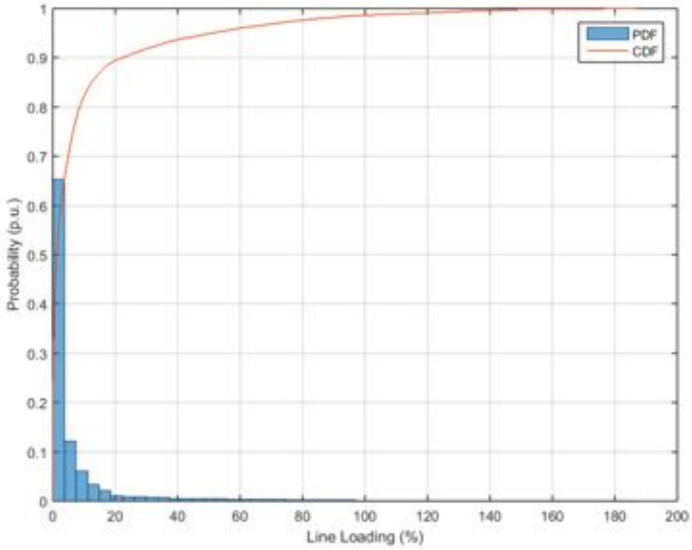


**Figure 17.** Probability distribution and cumulative probability distribution – Line Loading – Unity power factor.

The short circuit current calculation is performed according to the "complete method" as defined in [5]. The results for short circuit current obtained from the simulation of unity power factor scheme is graphically shown in Fig. 18.

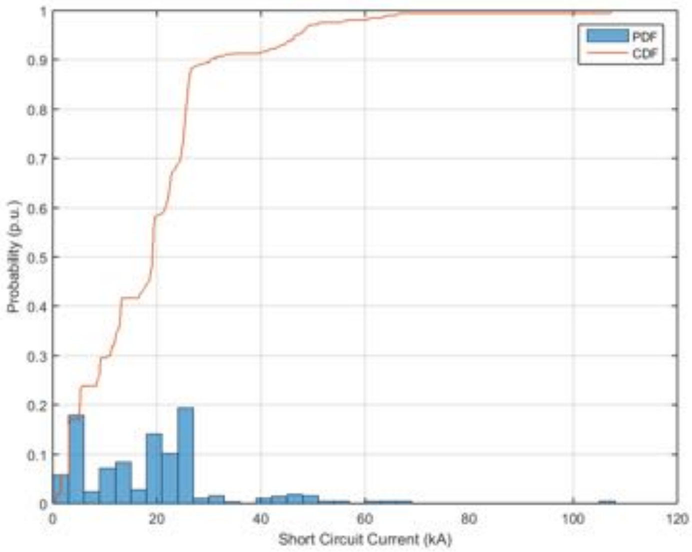


**Figure 18.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity power factor.

### A1.1.2 Power Factor equal to 0.95

The analysis presented in section A1.1.1 is repeated while setting the power factor to 0.95. By enabling the voltage regulation capability of inverters the voltage violations are reduced significantly at the low voltage side but as expected no improvement is observed as concerns the loading of lines. The results for voltage at low/medium voltage side, the line loading and the short circuit current for fixed power factor (equal to 0.95) are depicted in Figs. 19-23, respectively.

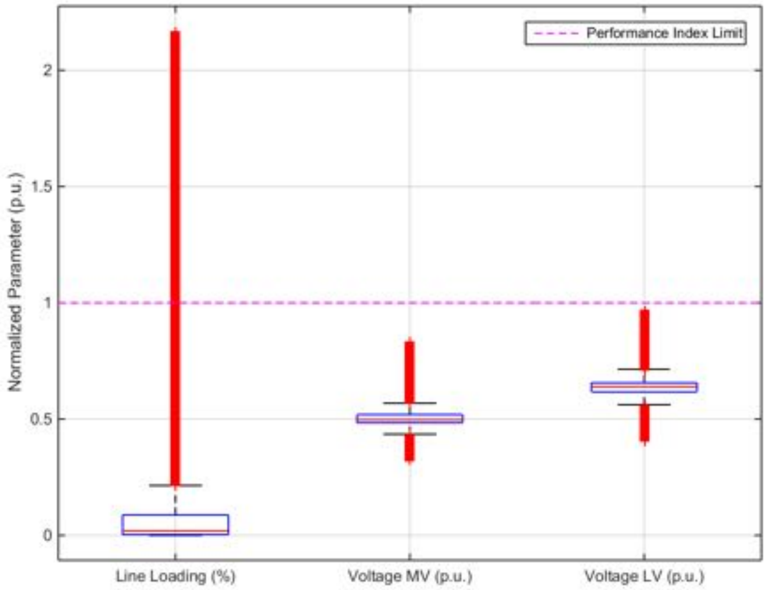


**Figure 19.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

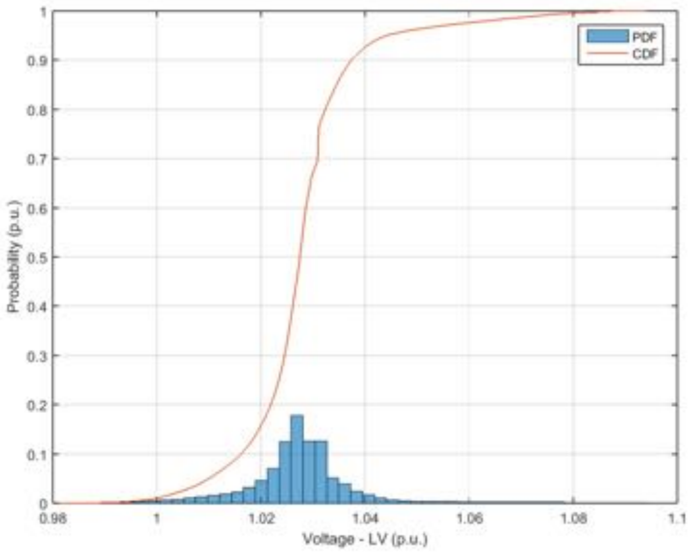


**Figure 20.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

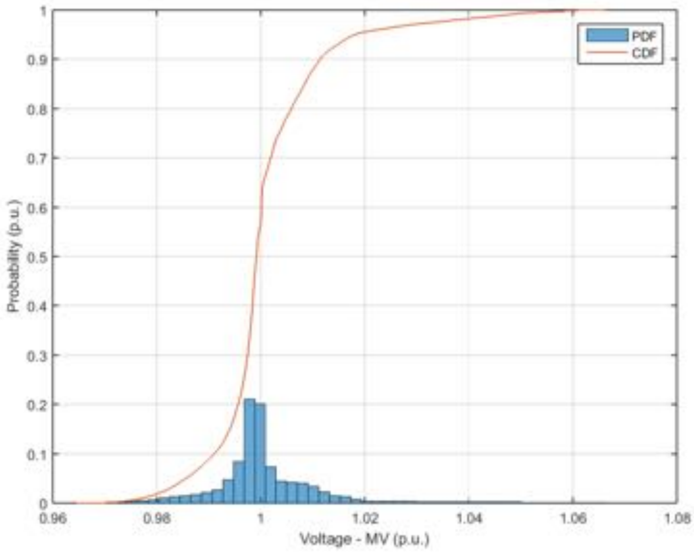


**Figure 21.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor equal to 0.95.

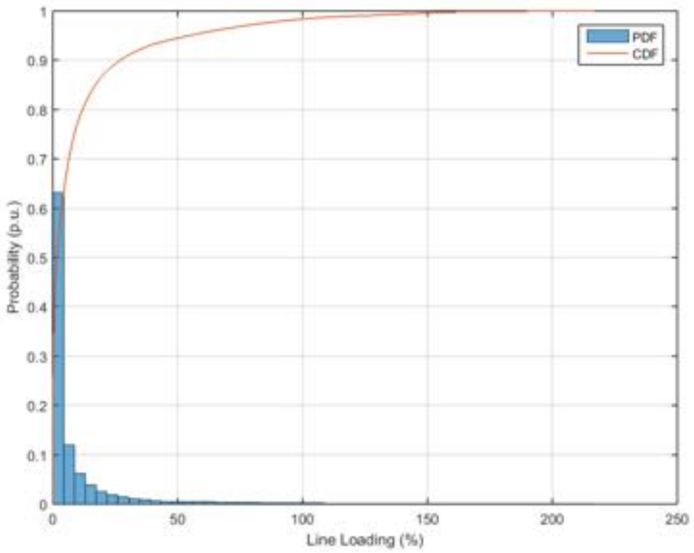


**Figure 22.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

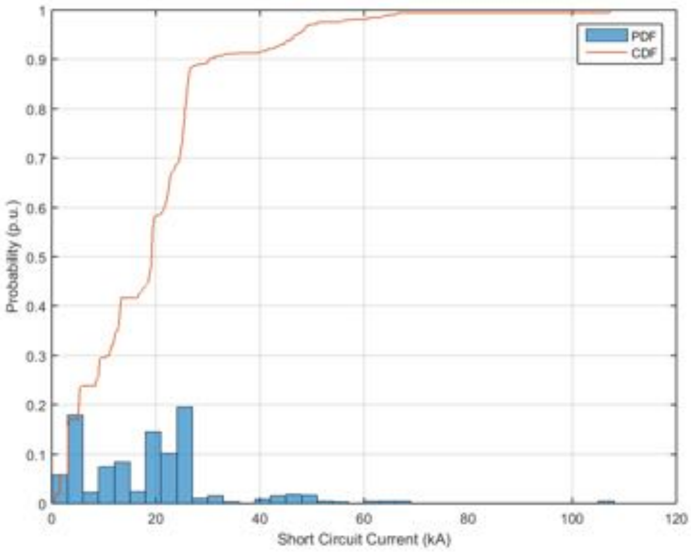


**Figure 23.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### A1.1.3 Power Factor cosφ(P)

The analysis presented in section A3.1.1 is repeated once more while adjusting the power factor according to the PV produced power as exactly shown in Fig. 12. The simulation results of this scenario are presented in Figs. 24-28). By enabling the voltage regulation capability of inverters the voltage violations are reduced significantly at low voltage side but as expected no improvement is observed as concerns the loading of lines.

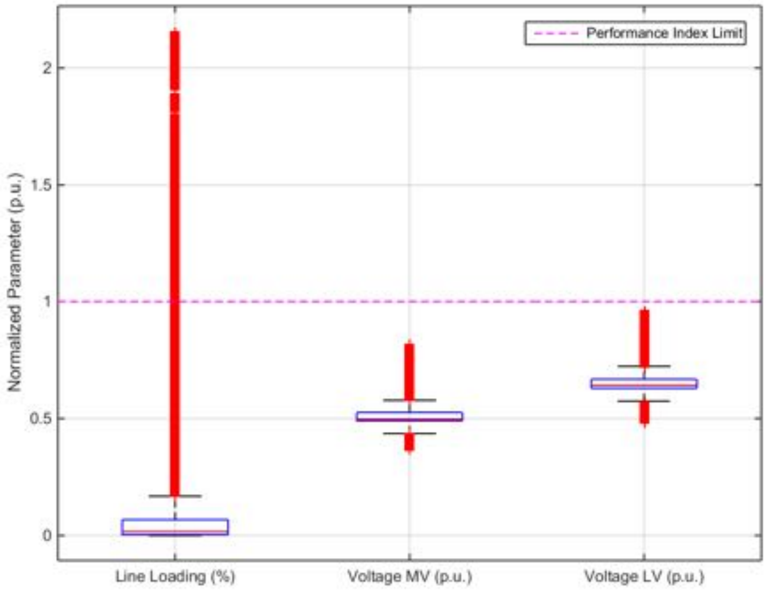


**Figure 24.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

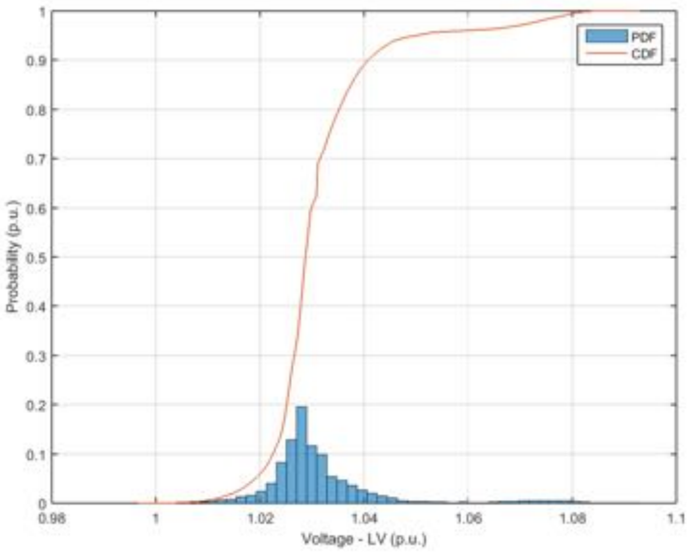


**Figure 25.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

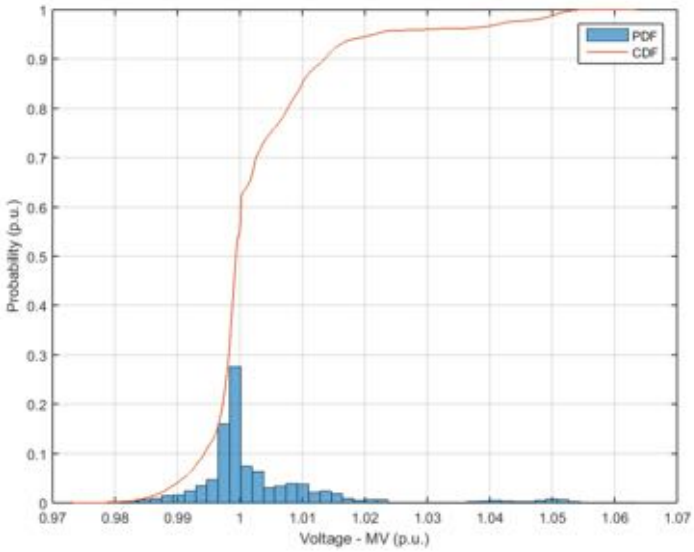


**Figure 26.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor cosφ(P).

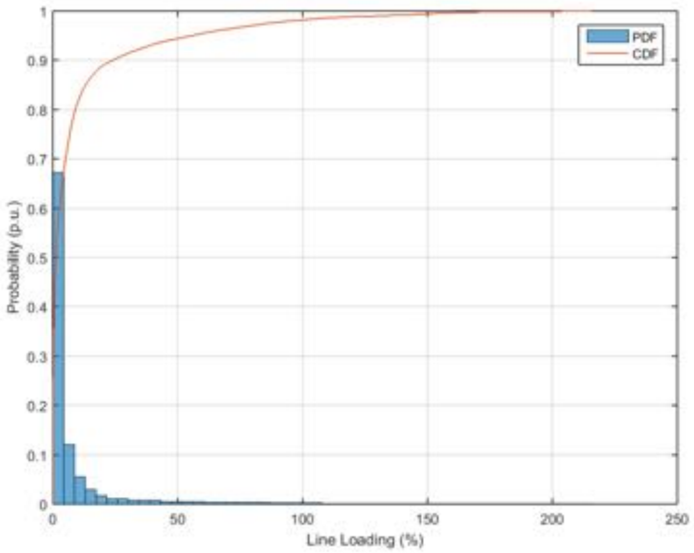


**Figure 27.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

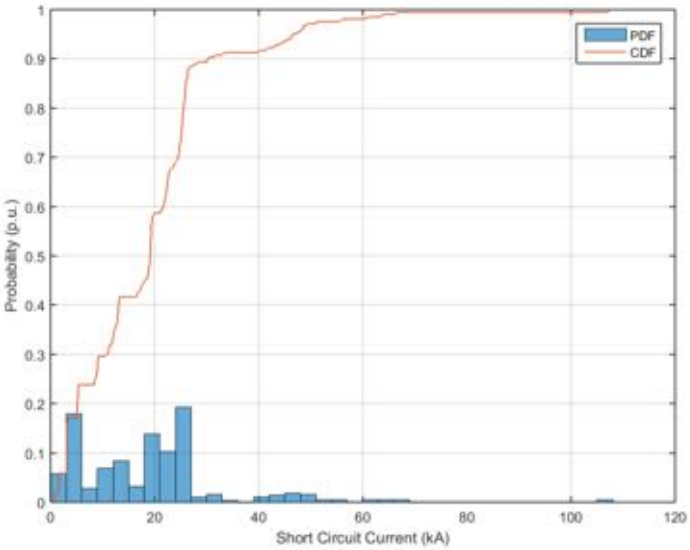


**Figure 28.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### A1.1.4 Summary and Discussion – Maximum Installed PV Capacity scenario

The results for the “Maximum Installed PV Capacity” scenario are summarized in Table 12 and 13. From the results, it can be seen that when no voltage regulation is adopted, voltage/line loading violations are observed. In the case of voltage regulation, it can be seen that voltage violations are reduced to zero but line loading violations remain. In addition, the loading of lines increases due to the reactive currents being absorbed for voltage regulation purposes. The short circuit currents are not affected by voltage regulation but they mostly depend on grid topology and transformer rated power. The “Maximum Installed PV Capacity” scenario is undertaken to reveal the violation of PI when the distribution grid is loaded fully with PV but it cannot give an answer about the hosting PV capacity limit which is much lower than the transformers total installed capacity. The PV hosting capacity limit is assessed accurately via Monte Carlo Simulations.

**Table 12.** Statistical analysis of PI parameters - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.483 | 0.406 | 0.483 |
| | 25th quantile | 0.631 | 0.617 | 0.629 |
| | Median | 0.646 | 0.637 | 0.644 |
| | Average | 0.685 | 0.639 | 0.656 |
| | Standard Deviation | 0.103 | 0.056 | 0.055 |
| | 75th quantile | 0.716 | 0.655 | 0.667 |
| | 95th quantile | 0.879 | 0.721 | 0.750 |
| | 99th quantile | 1.154 | 0.865 | 0.890 |
| | Maximum | 1.235 | 0.970 | 0.964 |
| **Number of elements of which the limit is violated** | | 33 out of 206 | 0 out of 206 | 0 out of 206 |
| **Voltage – Medium Voltage Side** | Minimum | 0.366 | 0.322 | 0.366 |
| | 25th quantile | 0.489 | 0.484 | 0.489 |
| | Median | 0.497 | 0.496 | 0.497 |
| | Average | 0.526 | 0.504 | 0.513 |
| | Standard Deviation | 0.088 | 0.055 | 0.056 |
| | 75th quantile | 0.532 | 0.517 | 0.525 |
| | 95th quantile | 0.698 | 0.591 | 0.608 |
| | 99th quantile | 0.955 | 0.735 | 0.752 |
| | Maximum | 1.035 | 0.831 | 0.817 |
| **Number of elements of which the limit is violated** | | 12 out of 206 | 0 out of 206 | 0 out of 206 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.001 | 0.001 | 0.001 |
| | Median | 0.013 | 0.017 | 0.013 |
| | Average | 0.088 | 0.102 | 0.095 |
| | Standard Deviation | 0.210 | 0.226 | 0.234 |
| | 75th quantile | 0.065 | 0.086 | 0.068 |
| | 95th quantile | 0.511 | 0.547 | 0.559 |
| | 99th quantile | 1.158 | 1.216 | 1.301 |
| | CDF-100% loading | 98.62% | 98.36% | 98.18% |
| | Maximum | 1.864 | 2.168 | 2.157 |
| **Number of elements of which the limit is violated** | | 33 out of 451 | 47 out of 451 | 46 out of 451 |

**Table 13.** Statistical analysis of Short Circuit Values - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 0.450 | 0.450 | 0.450 |
| | 25th quantile | 8.582 | 8.582 | 8.582 |
| | Median | 19.149 | 19.162 | 19.146 |
| | Average | 18.733 | 18.772 | 18.696 |
| | Standard Deviation | 14.286 | 14.301 | 14.273 |
| | 75th quantile | 25.182 | 25.211 | 25.159 |
| | 95th quantile | 46.718 | 46.819 | 46.709 |
| | 99th quantile | 64.479 | 64.829 | 64.075 |
| | Maximum | 107.218 | 107.218 | 107.238 |

The results for short circuit current obtained from the simulation of the No PV scenario is graphically shown in Fig. 29 for comparison purposes. From the results it can be concluded that the introduction of PV inside the distribution grid does not alter the levels of short circuit.

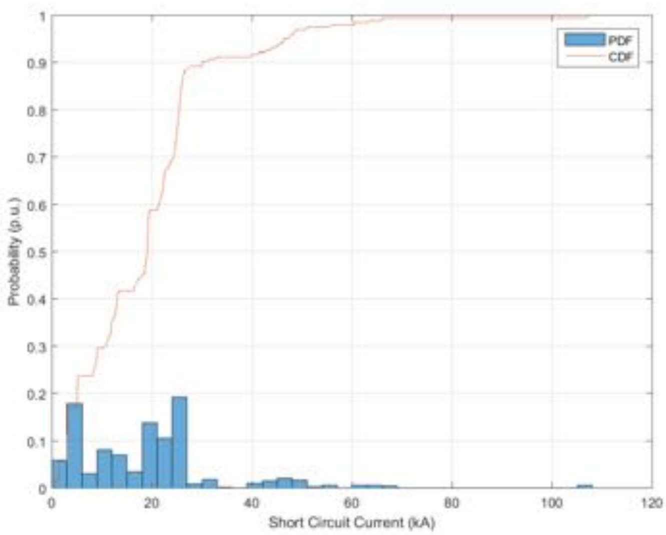


**Figure 29.** Probability distribution and cumulative probability distribution – Short Circuit Current – No PV.

## A1.2 Maximum PV Capacity per Distribution Substation

In the second scenario, each distribution substation individually is tested together with its upstream path up to the transmission substation, investigating if it can support PV capacity equal to the distribution transformer thermal limit under test. Consequently, more than one simulations are performed in the second scenario equal to the number of distribution substations. This analysis is done so as to verify if the design of each distribution substation and upstream path is done properly and if a bottleneck does exist lowering the PV hosting capacity.

### A1.2.1 Unity Power Factor Scheme

The maximum possible capacity per distribution substation is investigated for unity power factor and the results are shown in Figs. 30-33. In this situation, no violations are observed and in all cases PV power up to the thermal limit of transformer was possible to be installed without voltage regulation.

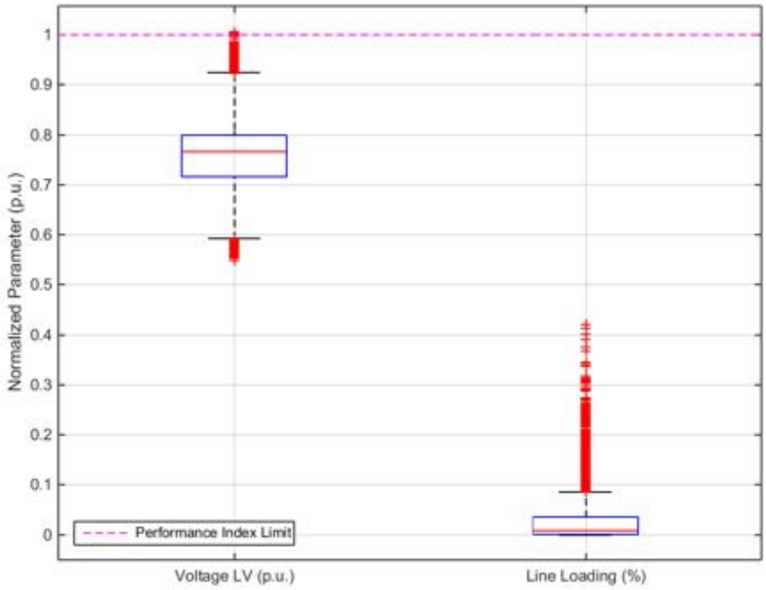


**Figure 30.** Performance Index parameters normalized to their limit – Unity Power Factor.

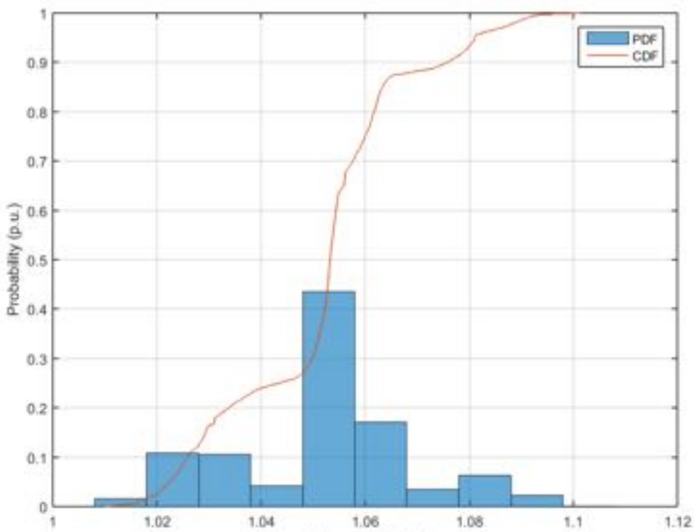


**Figure 31**. Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity Power Factor.

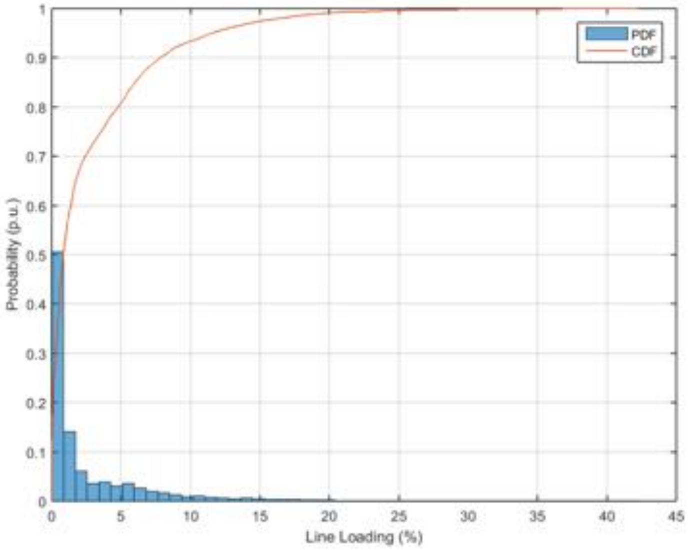


**Figure 32.** Probability distribution and cumulative probability distribution – Line Loading – Unity Power Factor.

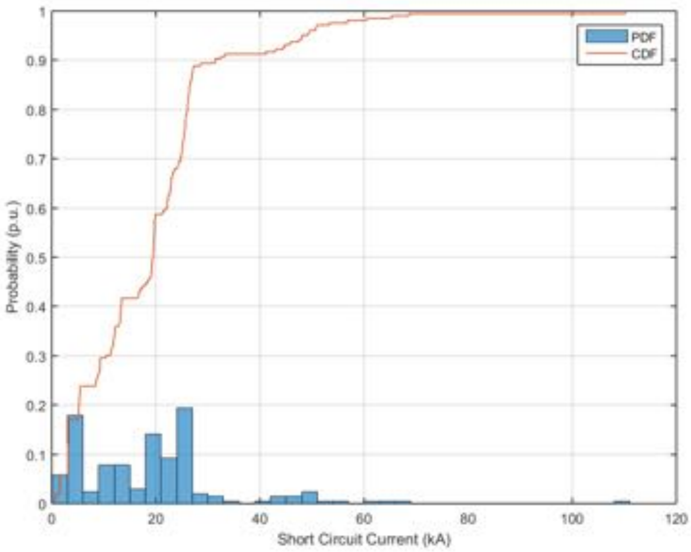


**Figure 33.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity Power Factor.

### A1.2.2 Power Factor equal to 0.95

The maximum possible capacity per distribution substation investigation is repeated by setting the power factor to 0.95. The results are exhibited in Figs. 34-37.

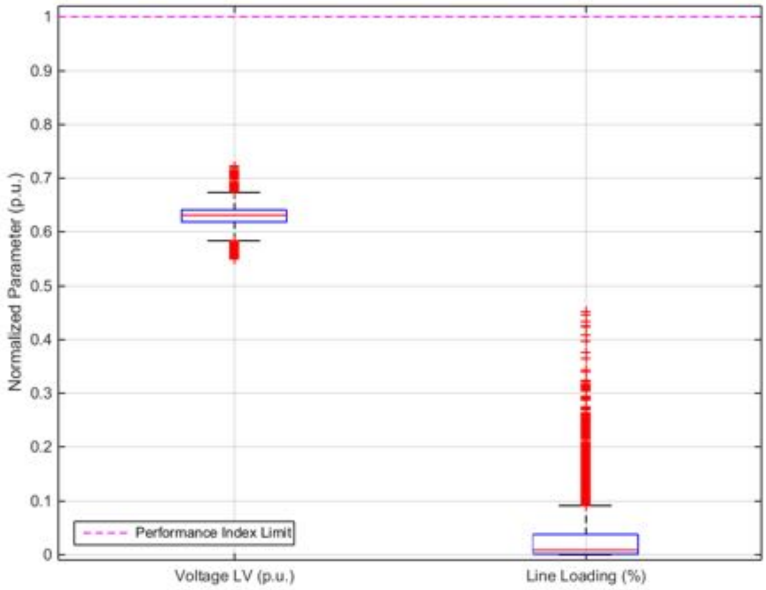


**Figure 34.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

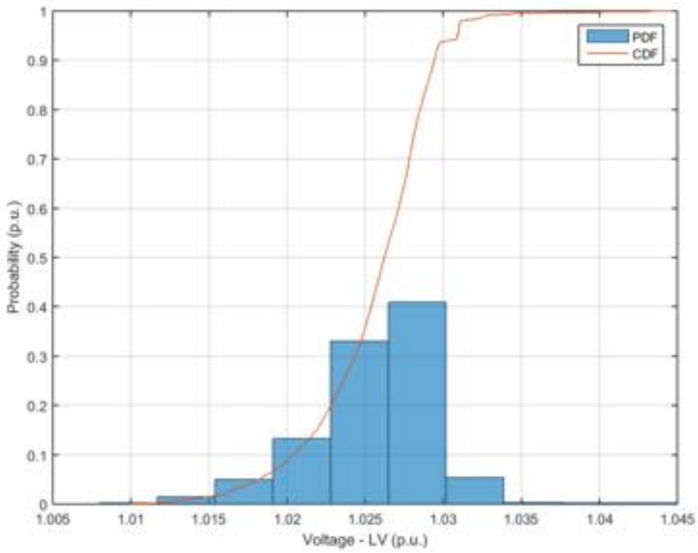


**Figure 35.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

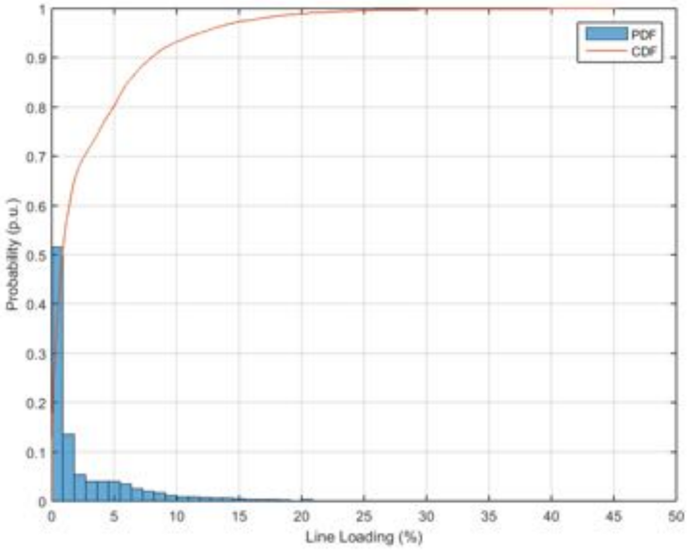


**Figure 36.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

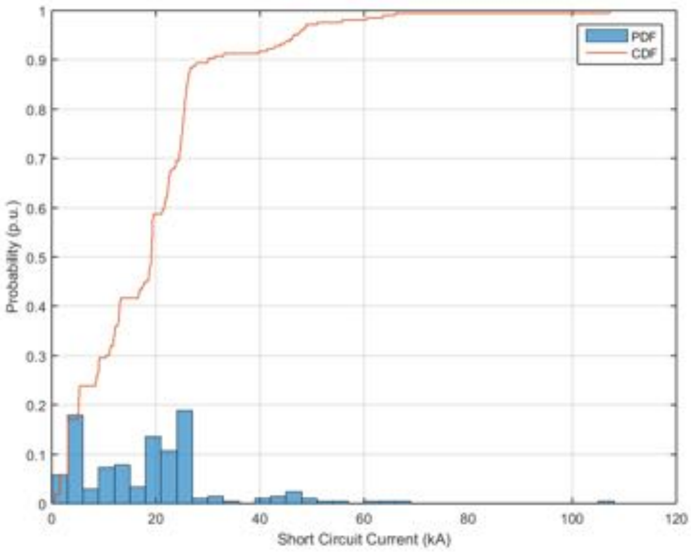


**Figure 37.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### A1.2.3 Power Factor cosφ(P)

The investigation for the maximum possible capacity of each distribution substation within the distribution grid is once more repeated for cosφ(P) power factor voltage regulation scheme. The results are shown in Figs. 38-41.

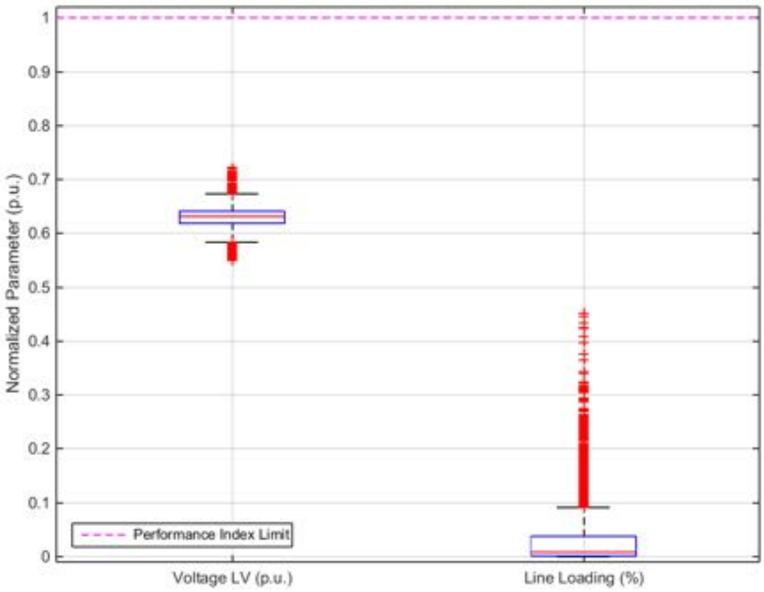


**Figure 38.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

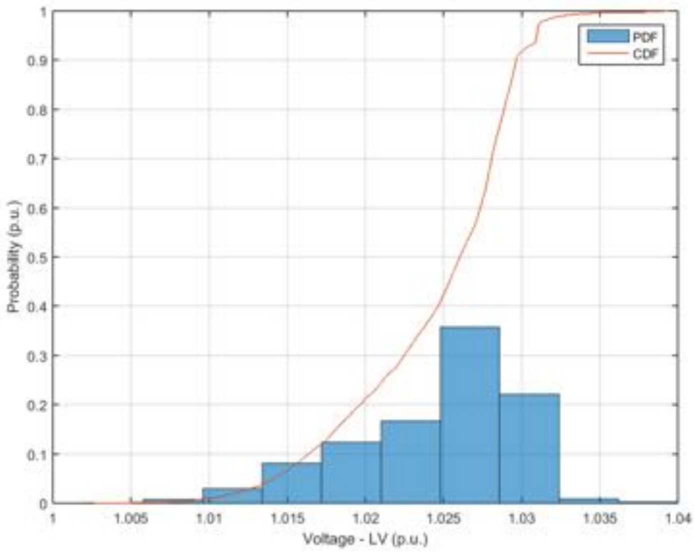


**Figure 39.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

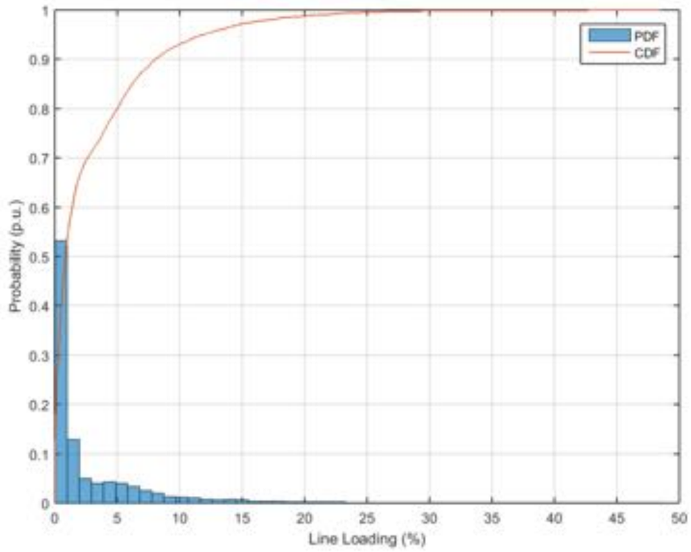


**Figure 40.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

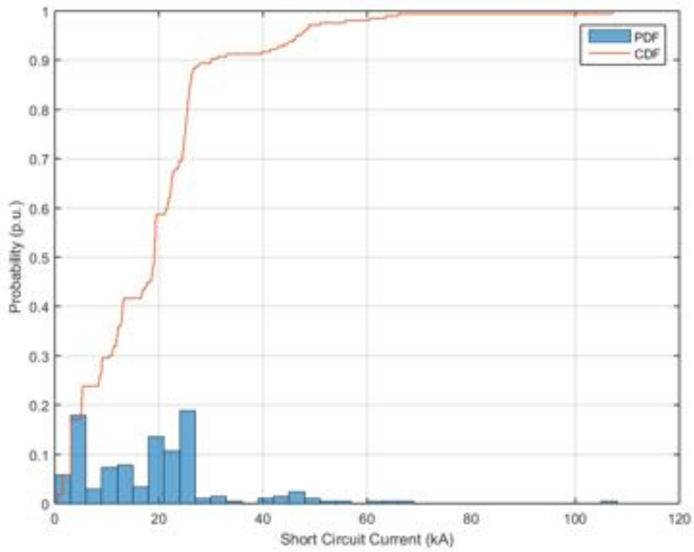


**Figure 41.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### A1.2.4 Summary and Discussion–Maximum PV Capacity per Distribution Substation

The results for the "Maximum PV Capacity per Distribution Substation" are presented in Tables 14 and 15. From this simulated scenario it can be seen that when loading individually each distribution substation with PV no limits are violated which depicts that the upstream lines are sized correctly in order to support PV production up to the nominal power of the substation's transformer. Despite this, it is evident from the "Maximum Installed PV Capacity" scenario that when installing PV at multiple locations inside a feeder it is quite possible to exceed the thermal limit of distribution lines.

**Table 14.** Statistical analysis of PI parameters - Maximum PV Capacity per Distribution Substation.

| | | Scenario | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.550 | 0.550 | 0.513 |
| | 25th quantile | 0.717 | 0.618 | 0.606 |
| | Median | 0.766 | 0.631 | 0.630 |
| | Average | 0.758 | 0.628 | 0.623 |
| | Standard Deviation | 0.007 | 0.000 | 0.001 |
| | 75th quantile | 0.800 | 0.641 | 0.642 |
| | 95th quantile | 0.905 | 0.655 | 0.655 |
| | 99th quantile | 0.955 | 0.664 | 0.663 |
| | Maximum | 1.000 | 0.723 | 0.697 |
| **Number of elements of which the limit is violated** | | 0 out of 206 | 0 out of 206 | 0 out of 206 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.002 | 0.002 | 0.002 |
| | Median | 0.008 | 0.008 | 0.008 |
| | Average | 0.027 | 0.028 | 0.028 |
| | Standard Deviation | 0.002 | 0.002 | 0.002 |
| | 75th quantile | 0.035 | 0.038 | 0.038 |
| | 95th quantile | 0.116 | 0.119 | 0.119 |
| | 99th quantile | 0.195 | 0.205 | 0.209 |
| | Maximum | 0.422 | 0.453 | 0.484 |
| **Number of elements of which the limit is violated** | | 0 out of 451 | 0 out of 451 | 0 out of 451 |

**Table 15.** Statistical analysis of Short Circuit Values - Maximum PV Capacity per Distribution Substation.

| | | Scenario | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 0.462 | 0.451 | 0.451 |
| | 25th quantile | 8.576 | 8.577 | 8.577 |
| | Median | 19.422 | 19.139 | 19.139 |
| | Average | 19.025 | 18.630 | 18.630 |
| | Standard Deviation | 14.705 | 14.277 | 14.277 |
| | 75th quantile | 25.470 | 25.061 | 25.061 |
| | 95th quantile | 48.333 | 46.648 | 46.648 |
| | 99th quantile | 66.777 | 64.667 | 64.667 |
| | Maximum | 110.236 | 107.212 | 107.212 |

## A1.3 Assessing PV Capacity using Monte Carlo method

### A1.3.1 Unity Power Factor Operation

By applying the Monte Carlo technique, it was further possible to assess the PV hosting capacity of the reference grid under consideration. In particular, by performing a large number of simulations (300000) and comparing against the violations of the PI (Fig. 45) it was possible to estimate the PV hosting capacity which is calculated to be around 32 MWp. From the results it is evident that voltage violations can occur for unity power factor case) above this PV capacity as well as violations of line thermal limits. The outcome from the Monte Carlo simulations is presented in Figures 42-49.

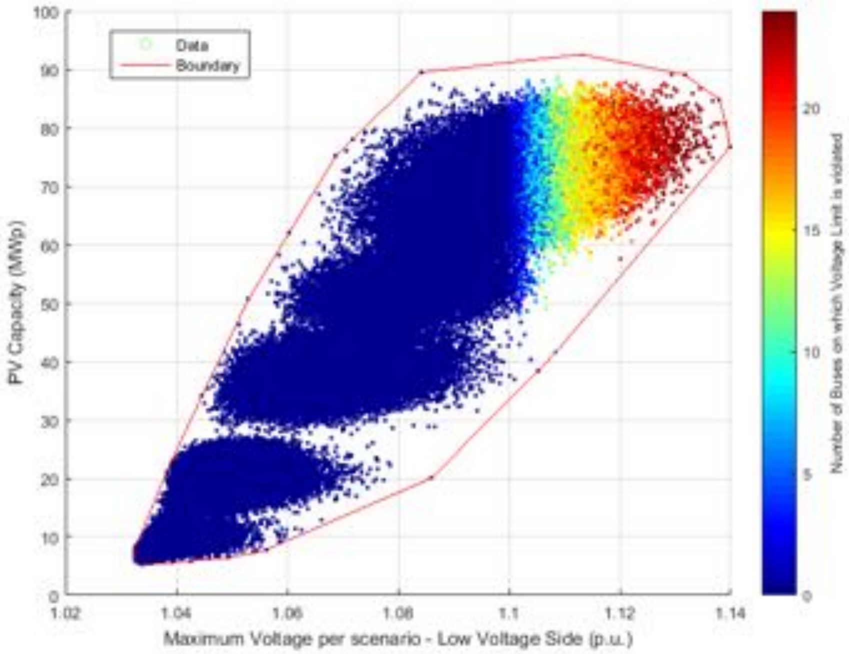


**Figure 42.** PV Capacity against Voltage – Low voltage side - Unity Power Factor.

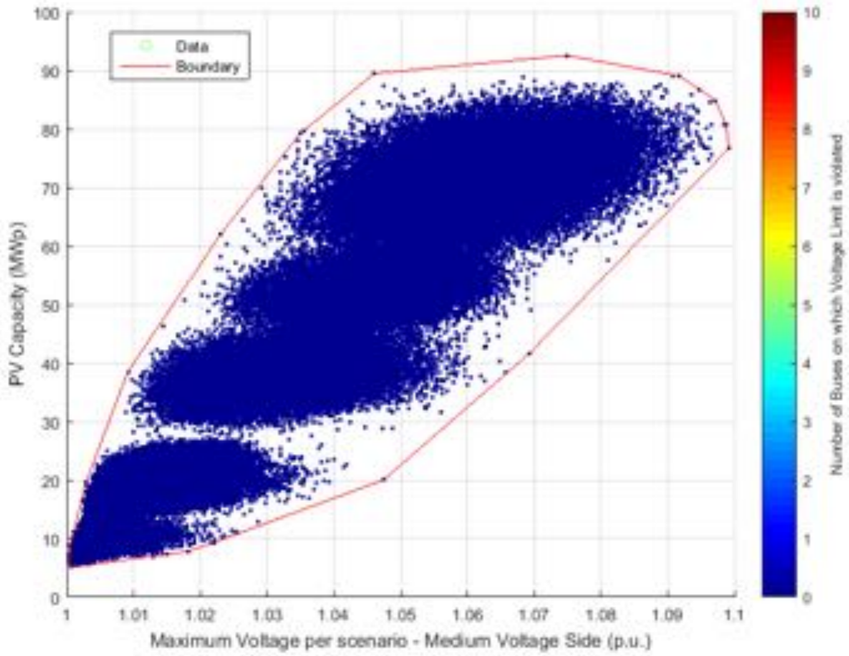


**Figure 43.** PV Capacity against Voltage – Medium voltage side - Unity Power Factor.

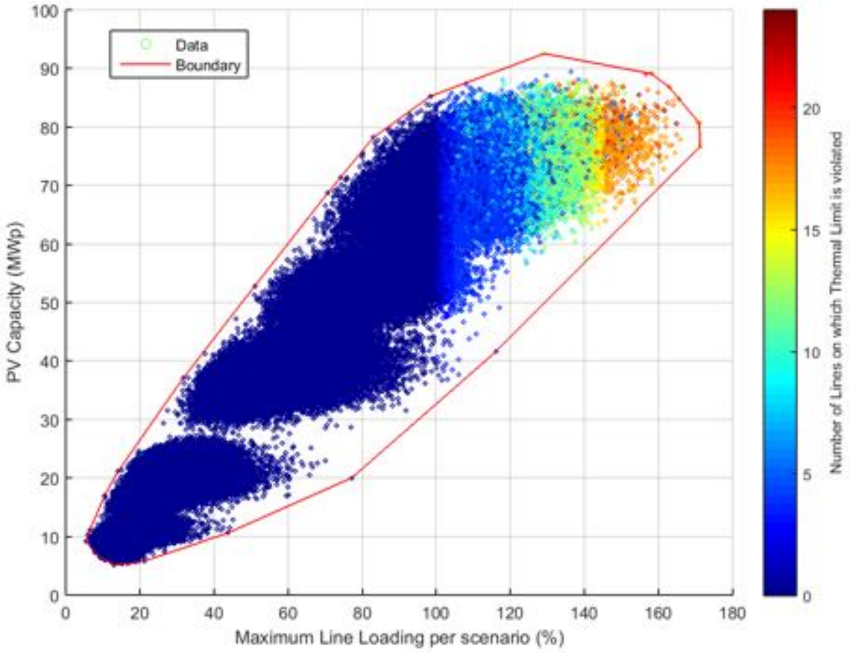


**Figure 44.** PV Capacity against Line Loading - Unity Power Factor.

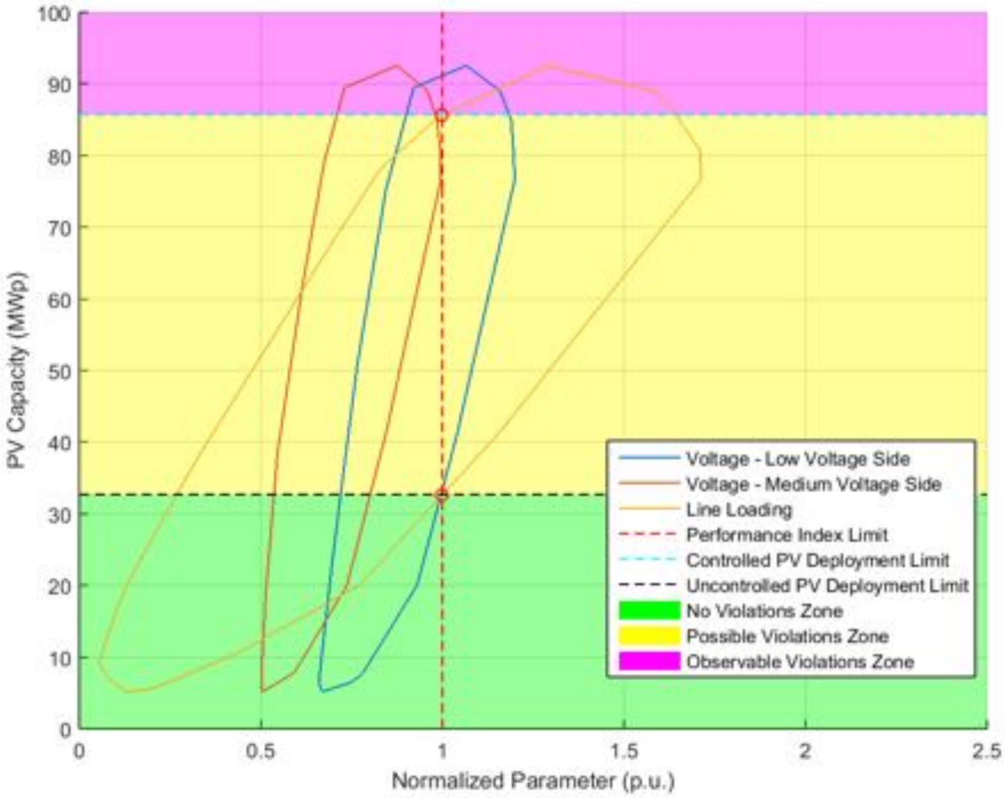


**Figure 45.** Normalized performance index parameters - Unity Power Factor.

In Fig. 45, by the term "uncontrolled PV deployment" it is meant that the PV systems are installed in the grid under consideration without any spatial based regulations/restrictions. In the "controlled PV deployment" region/zone, the PV systems must be installed in such a spatial/locational way in order not to violate the performance index. Also, the "no violations" zone is referring to the hosting PV capacities that do not cause any violations of the PI regardless of the size/location of the PV systems. Furthermore, the 'possible violations" zone denotes the PV capacities able to violate the PI based upon the size/locations of PV systems. Finally, the "observable violations" zone includes the capacities able to violate the PI regardless of the size/location of the PV systems. From Figs. 45 and 46, it can be concluded that the distance from transmission substation at which PV systems are installed is considered important if it is required to increase the installed PV power above PV hosting capacity [16]. The distance from the transmission transformer is able to affect the variation of voltage; the longer the cable/line in which the energy/power flows, the higher the impedance seen by a generator/load (connected on the sending/ receiving end respectively) and for this reason the variation of voltage on the busbar where the generator/load is connected will be larger. As regards the methodology, the data obtained from the 300000 Monte Carlo simulations for all 206 busbars/distribution substations (having a specific distance each from the transmission transformer) are analysed in order to obtain the results of Fig. 46. The results can be interpreted as follows: a) As soon as PV systems are installed close to the transmission transformer it is less likely to have voltage violations even at higher PV hosting capacities, b) The busbars located at the end of feeders are more likely to experience voltage violations at higher PV capacities c) If the PV capacity is allocated on distribution substations located less than 6 Km far from the transmission transformer it is more likely to host higher PV capacities without the need of applying voltage regulation measures (Fig. 46). With the term "distance" the meaning is the distance of the distribution substation from the transmission transformer (from the main busbar of the transmission substation).

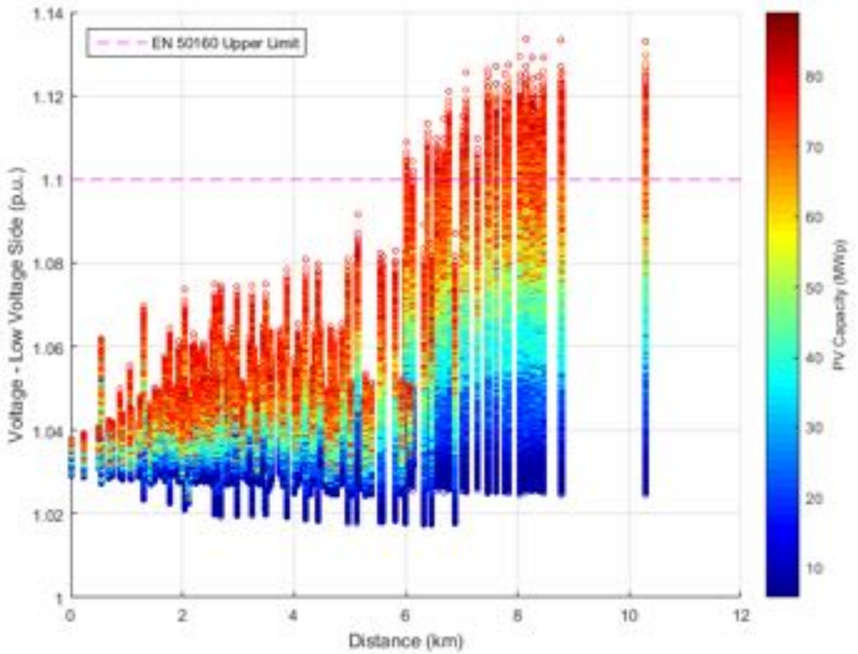


**Figure 46.** Voltage at low voltage side against distance from transmission substation - Unity Power Factor.

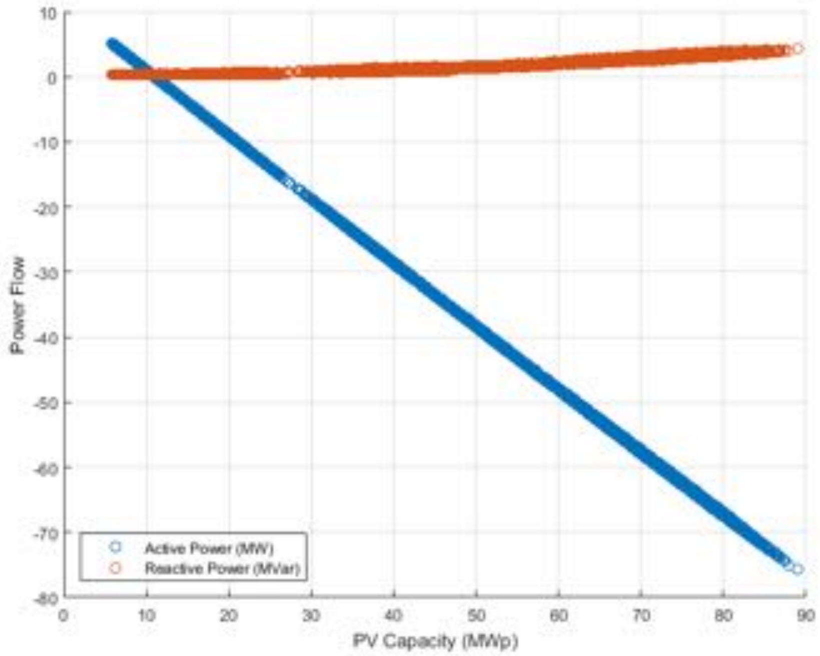


**Figure 47.** Power flow at PCC (connection of the reference substation with HV network) against PV capacity - Unity Power Factor (negative sign denotes reverse power flow).

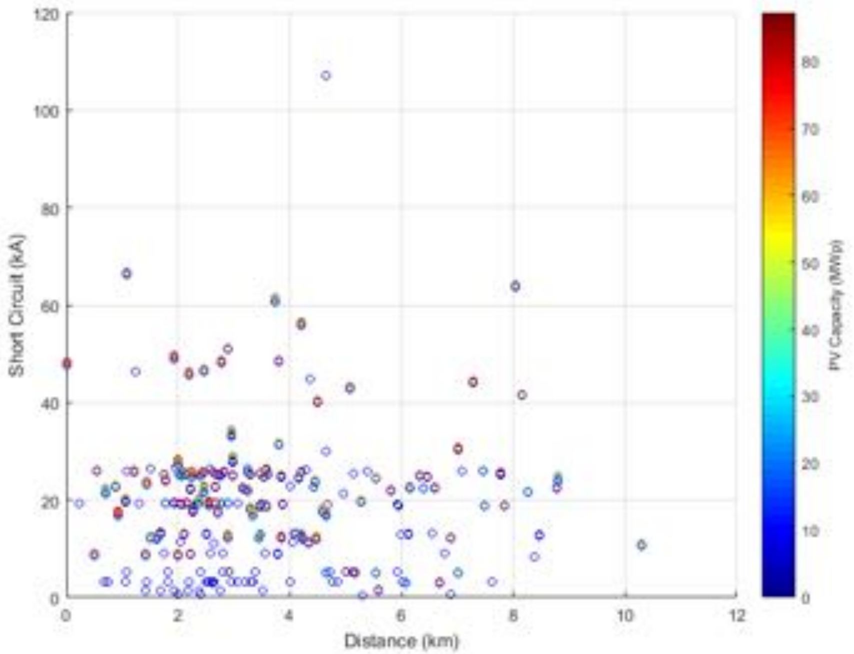


**Figure 48.** Short circuit current against distance - Unity Power Factor.

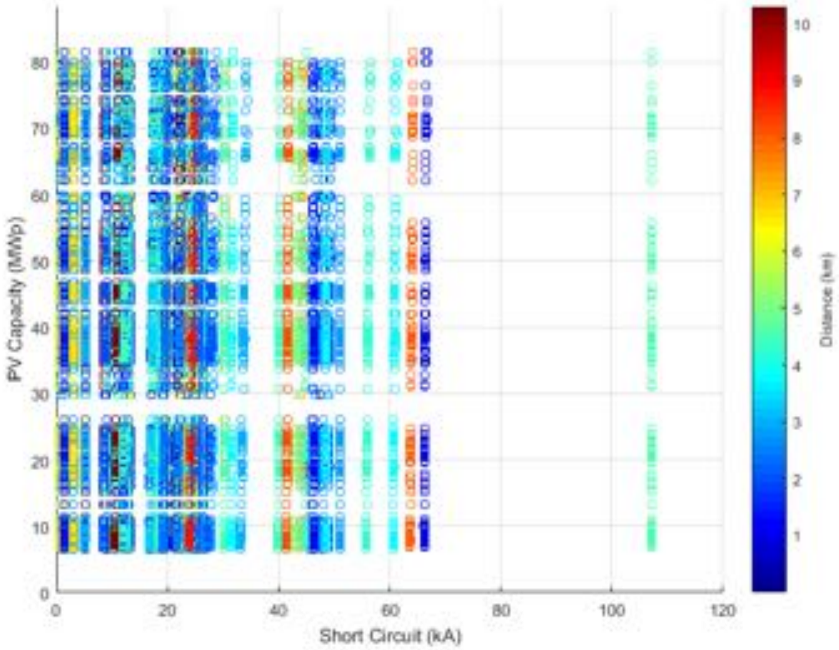


**Figure 49.** PV Capacity against Short circuit current - Unity Power Factor.

### A1.3.2 Power Factor equal to 0.95

After repeating the Monte Carlo simulations with the power factor of PV system set to 0.95 it has been observed that the voltage violations are eliminated but still the line loading thermal limit is exceeded. The results are shown in Figs. 50 – 57.

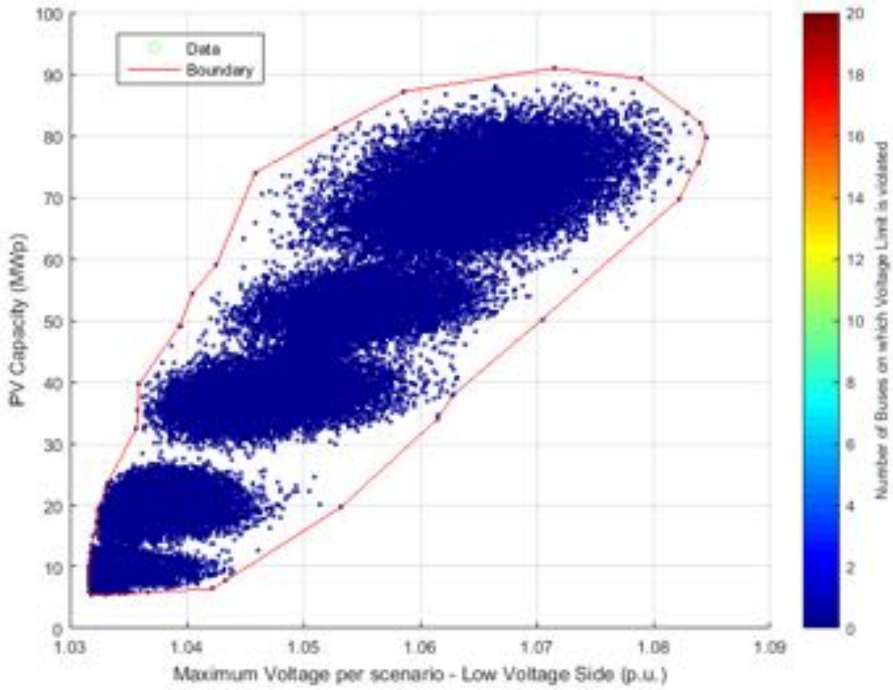


**Figure 50.** PV Capacity against Voltage – Low voltage side - Power Factor equal to 0.95.

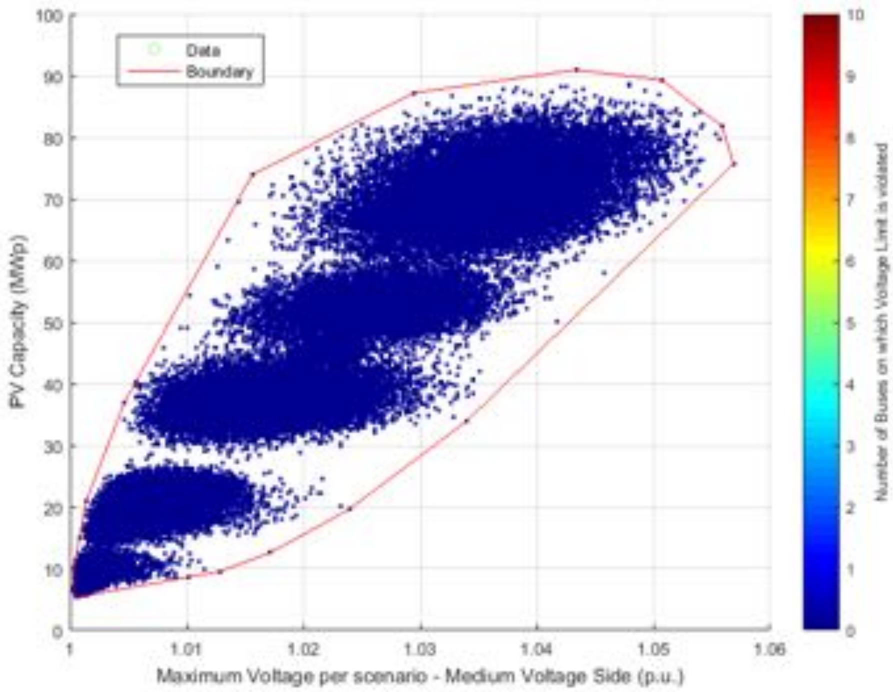


**Figure 51.** PV Capacity against Voltage – Medium voltage side - Power Factor equal to 0.95.

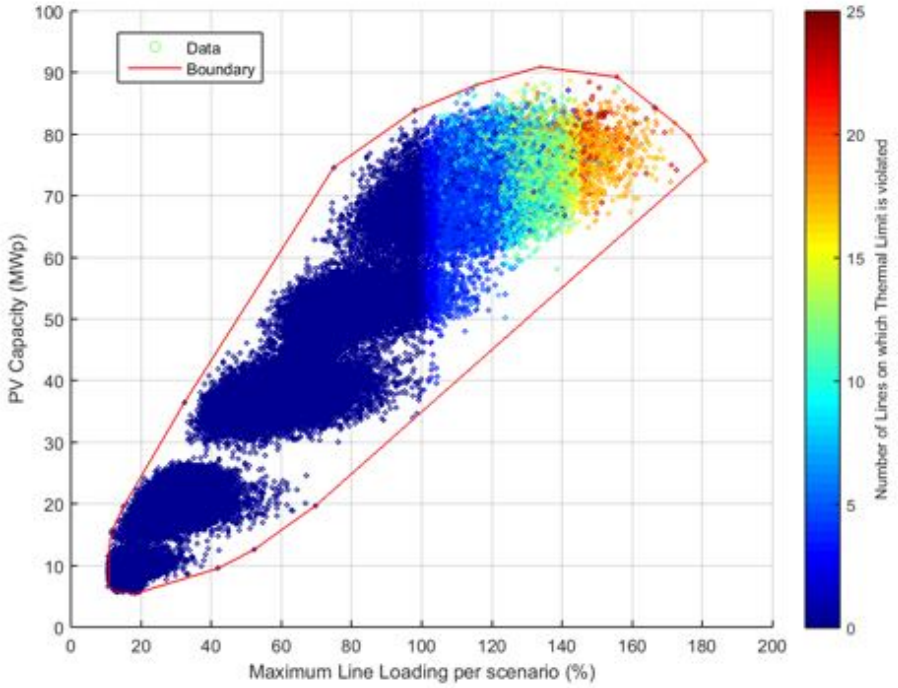


**Figure 52.** PV Capacity against Line Loading - Power Factor equal to 0.95.

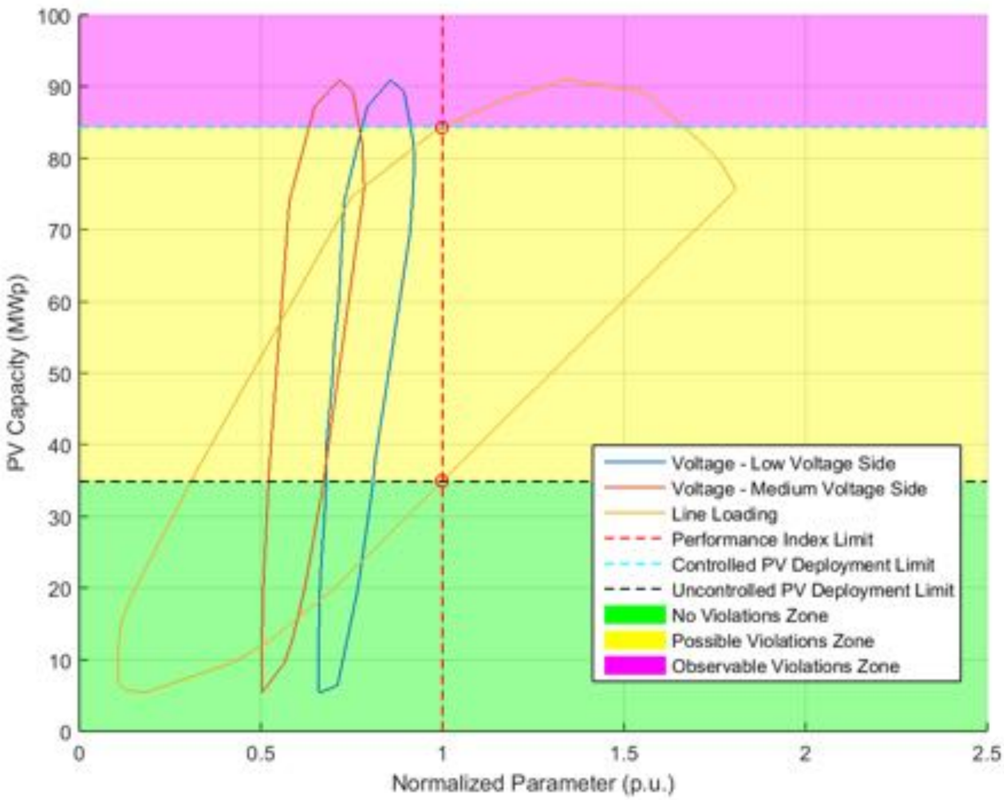


**Figure 53.** Normalized performance index parameters - Power Factor equal to 0.95.

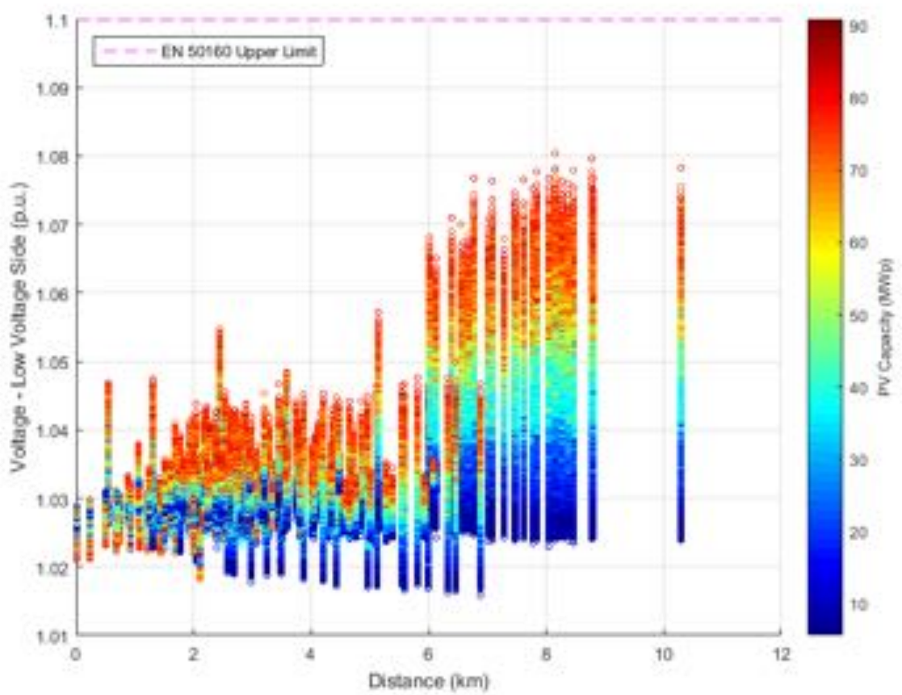


**Figure 54.** Voltage at low voltage side against Distance from transmission substation - Power Factor equal to 0.95.

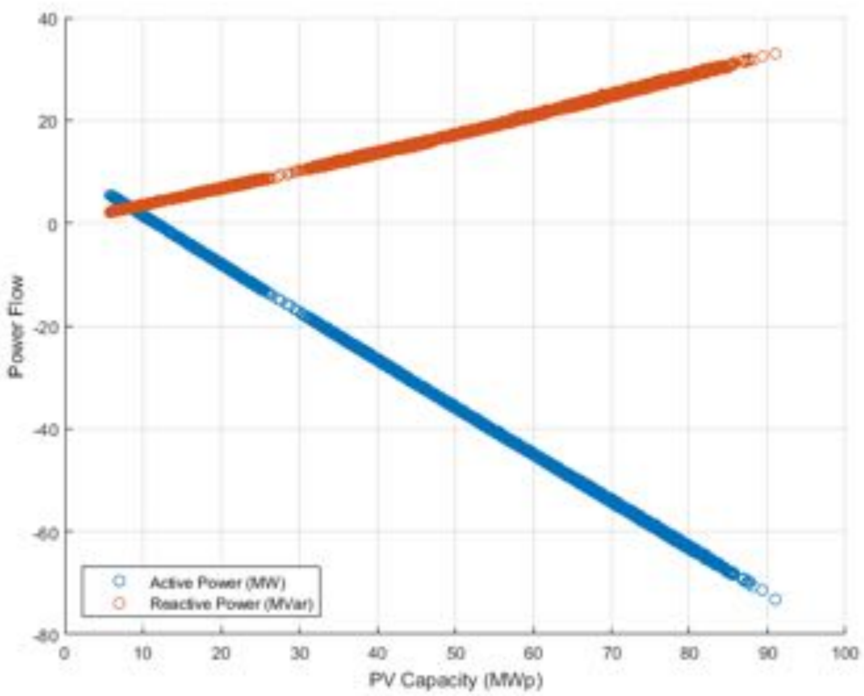


**Figure 55.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor equal to 0.95.

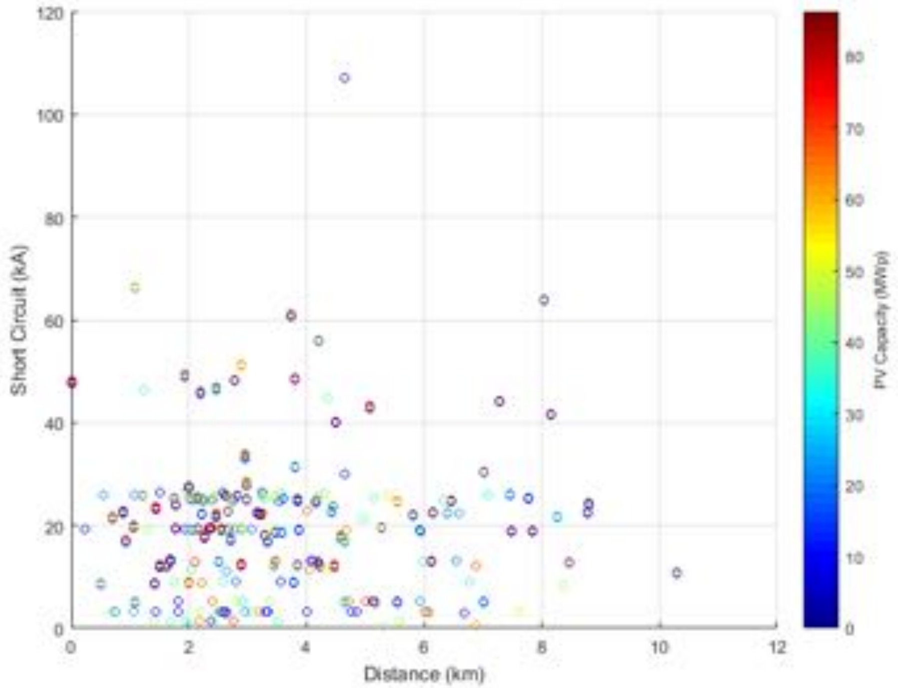


**Figure 56.** Short circuit current against Distance - Power Factor equal to 0.95.

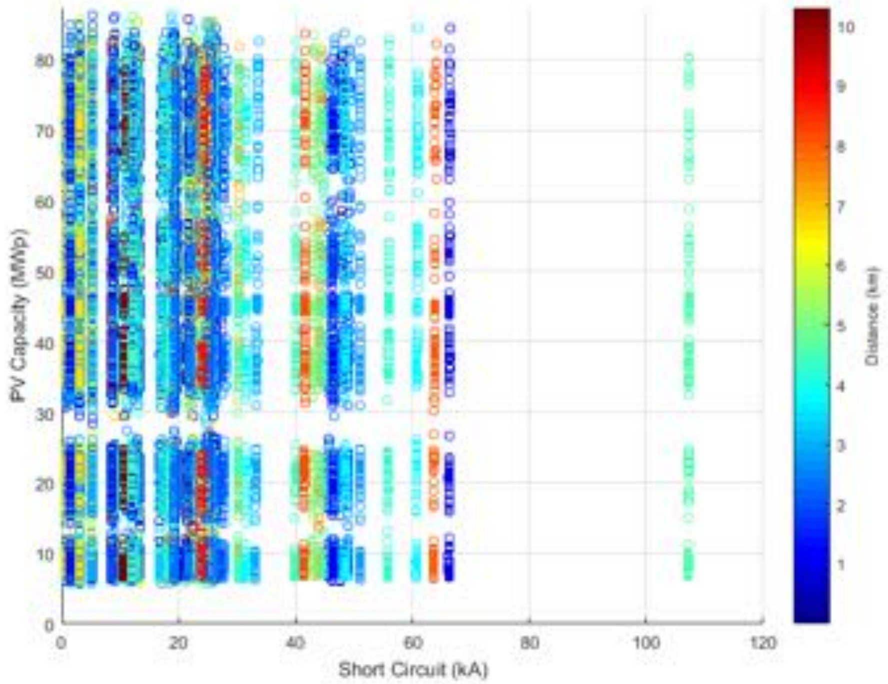


**Figure 57.** PV Capacity against Short Circuit current - Power Factor equal to 0.95.

### A1.3.3 Power Factor cosφ(P)

The results for cosφ(P) power factor scheme are shown in Figs. 58 – 65 and lead to similar outcomes as the previous subsection (A3.3.2). More specifically, it is observed that no voltage violations are observed when applying voltage regulation but still the thermal limits of lines start to be exceeded above a certain PV capacity value.

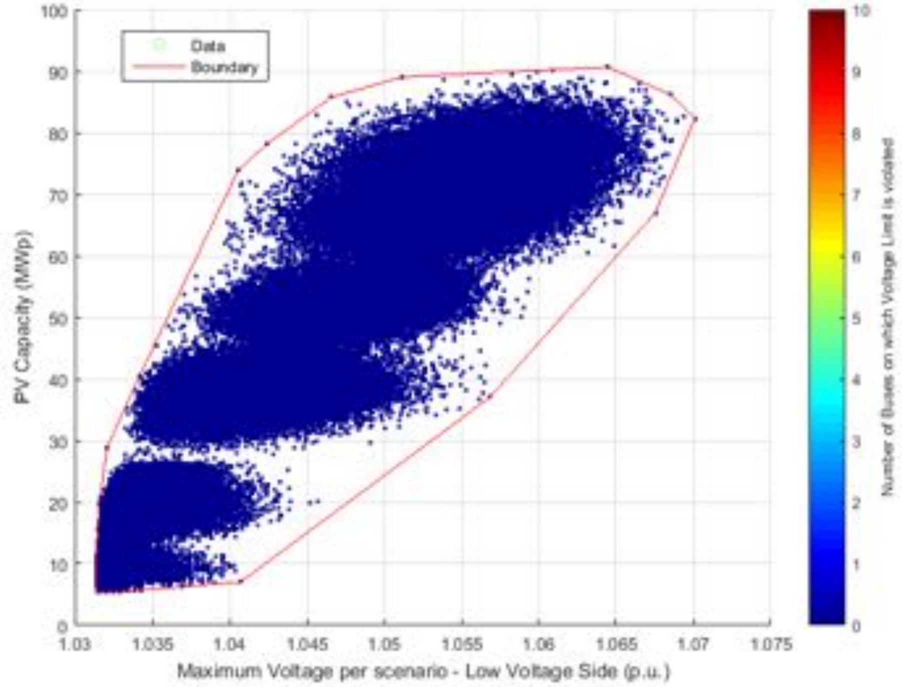


**Figure 58.** PV Capacity against Voltage – Low voltage side - Power Factor cosφ(P).

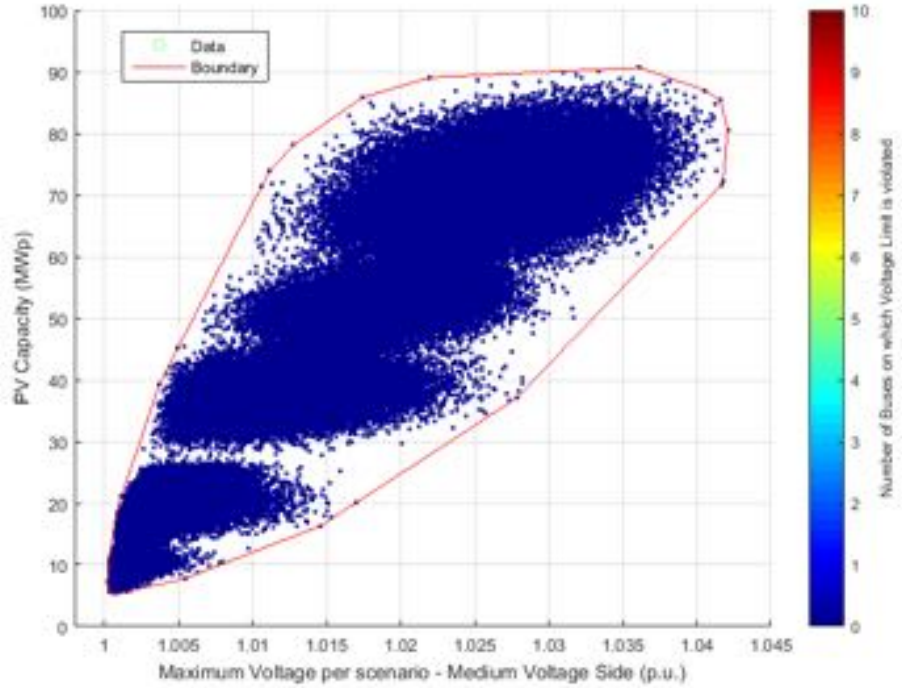


**Figure 59.** PV Capacity against Voltage – Medium voltage side - Power Factor cosφ(P).

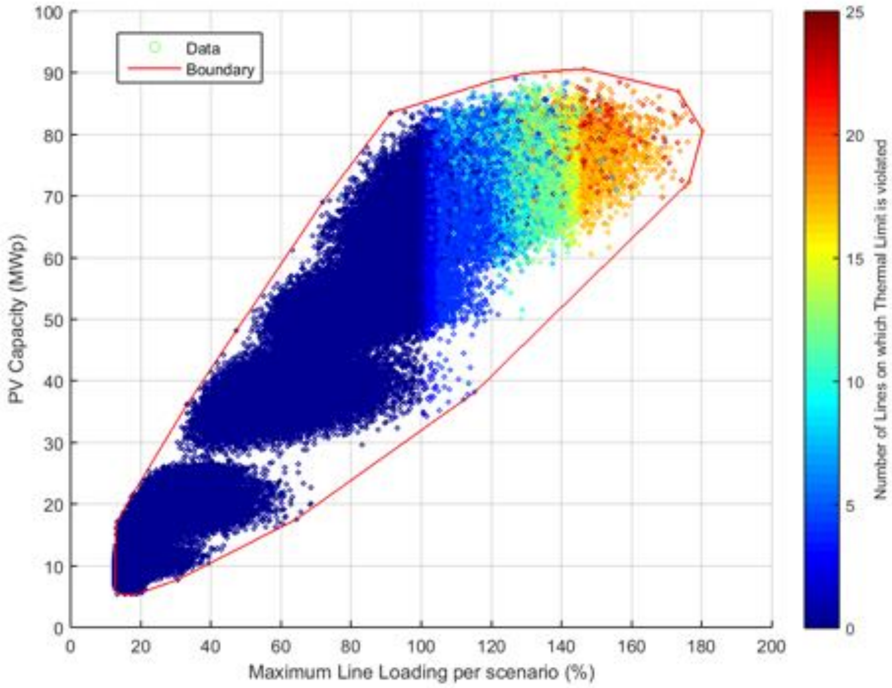


**Figure 60.** PV Capacity against Line Loading - Power Factor cosφ(P).

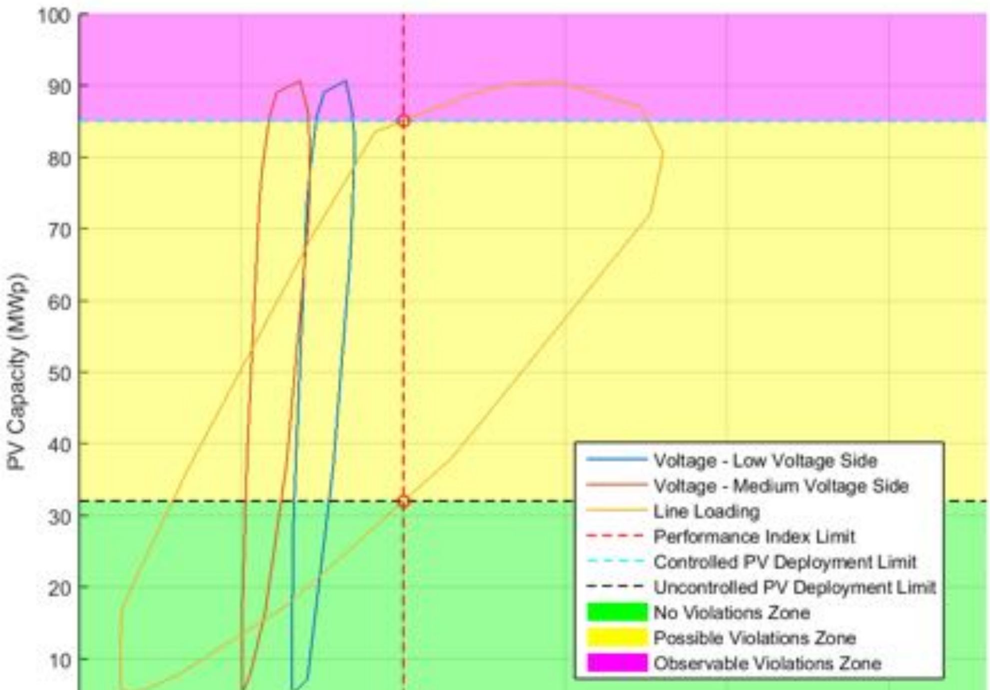


**Figure 61.** Normalized performance index parameters - Power Factor cosφ(P).

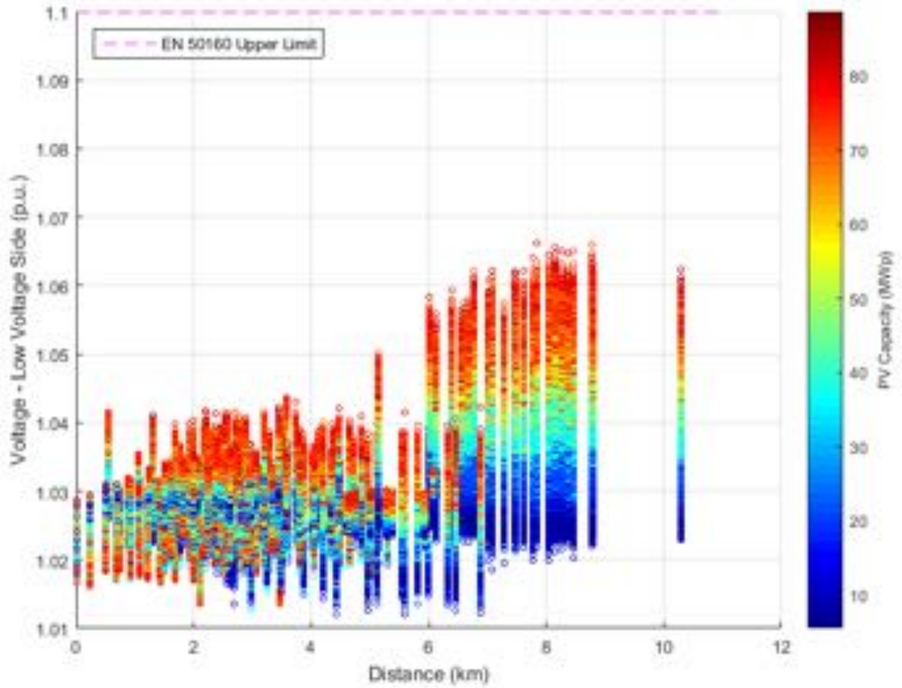


**Figure 62.** Voltage at low voltage side against distance from transmission substation - Power Factor cosφ(P).

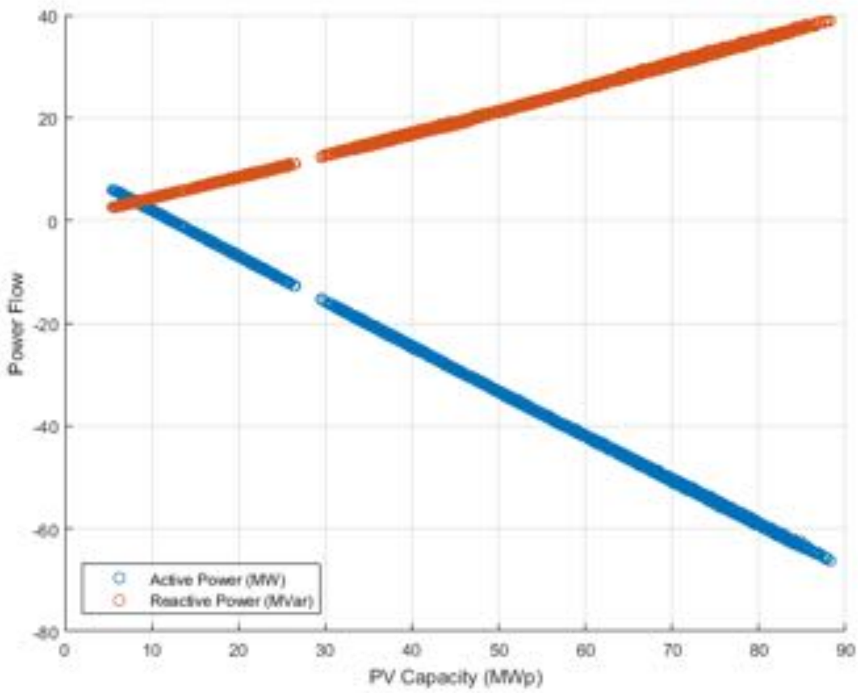


**Figure 63.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor cosφ(P).

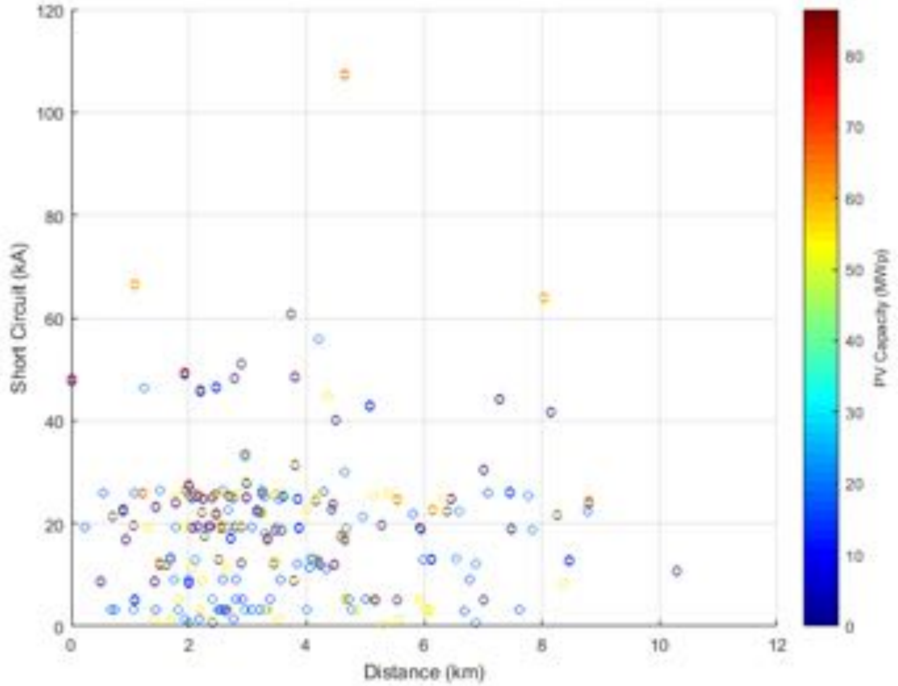


**Figure 64.** Short circuit current against distance - Power Factor cosφ(P).

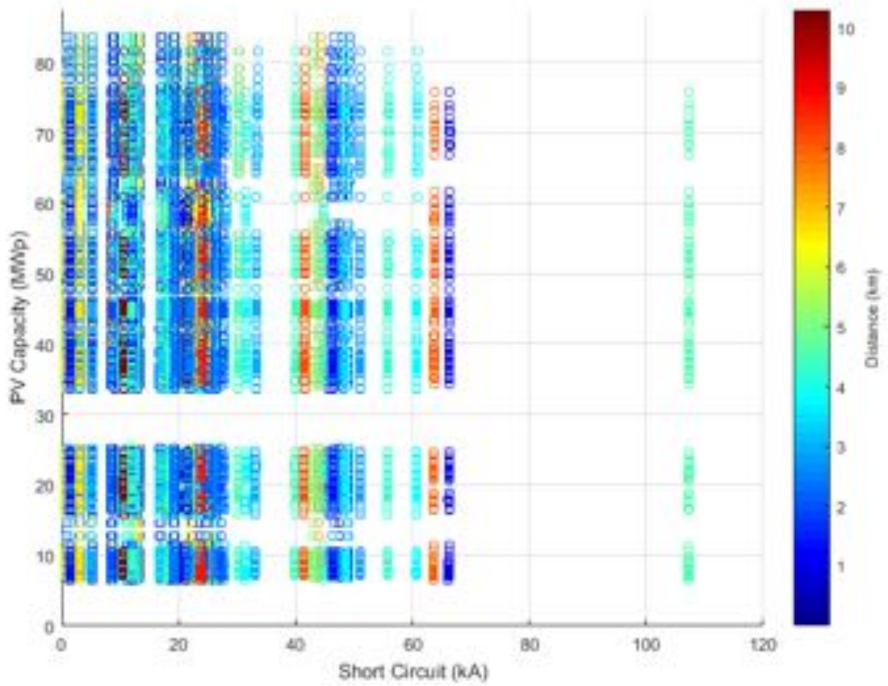


**Figure 65.** PV Capacity against short circuit current - Power Factor cosφ(P).

### A1.3.4 Summary – Monte Carlo Simulation

The results of the Monte Carlo simulations are summarized in the following two tables:

**Table 16.** Categorization of violations into zones.

| Scenario | No Violations Zone (MWp) | Possible Violations Zone (MWp) | Observable Violations Zone (MWp) |
|---|---|---|---|
| **Unity Power Factor** | below 32.7 | 32.7 – 85.6 | above 85.6 |
| **Power Factor equal to 0.95** | below 34.9 | 34.9 – 84.3 | above 84.3 |
| **Power Factor cosφ(P)** | below 32.0 | 32.0 – 85.1 | above 85.1 |

**Table 17.** Uncontrolled/Controlled PV Deployment Limit.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| **Unity Power Factor** | 33.4 | 91.1 | above 92.5 | above 92.5 | 32.7 | 85.6 |
| **Power Factor equal to 0.95** | above 90.9 | above 90.9 | above 90.9 | above 90.9 | 34.9 | 84.3 |
| **Power Factor cosφ(P)** | above 90.7 | above 90.7 | above 90.7 | above 90.7 | 32 | 85.1 |

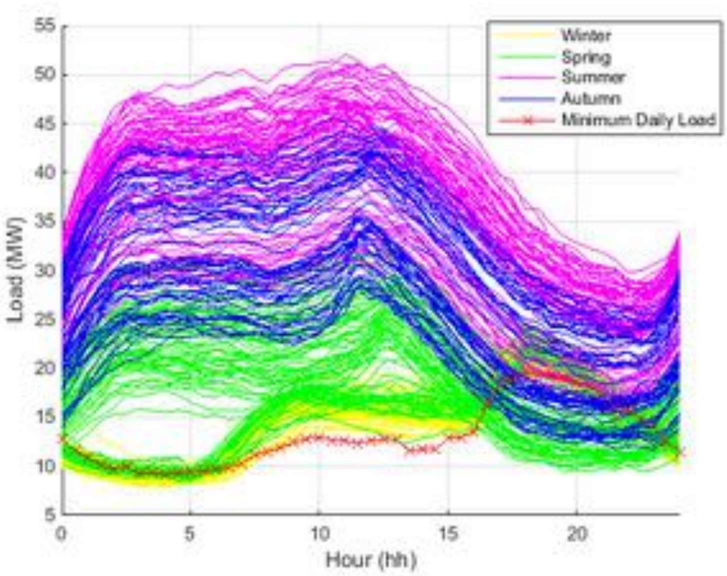


**Figure 66.** Hadjipasxalis S/S - Minimum daily load

# Appendix B

# B. Athienou s/s - Executive Summary

The results of the PV hosting capacity for Athienou substation with two 16 MVA transmission transformers (with a total distribution transformer capacity of 24.511 MVA), 4 feeders, 138 distribution substations/transformers/busbars and 255 distribution lines either underground or overhead located in Larnaca district area, are presented and analysed in this Appendix. For this PV hosting capacity assessment, it was assumed that the inverter of PV systems is oversized by 10% (as imposed by newly formulated regulations).

## B.1 Results

### B1.1 Maximum Installed PV Capacity scenario

#### B1.1.1 Unity Power Factor Operation

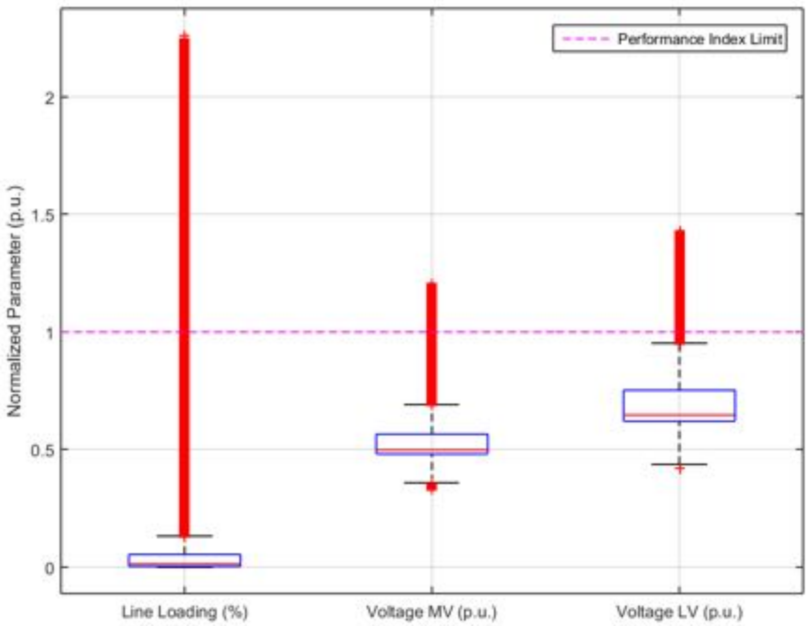


**Figure 67.** Performance Index parameters normalized to their limit – Unity Power Factor.

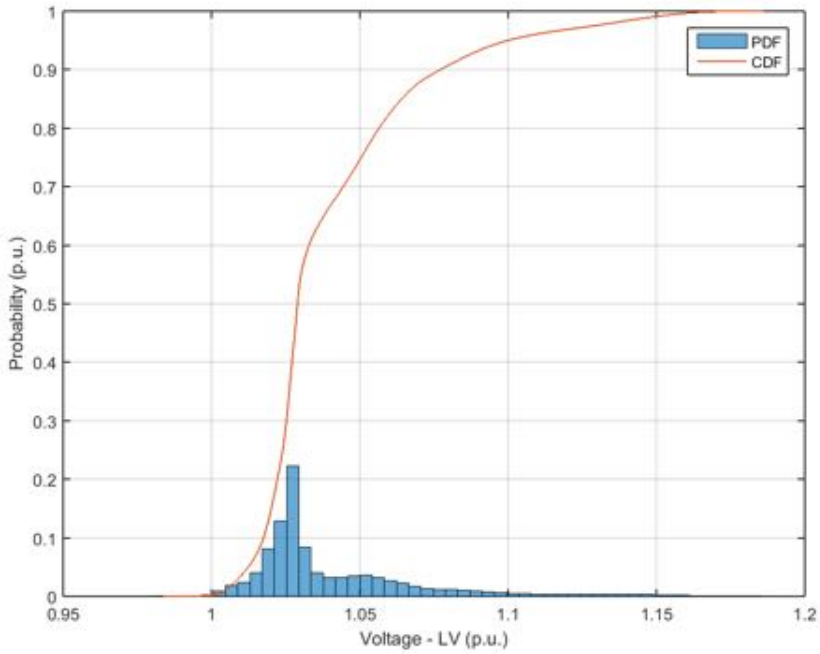


**Figure 68.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity power factor.

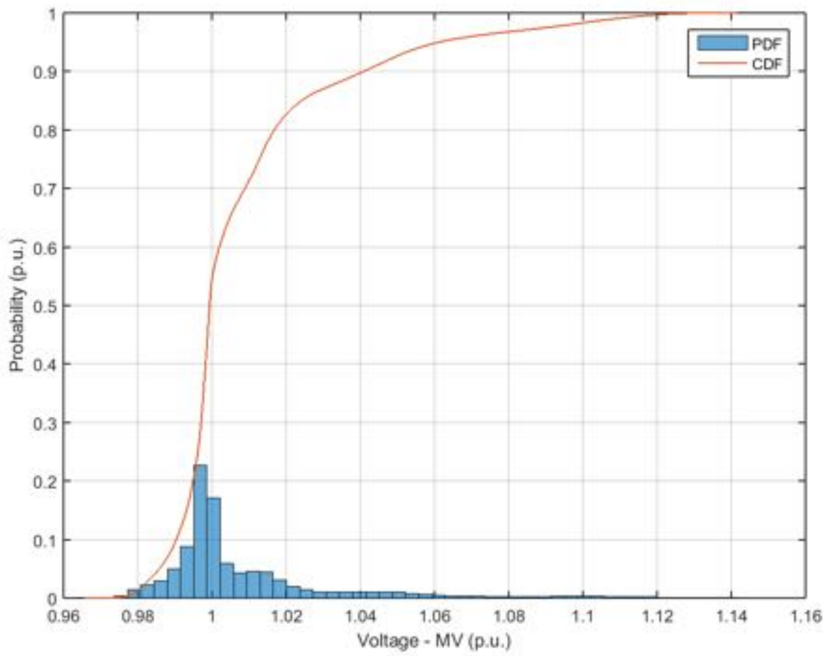


**Figure 69.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Unity power factor.

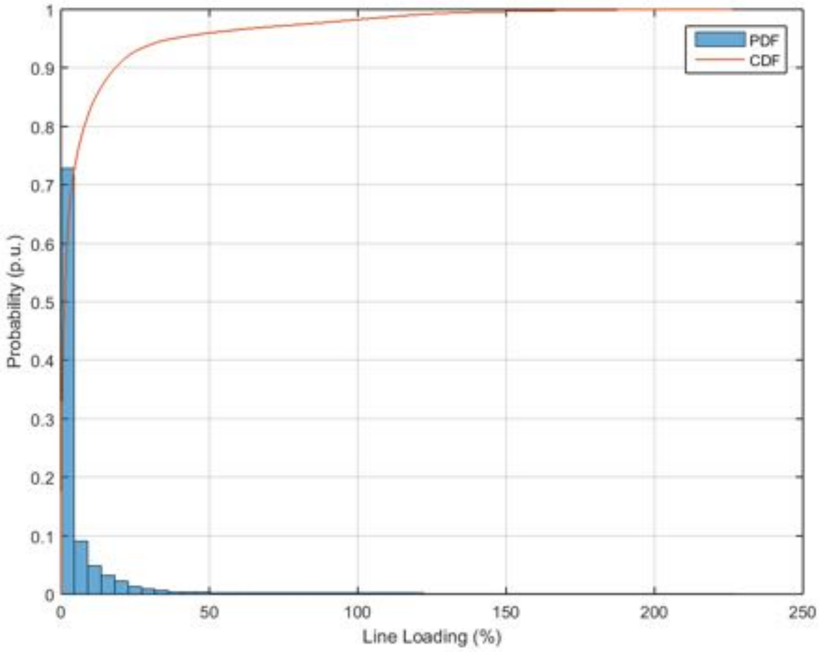


**Figure 70.** Probability distribution and cumulative probability distribution – Line Loading – Unity power factor.

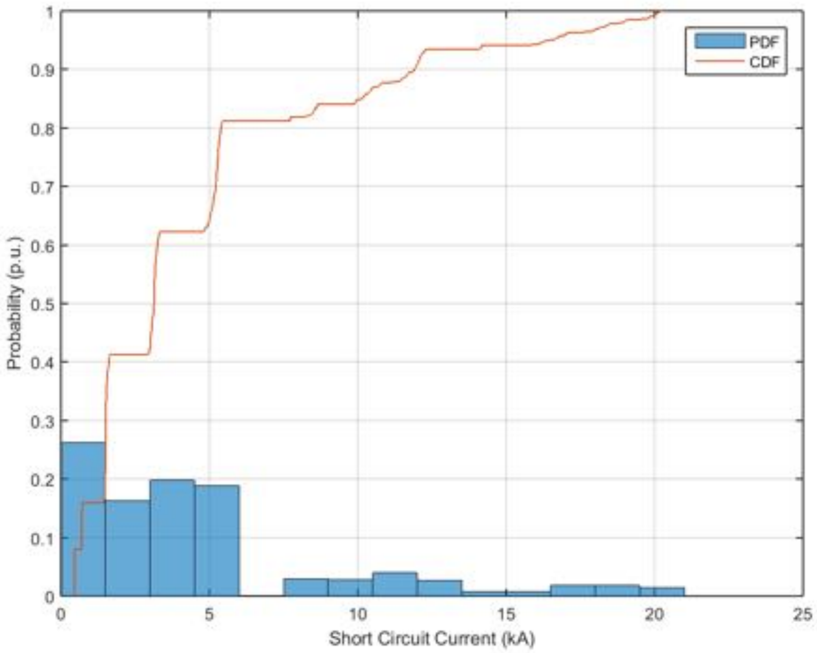


**Figure 71.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity power factor.

### B1.1.2 Power Factor equal to 0.95

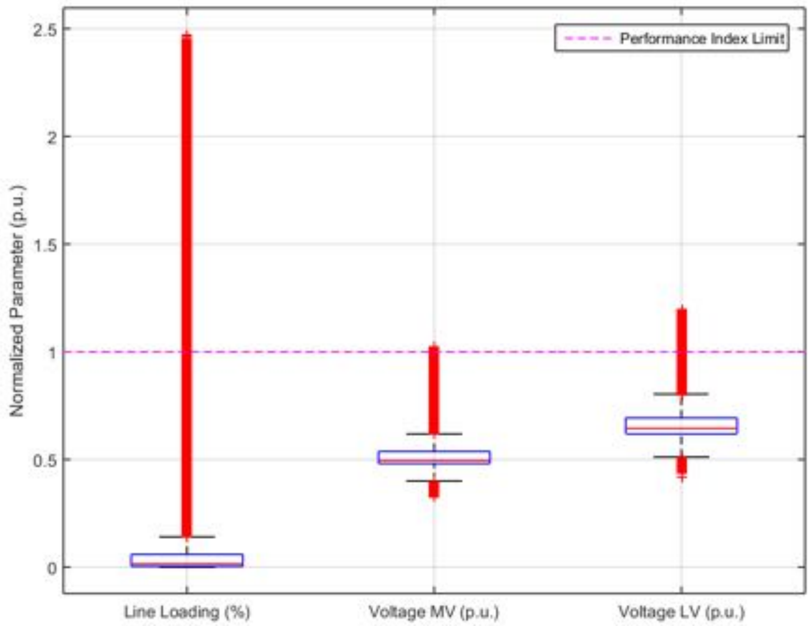


**Figure 72.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

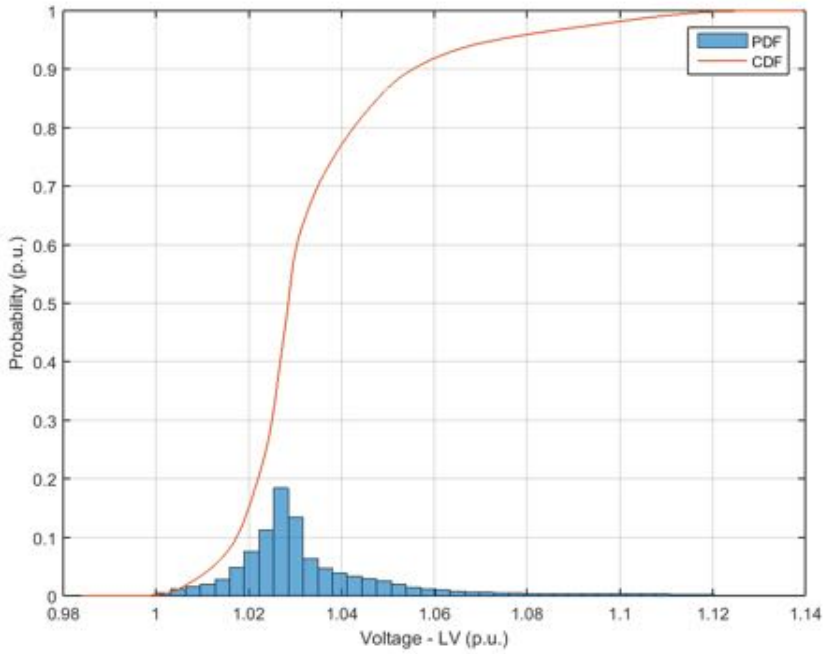


**Figure 73.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

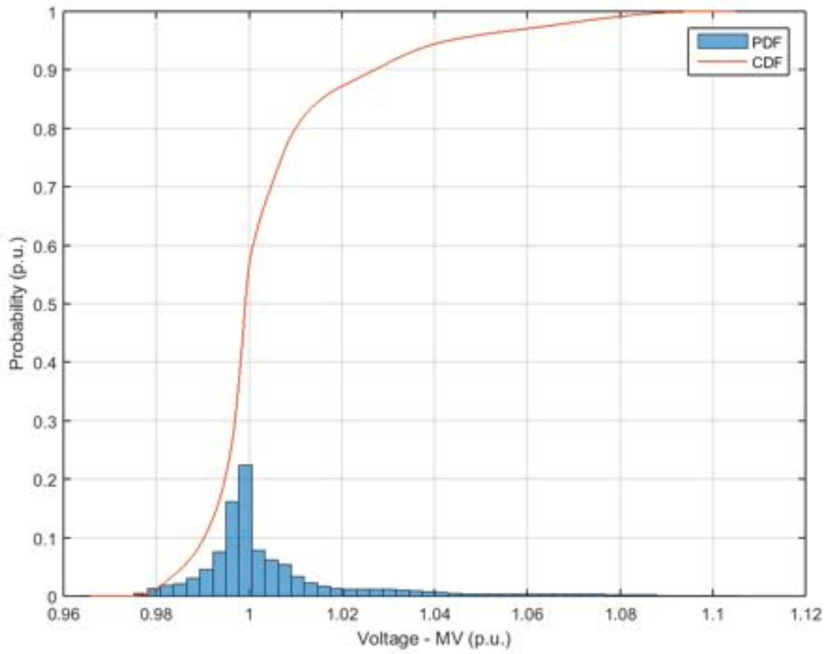


**Figure 74.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor equal to 0.95.

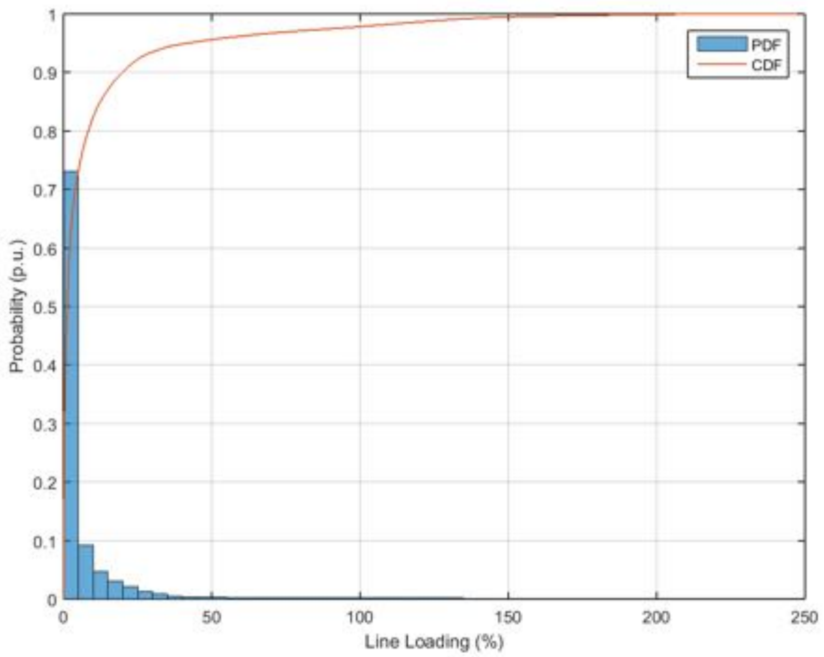


**Figure 75.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

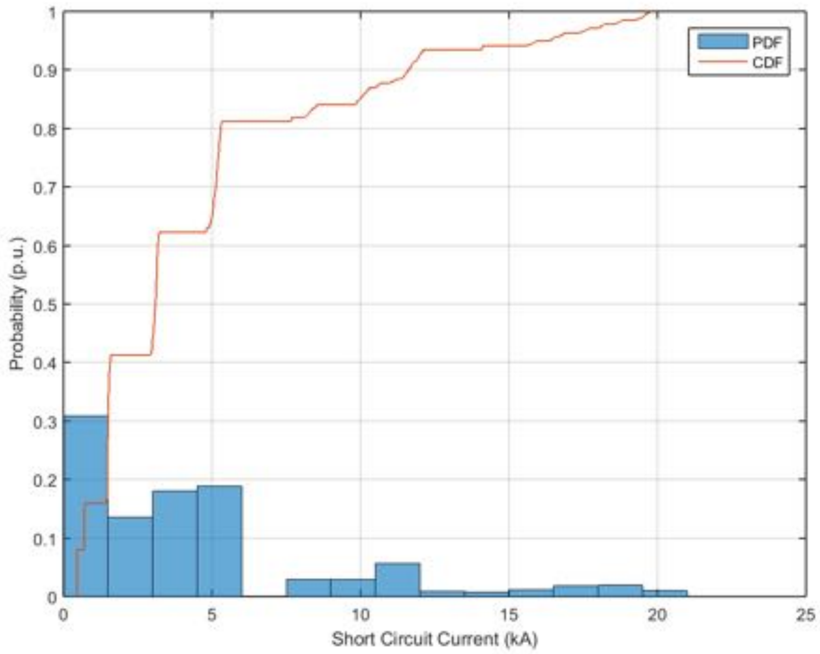


**Figure 76.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### B1.1.3 Power Factor cosφ(P)

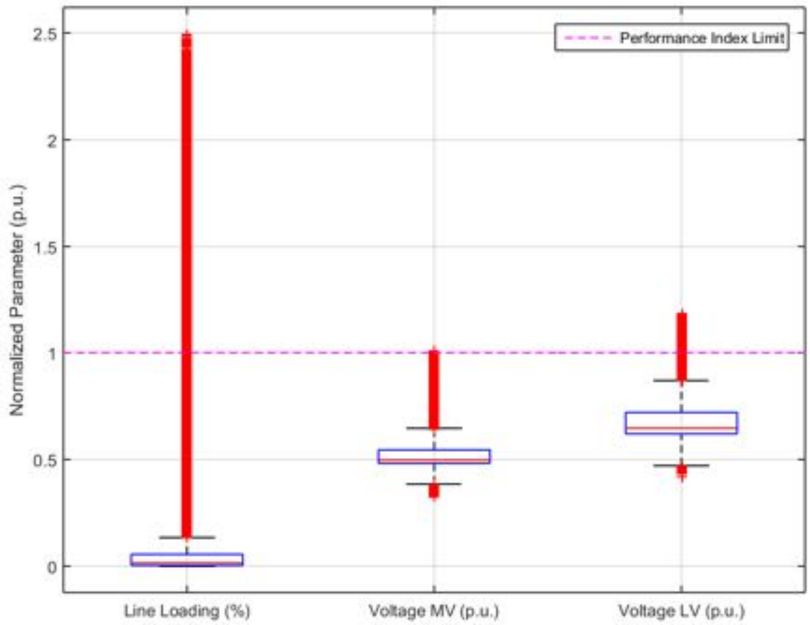


**Figure 77.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

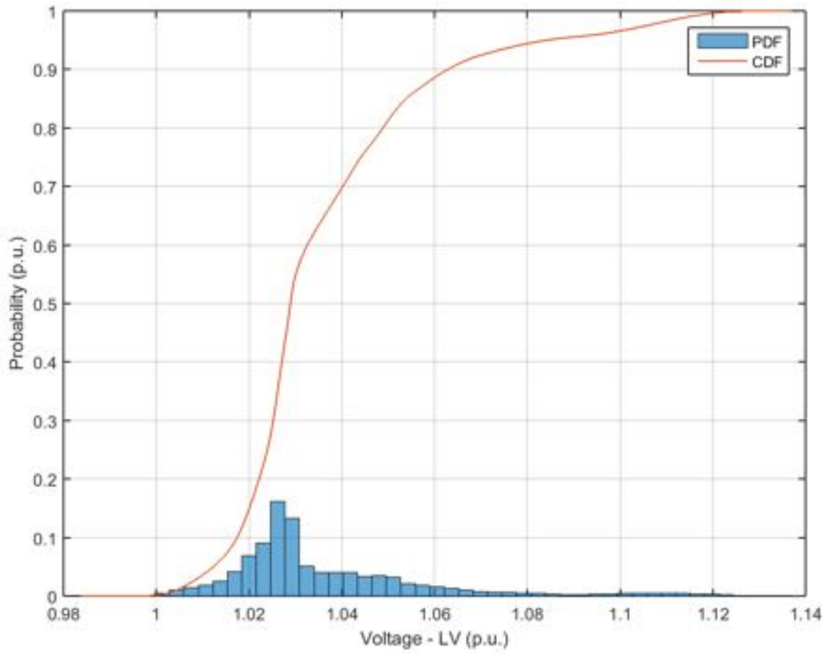


**Figure 78.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

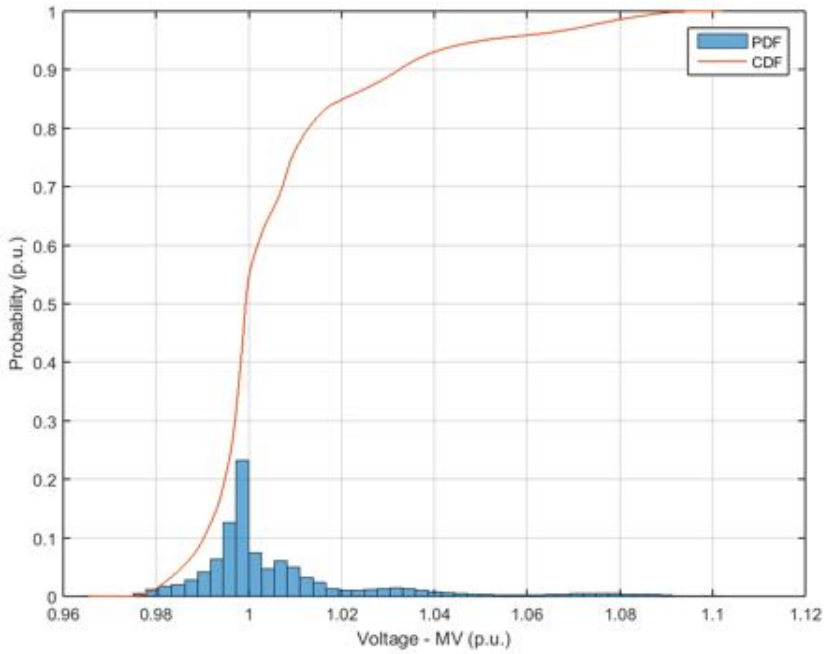


**Figure 79.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor cosφ(P).

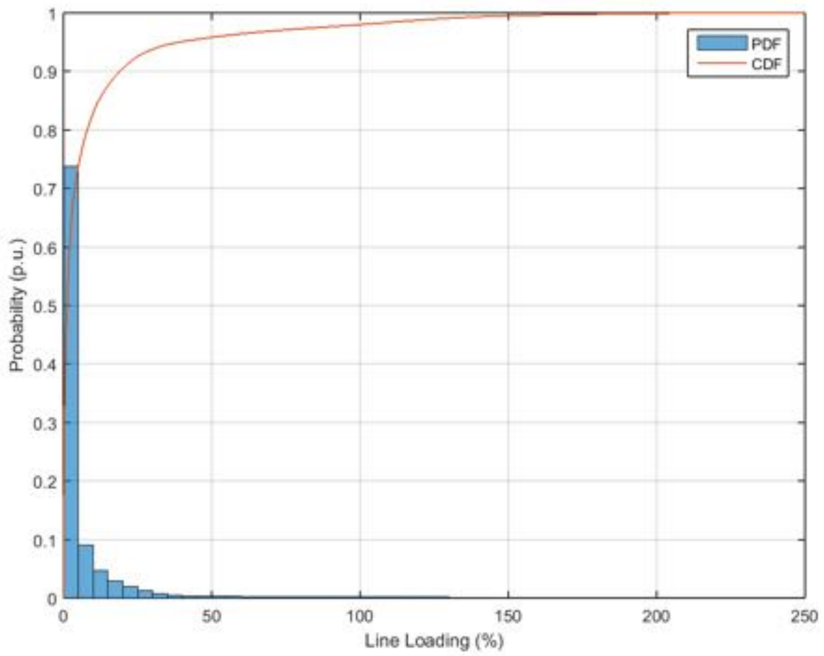


**Figure 80.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

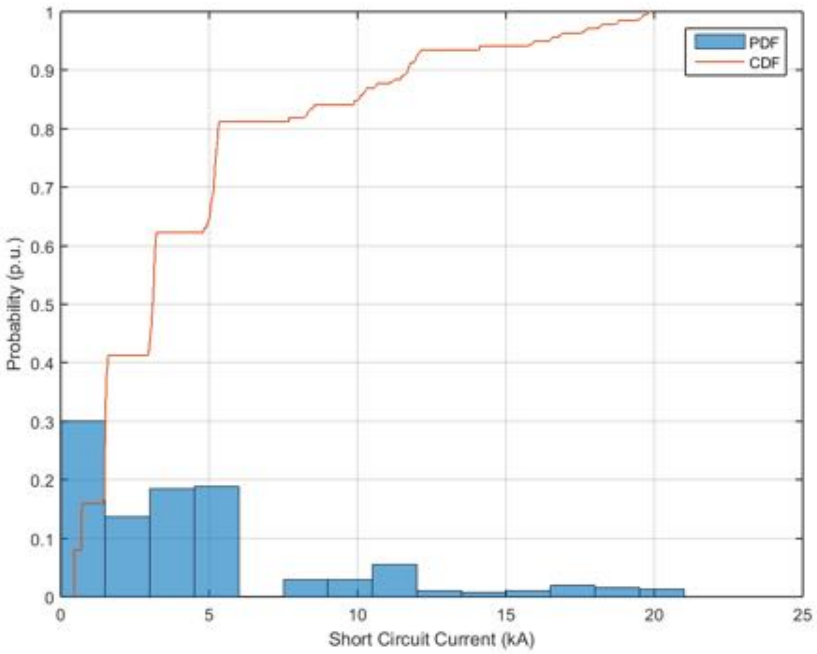


**Figure 81.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### B1.1.4 Summary and Discussion – Maximum Installed PV Capacity scenario

**Table 18.** Statistical analysis of PI parameters - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.420 | 0.420 | 0.419 |
| | 25th quantile | 0.620 | 0.619 | 0.620 |
| | Median | 0.645 | 0.643 | 0.645 |
| | Average | 0.701 | 0.668 | 0.682 |
| | Standard Deviation | 0.020 | 0.009 | 0.012 |
| | 75th quantile | 0.752 | 0.692 | 0.721 |
| | 95th quantile | 1.000 | 0.867 | 0.921 |
| | 99th quantile | 1.242 | 1.041 | 1.074 |
| | Maximum | 1.430 | 1.197 | 1.184 |
| **Number of elements of which the limit is violated** | | 50 out of 138 | 22 out of 138 | 23 out of 138 |
| **Voltage – Medium Voltage Side** | Minimum | 0.328 | 0.328 | 0.328 |
| | 25th quantile | 0.481 | 0.480 | 0.481 |
| | Median | 0.497 | 0.496 | 0.497 |
| | Average | 0.543 | 0.523 | 0.531 |
| | Standard Deviation | 0.015 | 0.008 | 0.010 |
| | 75th quantile | 0.564 | 0.535 | 0.546 |
| | 95th quantile | 0.806 | 0.714 | 0.753 |
| | 99th quantile | 1.043 | 0.892 | 0.916 |
| | Maximum | 1.207 | 1.024 | 1.011 |
| **Number of elements of which the limit is violated** | | 22 out of 138 | 16 out of 138 | 5 out of 138 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.002 | 0.002 | 0.002 |
| | Median | 0.012 | 0.013 | 0.012 |
| | Average | 0.080 | 0.087 | 0.083 |
| | Standard Deviation | 0.044 | 0.053 | 0.050 |
| | 75th quantile | 0.054 | 0.058 | 0.055 |
| | 95th quantile | 0.376 | 0.418 | 0.391 |
| | 99th quantile | 1.174 | 1.296 | 1.265 |
| | Maximum | 2.262 | 2.473 | 2.496 |
| | CDF-100% loading | 98.26% | 97.82% | 98.01% |
| **Number of elements of which the limit is violated** | | 30 out of 255 | 30 out of 255 | 30 out of 255 |

**Table 19.** Statistical analysis of Short Circuit Values - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 0.448 | 0.447 | 0.449 |
| | 25th quantile | 1.498 | 1.488 | 1.490 |
| | Median | 3.070 | 3.091 | 3.096 |
| | Average | 4.416 | 4.509 | 4.524 |
| | Standard Deviation | 4.363 | 4.565 | 4.583 |
| | 75th quantile | 5.138 | 5.209 | 5.222 |
| | 95th quantile | 15.531 | 16.367 | 16.466 |
| | 99th quantile | 18.245 | 19.494 | 19.574 |
| | Maximum | 20.144 | 19.783 | 19.835 |

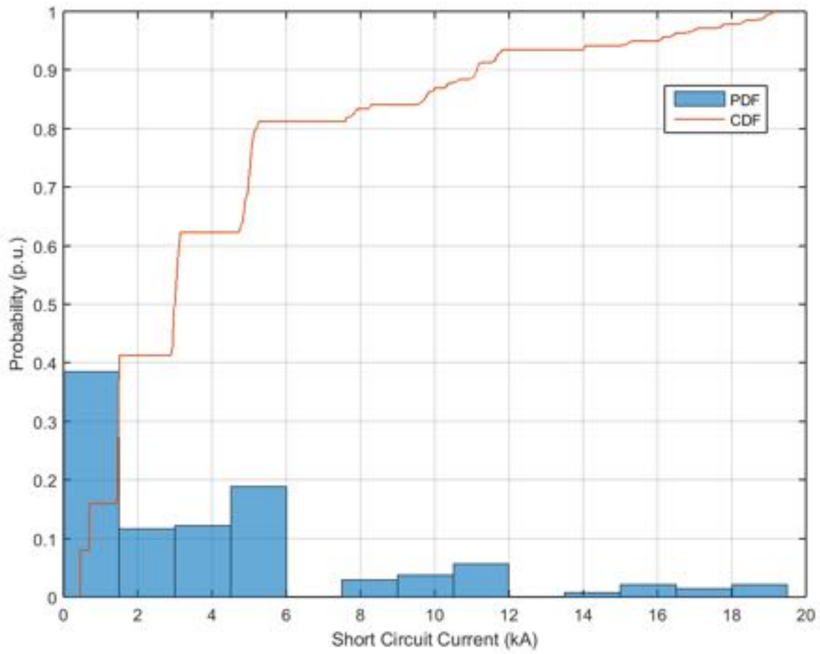


**Figure 82.** Probability distribution and cumulative probability distribution – Short Circuit Current – No PV.

## B1.2 Maximum PV Capacity per Distribution Substation

### B1.2.1 Unity Power Factor Scheme

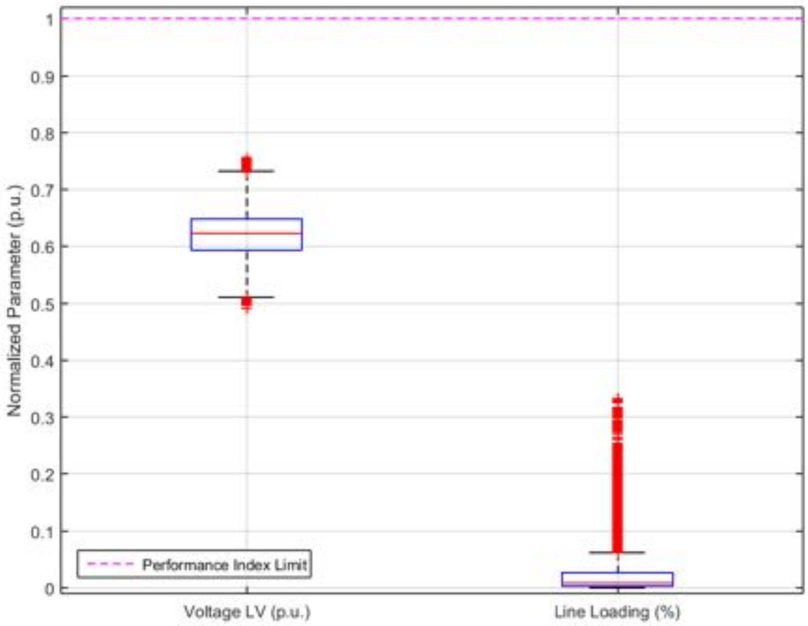


**Figure 83.** Performance Index parameters normalized to their limit – Unity Power Factor.

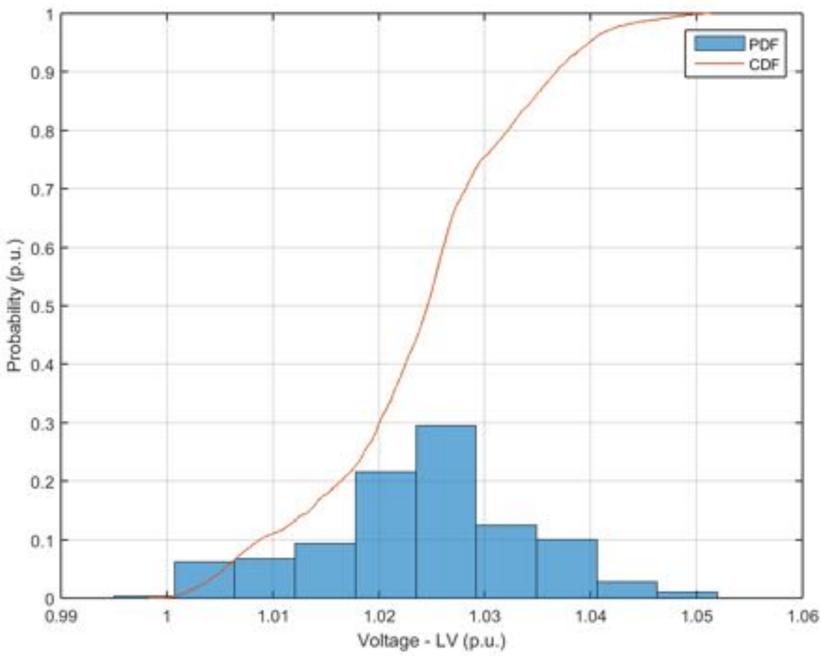


**Figure 84.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity Power Factor.

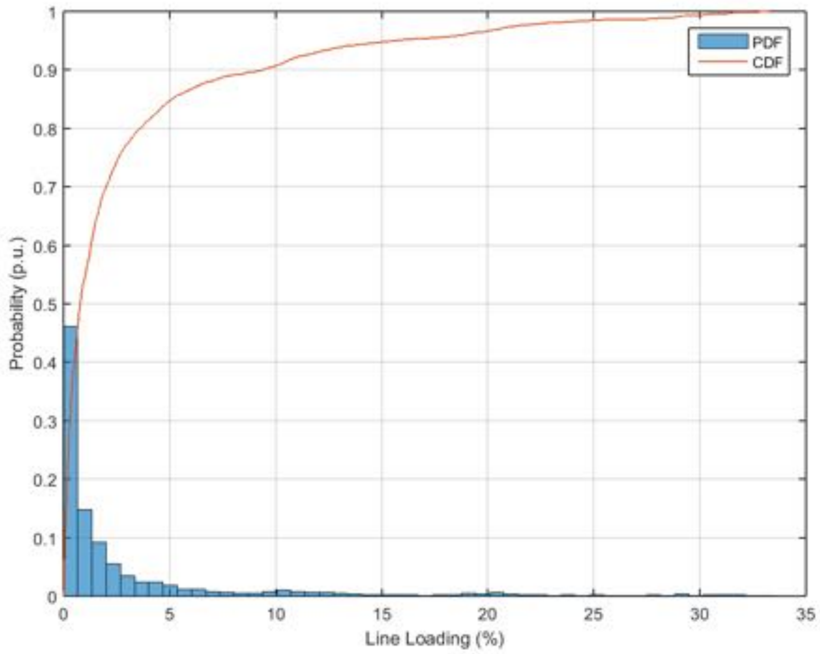


**Figure 85.** Probability distribution and cumulative probability distribution – Line Loading – Unity Power Factor.

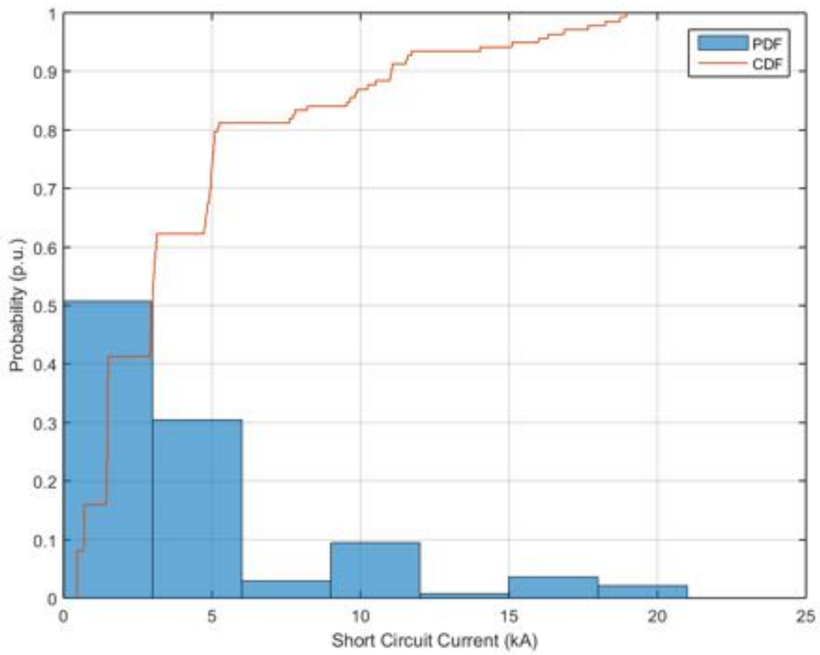


**Figure 86.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity Power Factor.

### B1.2.2 Power Factor equal to 0.95

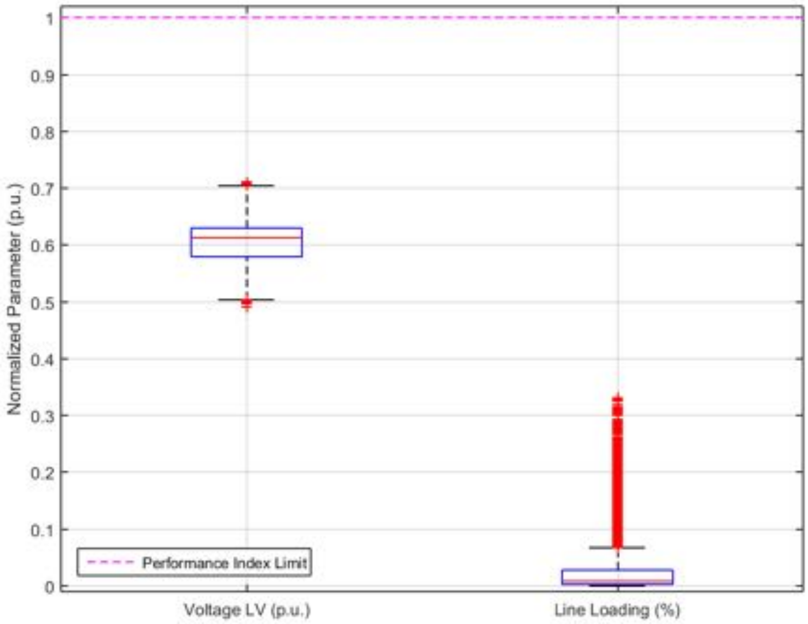


**Figure 87.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

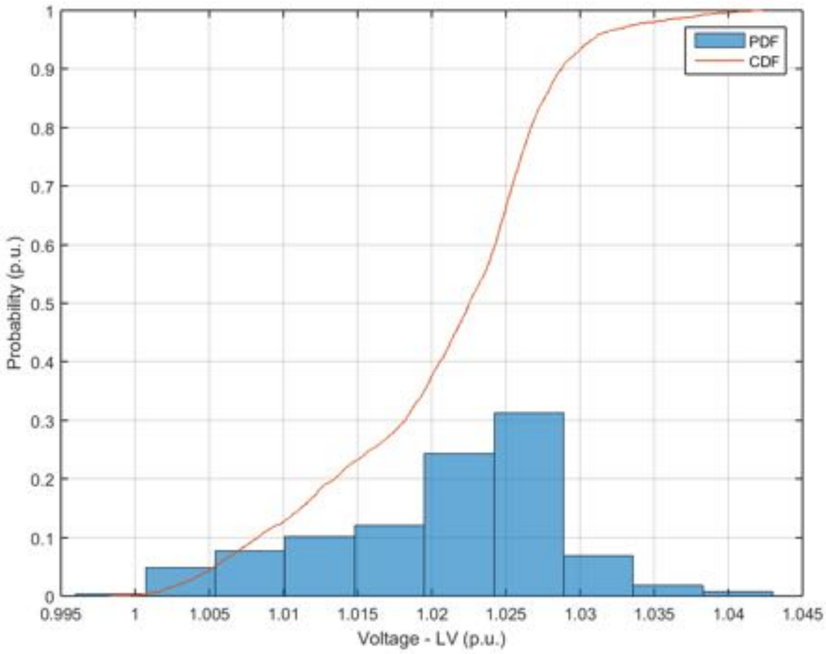


**Figure 88.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

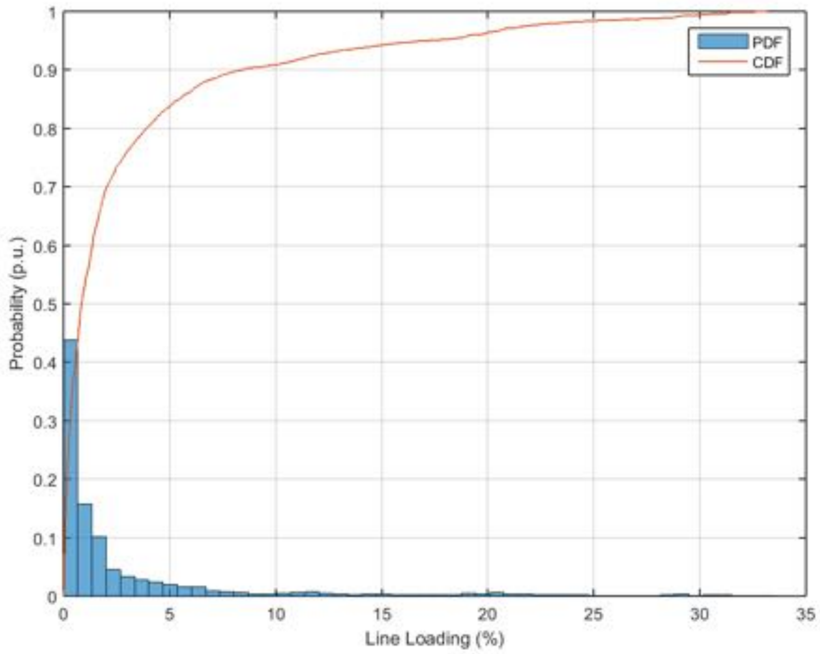


**Figure 89.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

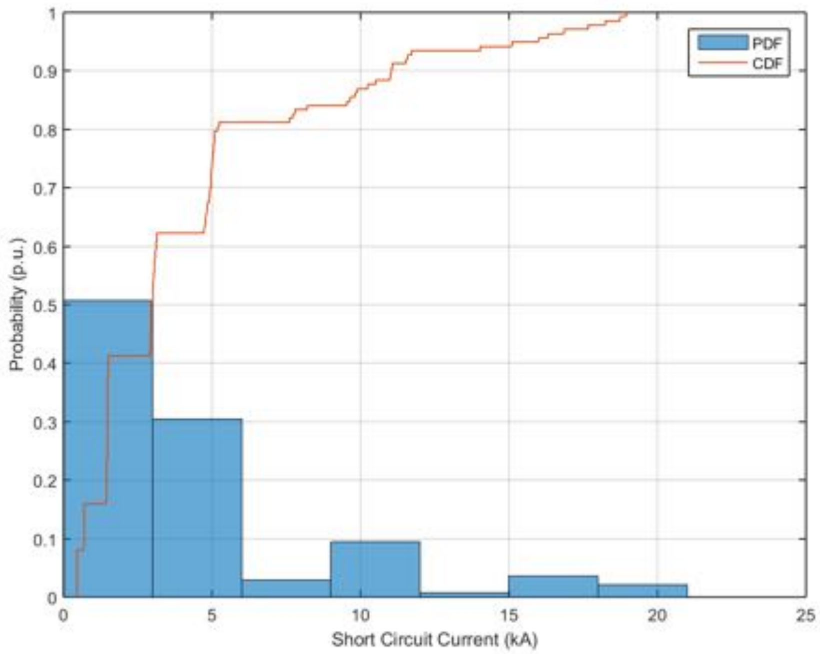


**Figure 90.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### B1.2.3 Power Factor cosφ(P)

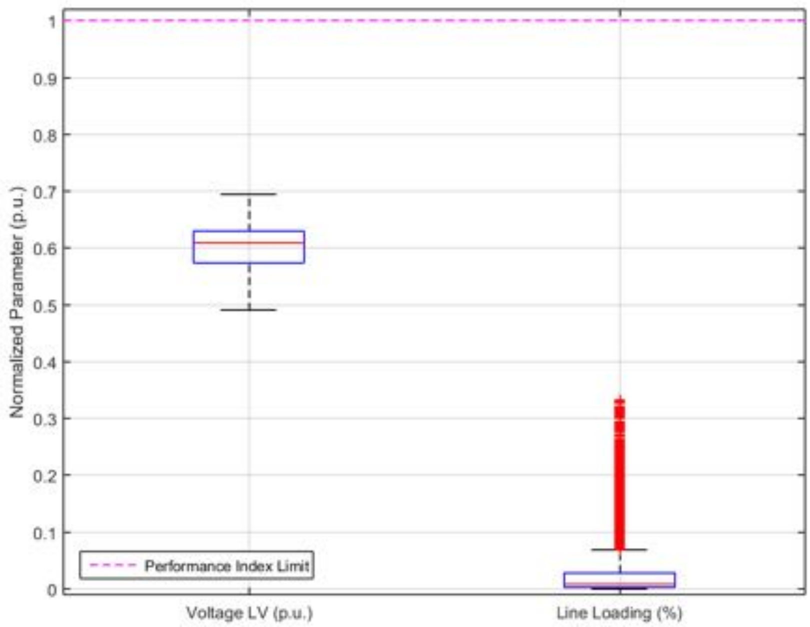


**Figure 91.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

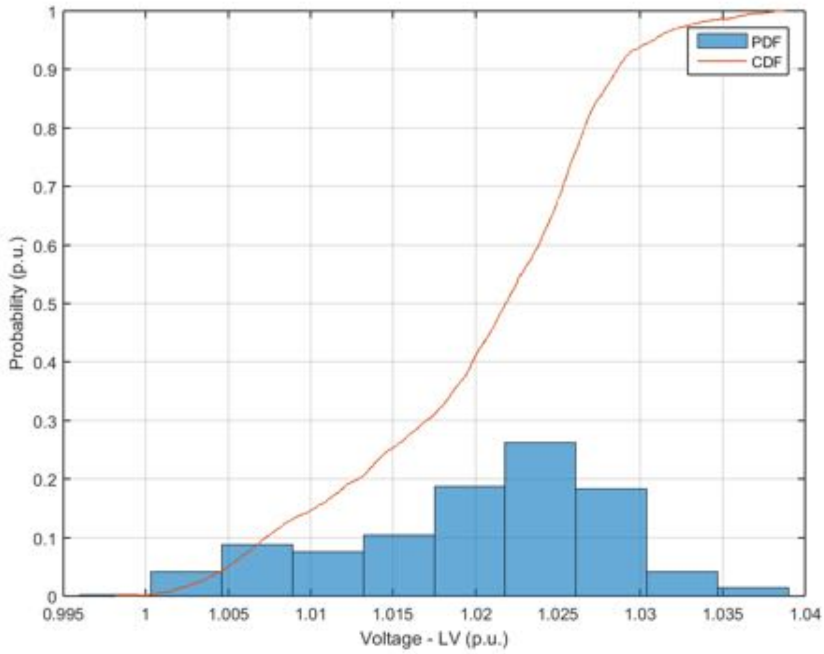


**Figure 92.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

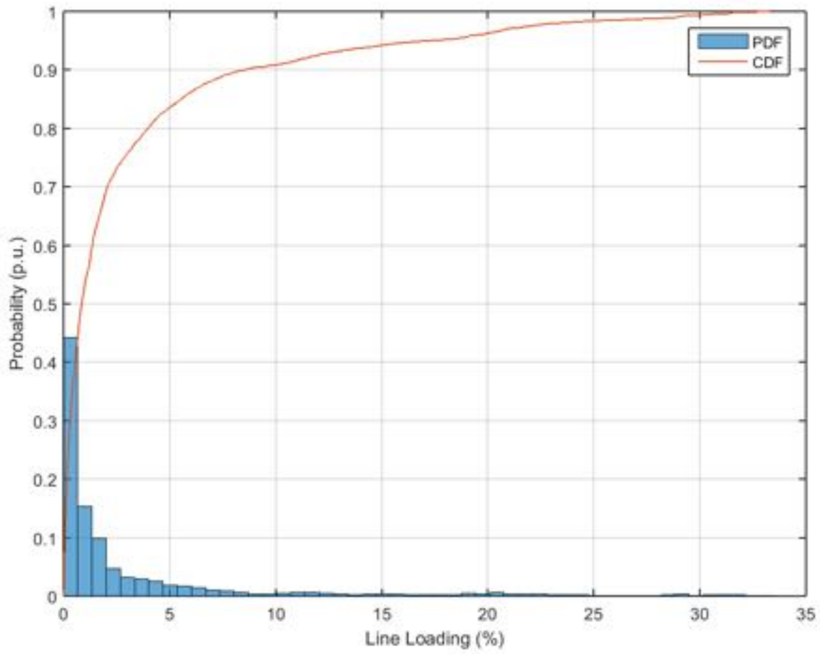


**Figure 93.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

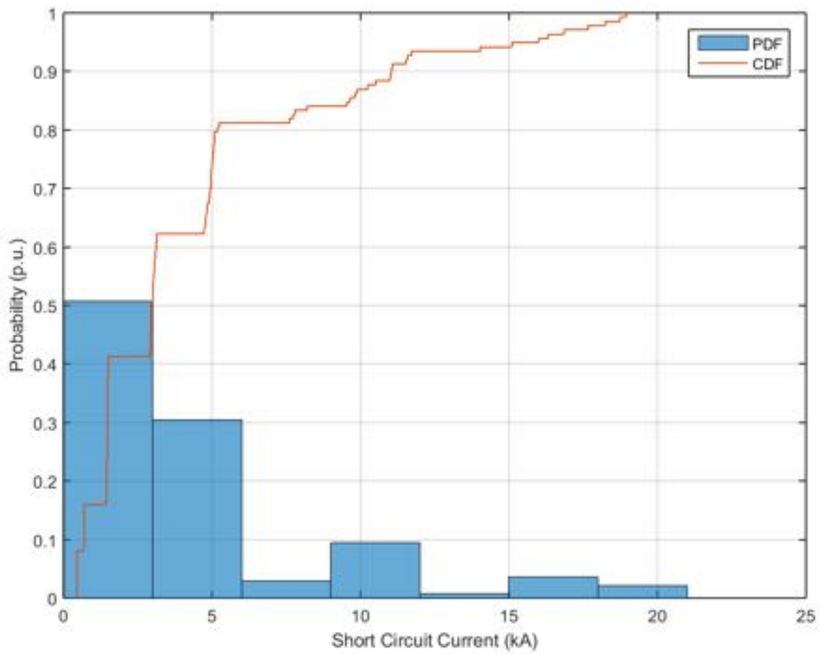


**Figure 94.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### B1.2.4 Summary and Discussion–Maximum PV Capacity per Distribution Substation

**Table 20.** Statistical analysis of PI parameters - Maximum PV Capacity per Distribution Substation.

| | | Scenario | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.492 | 0.492 | 0.491 |
| | 25th quantile | 0.593 | 0.580 | 0.574 |
| | Median | 0.623 | 0.613 | 0.609 |
| | Average | 0.620 | 0.604 | 0.601 |
| | Standard Deviation | 0.002 | 0.002 | 0.002 |
| | 75th quantile | 0.649 | 0.630 | 0.630 |
| | 95th quantile | 0.699 | 0.654 | 0.654 |
| | 99th quantile | 0.732 | 0.689 | 0.680 |
| | Maximum | 0.757 | 0.711 | 0.694 |
| **Number of elements of which the limit is violated** | | 0 out of 138 | 0 out of 138 | 0 out of 138 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.002 | 0.002 | 0.002 |
| | Median | 0.008 | 0.008 | 0.009 |
| | Average | 0.030 | 0.031 | 0.031 |
| | Standard Deviation | 0.003 | 0.003 | 0.003 |
| | 75th quantile | 0.026 | 0.028 | 0.029 |
| | 95th quantile | 0.157 | 0.172 | 0.173 |
| | 99th quantile | 0.289 | 0.288 | 0.289 |
| | Maximum | 0.332 | 0.332 | 0.333 |
| **Number of elements of which the limit is violated** | | 0 out of 255 | 0 out of 255 | 0 out of 255 |

**Table 21.** Statistical analysis of Short Circuit Values - Maximum PV Capacity per Distribution Substation.

| | | Scenario | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 0.444 | 0.444 | 0.444 |
| | 25th quantile | 1.466 | 1.466 | 1.466 |
| | Median | 2.967 | 2.967 | 2.967 |
| | Average | 4.363 | 4.363 | 4.363 |
| | Standard Deviation | 4.419 | 4.419 | 4.419 |
| | 75th quantile | 5.018 | 5.018 | 5.018 |
| | 95th quantile | 15.636 | 15.636 | 15.636 |
| | 99th quantile | 18.768 | 18.768 | 18.768 |
| | Maximum | 18.949 | 18.949 | 18.948 |

## B1.3 Assessing PV Capacity using Monte Carlo method

### B1.3.1 Unity Power Factor Operation

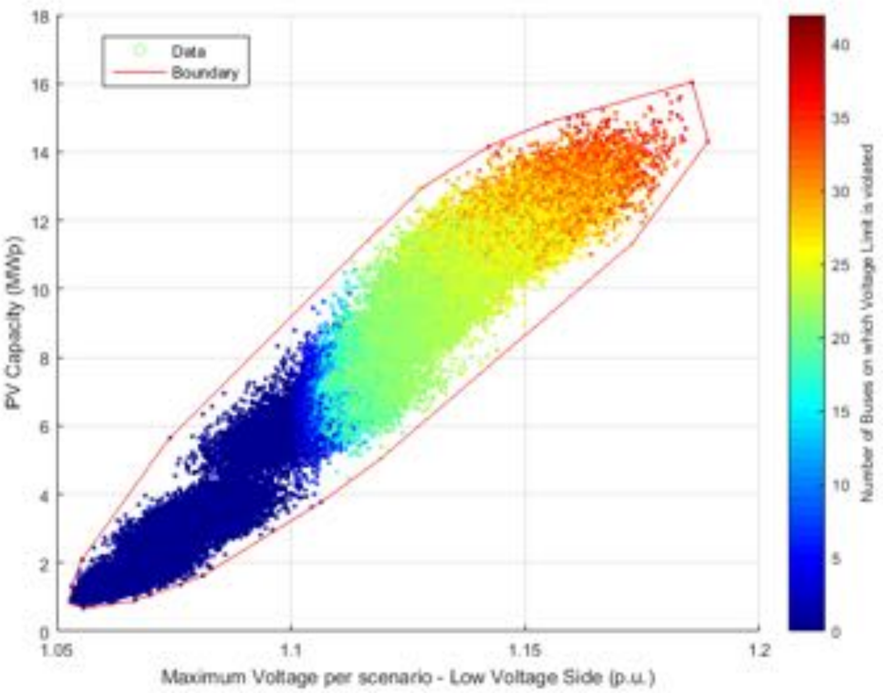


**Figure 95.** PV Capacity against Voltage – Low voltage side - Unity Power Factor.

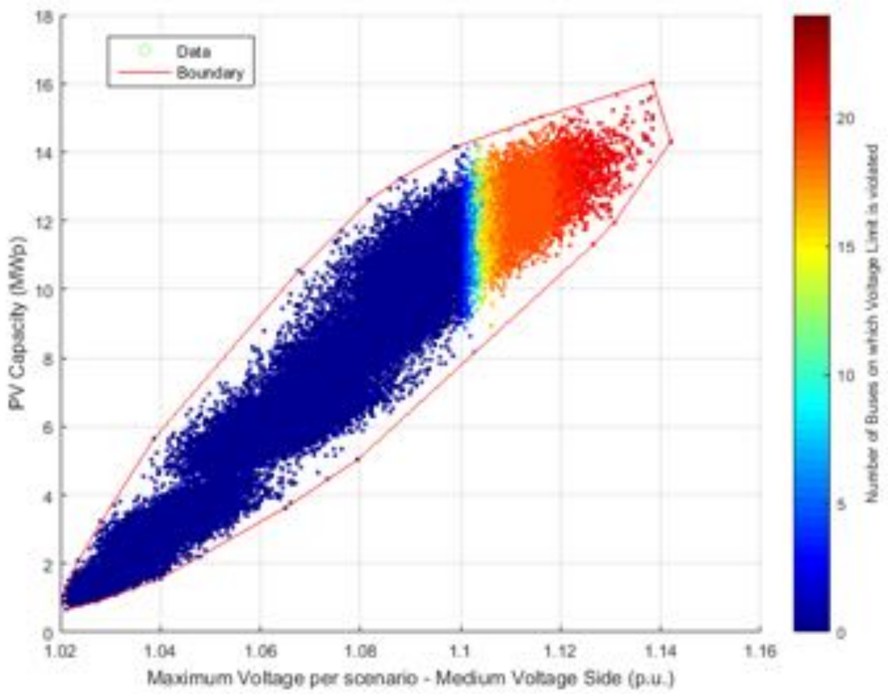


**Figure 96.** PV Capacity against Voltage – Medium voltage side - Unity Power Factor.

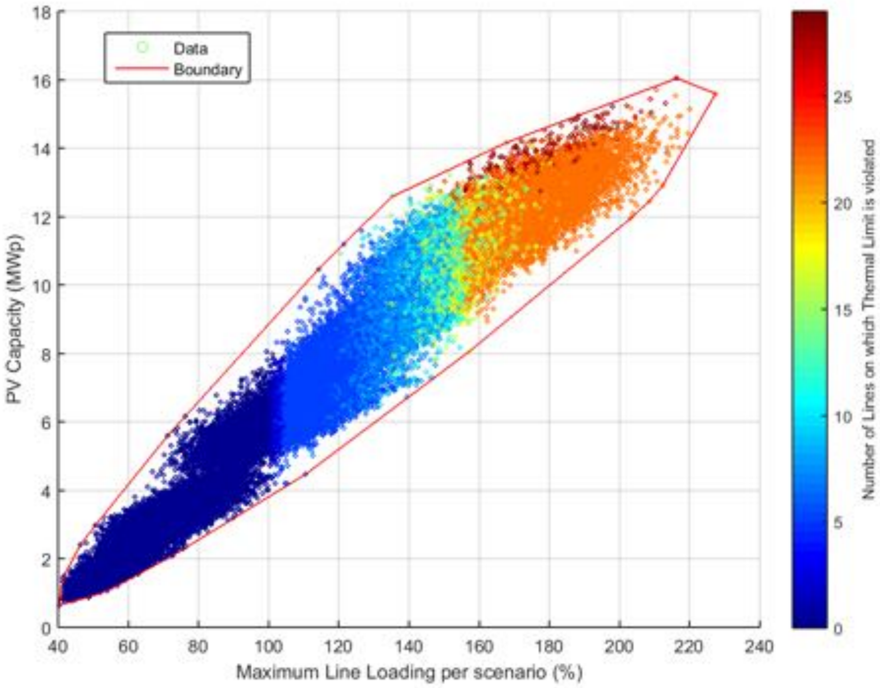


**Figure 97.** PV Capacity against Line Loading - Unity Power Factor.

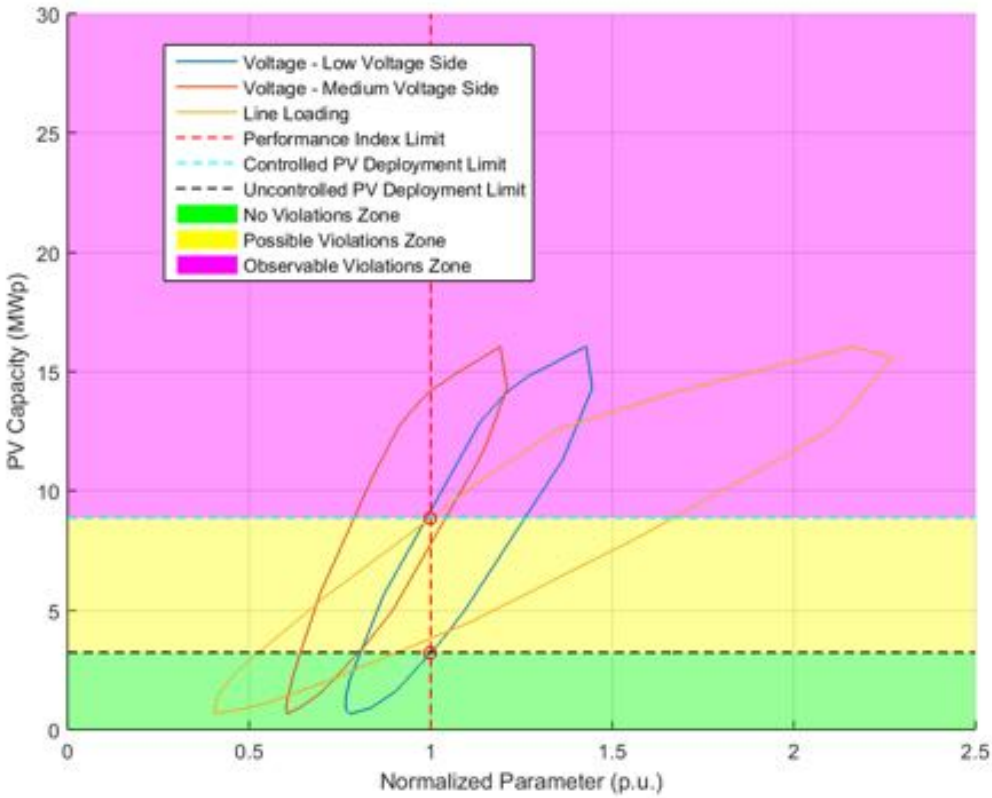


**Figure 98.** Normalized performance index parameters - Unity Power Factor.

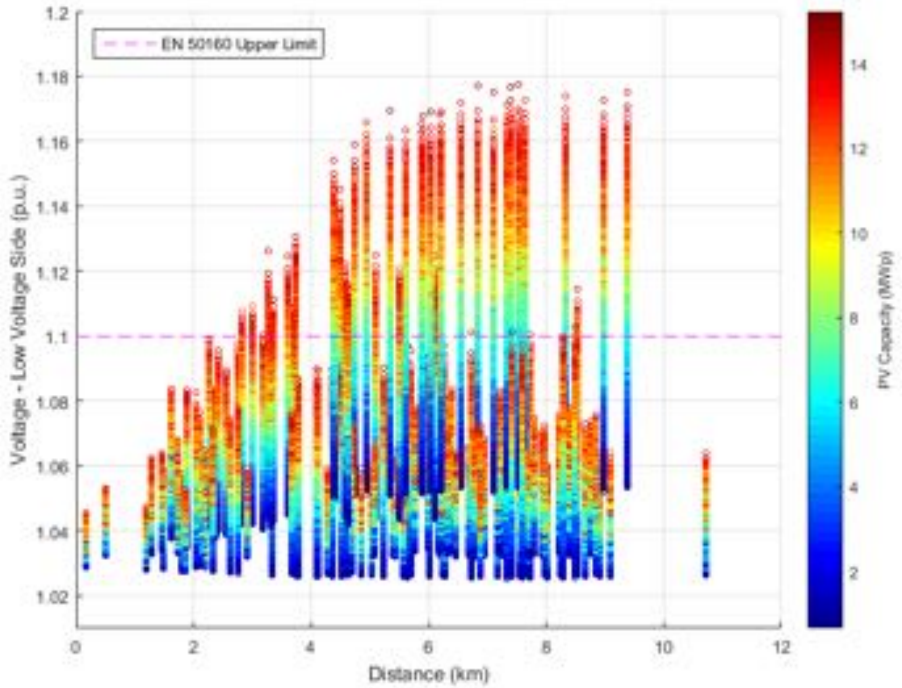


**Figure 99.** Voltage at low voltage side against distance from transmission substation - Unity Power Factor.

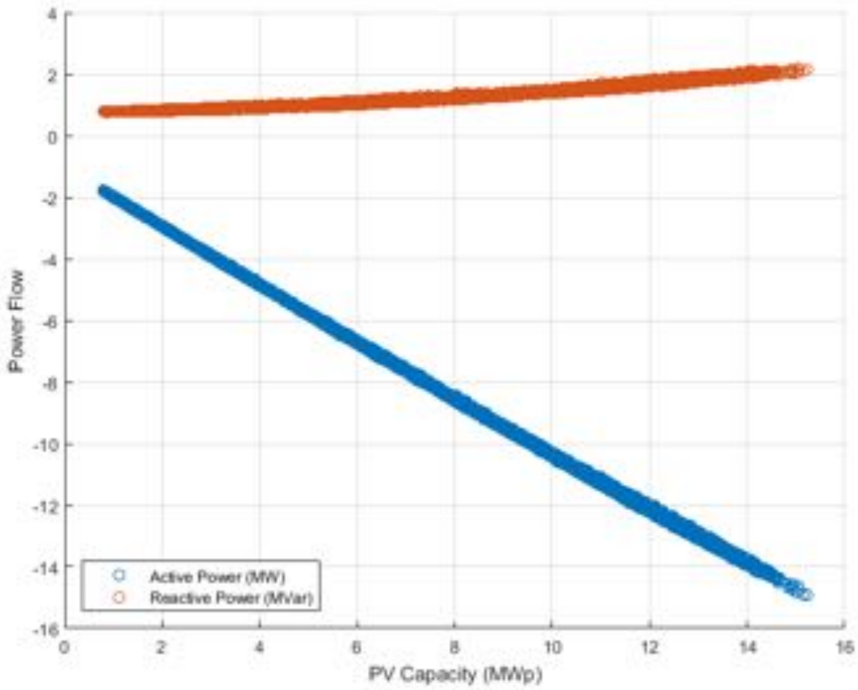


**Figure 100.** Power flow at PCC (connection of the reference substation with HV network) against PV capacity - Unity Power Factor (negative sign denotes reverse power flow).

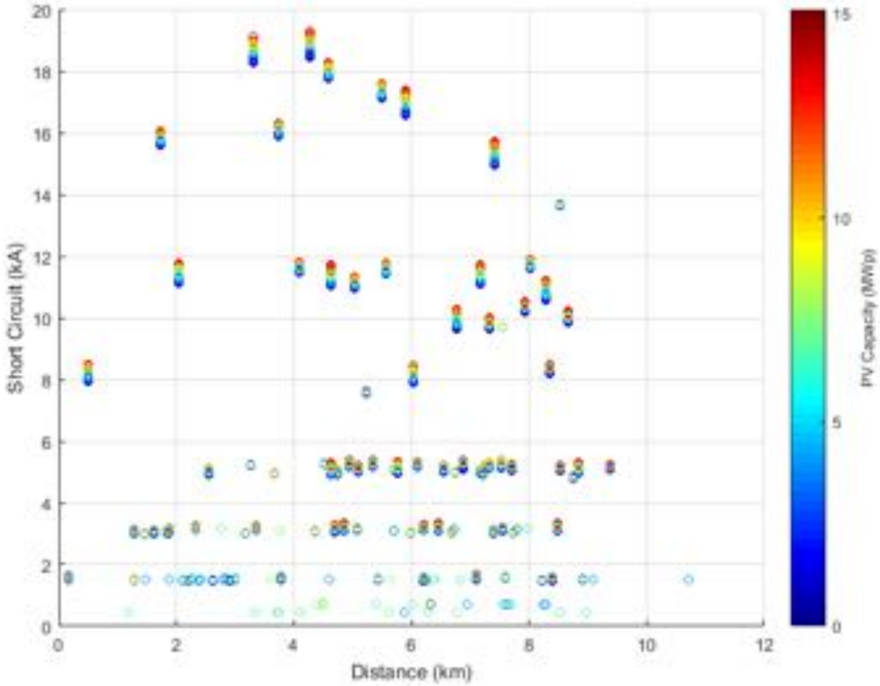


**Figure 101.** Short circuit current against distance - Unity Power Factor.

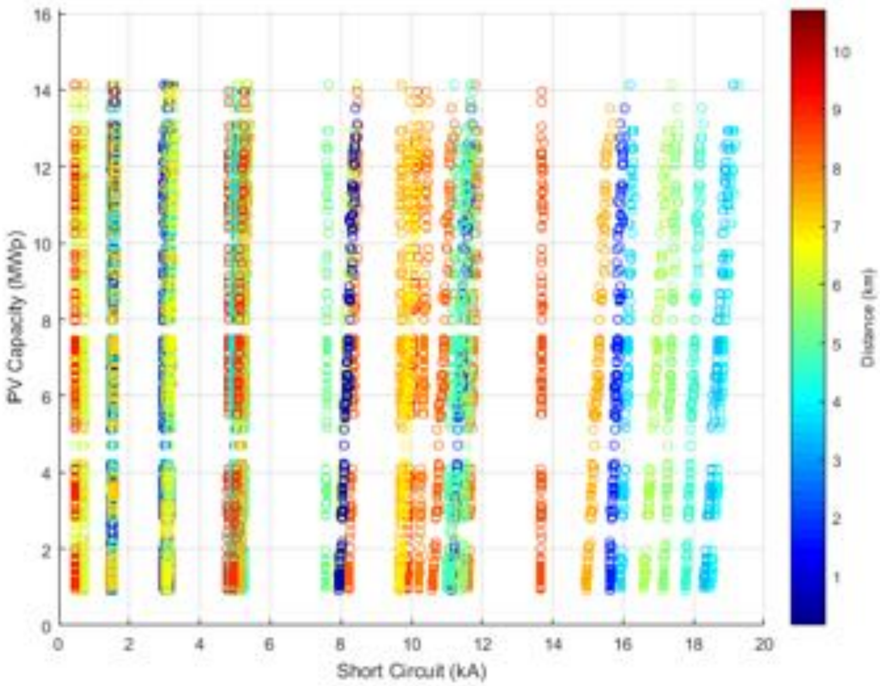


**Figure 102.** PV Capacity against Short circuit current - Unity Power Factor.

### B1.3.2 Power Factor equal to 0.95

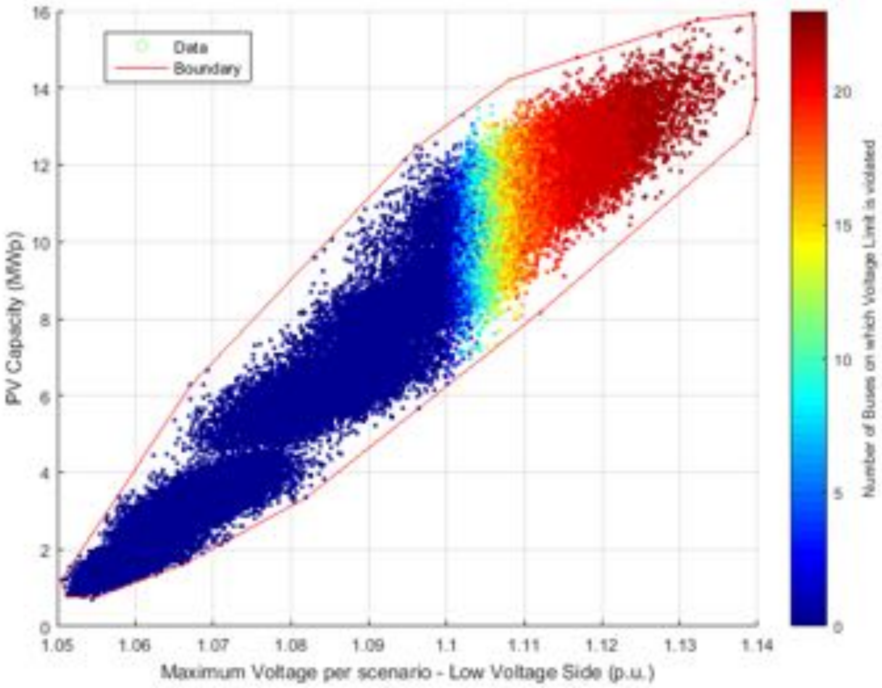


**Figure 103.** PV Capacity against Voltage – Low voltage side - Power Factor equal to 0.95.

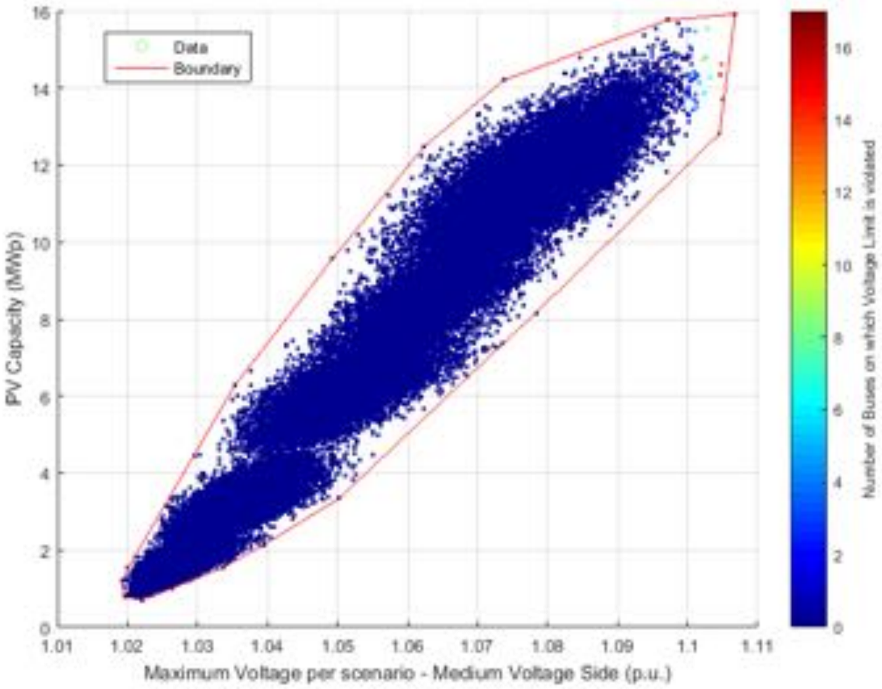


**Figure 104.** PV Capacity against Voltage – Medium voltage side - Power Factor equal to 0.95.

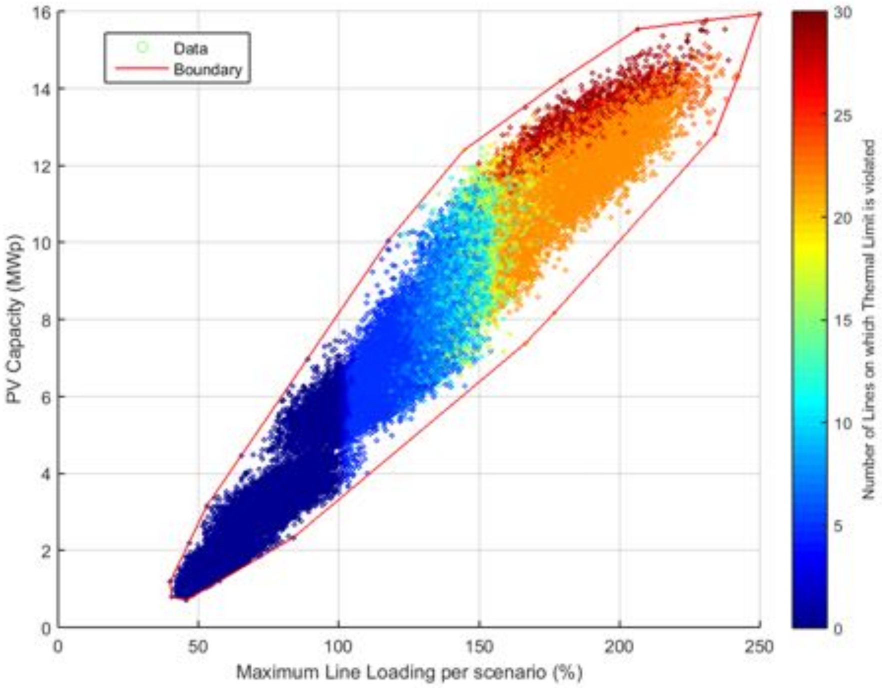


**Figure 105.** PV Capacity against Line Loading - Power Factor equal to 0.95.

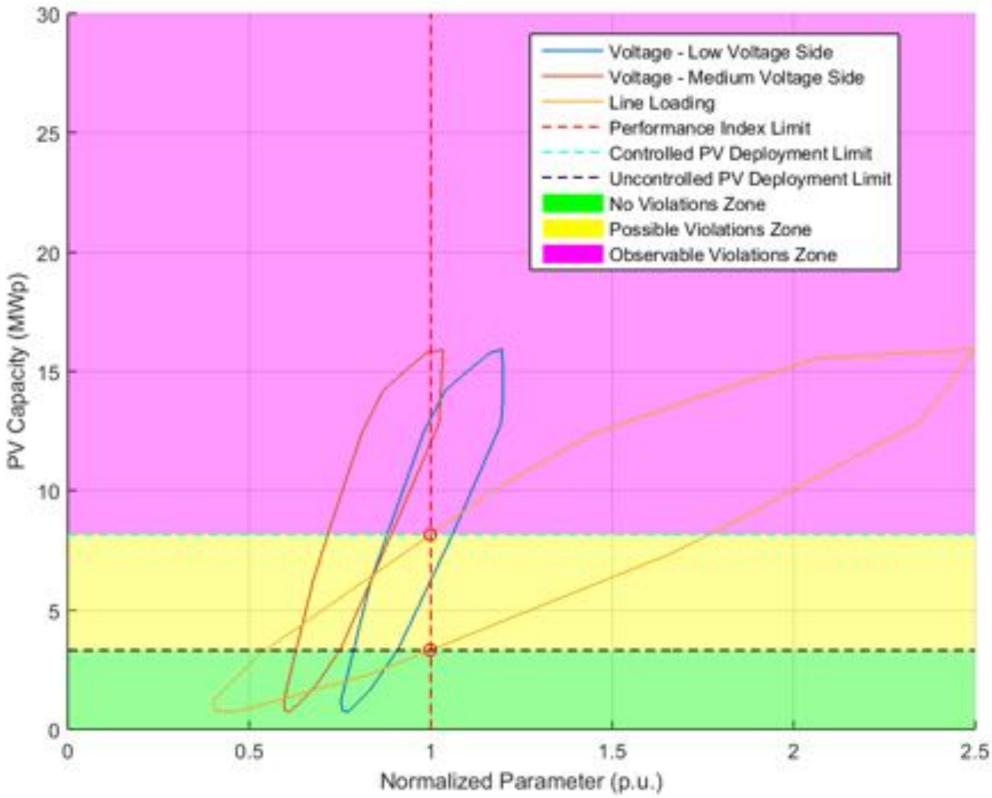


**Figure 106.** Normalized performance index parameters - Power Factor equal to 0.95.

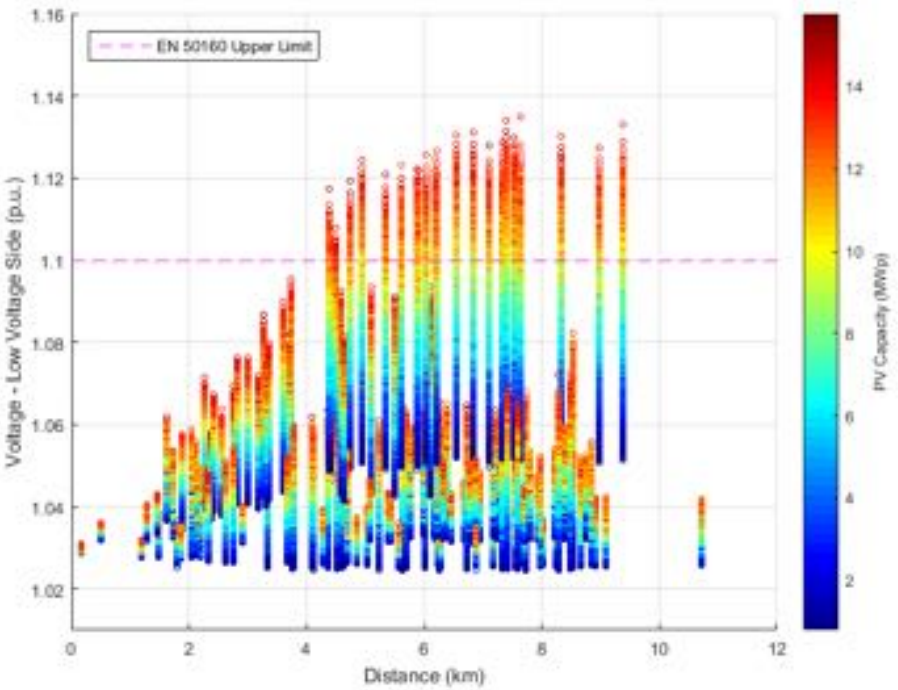


**Figure 107.** Voltage at low voltage side against Distance from transmission substation - Power Factor equal to 0.95.

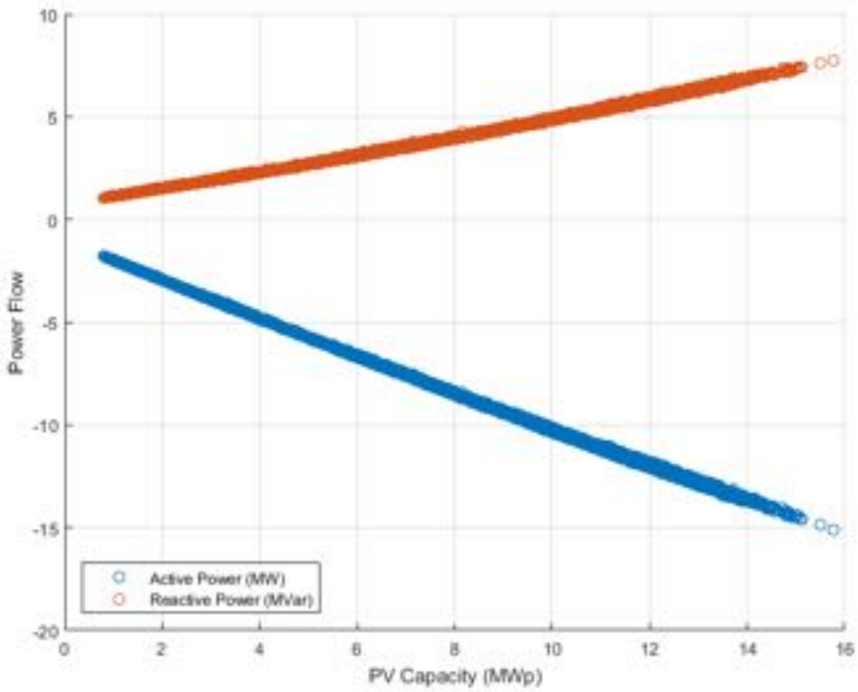


**Figure 108.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor equal to 0.95.

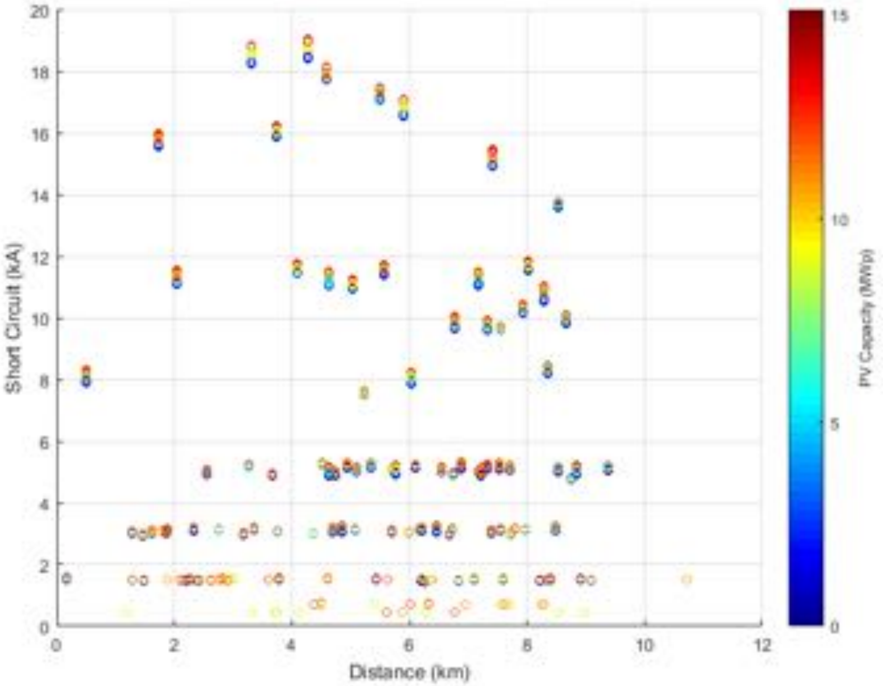


**Figure 109.** Short circuit current against Distance - Power Factor equal to 0.95.

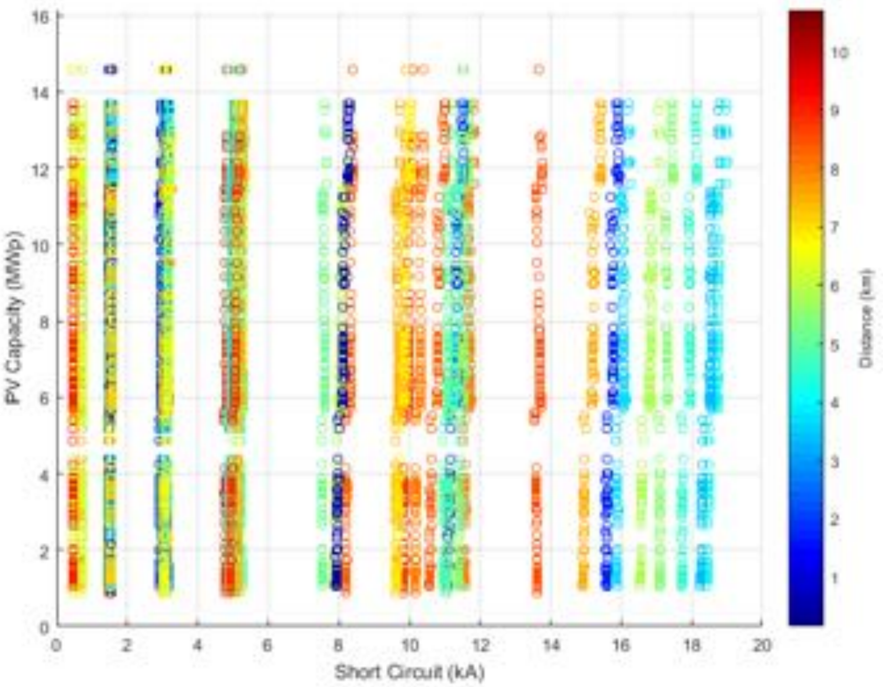


**Figure 110.** PV Capacity against Short Circuit current - Power Factor equal to 0.95.

### B1.3.3 Power Factor cosφ(P)

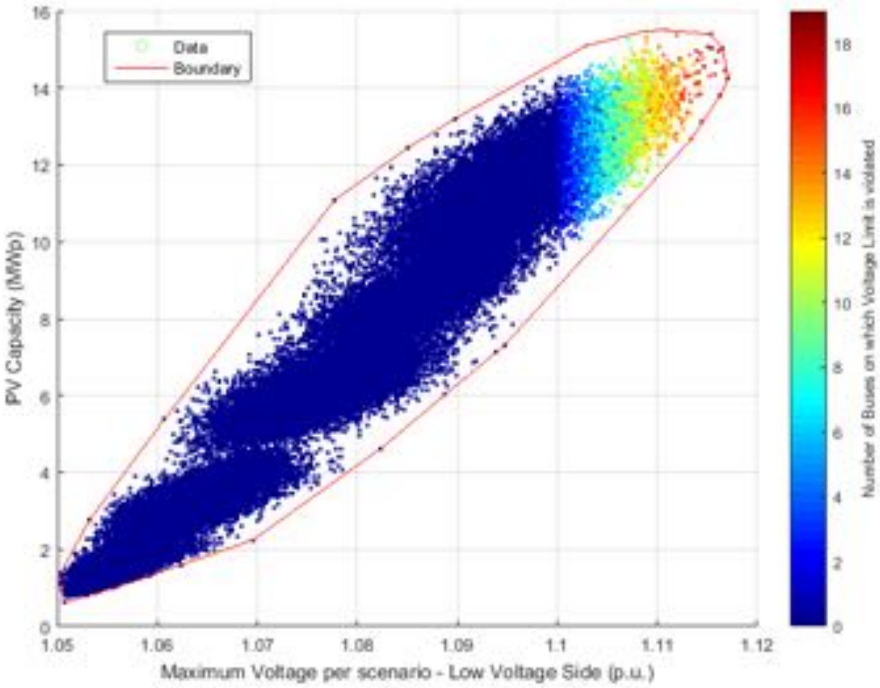


**Figure 111.** PV Capacity against Voltage – Low voltage side - Power Factor cosφ(P).

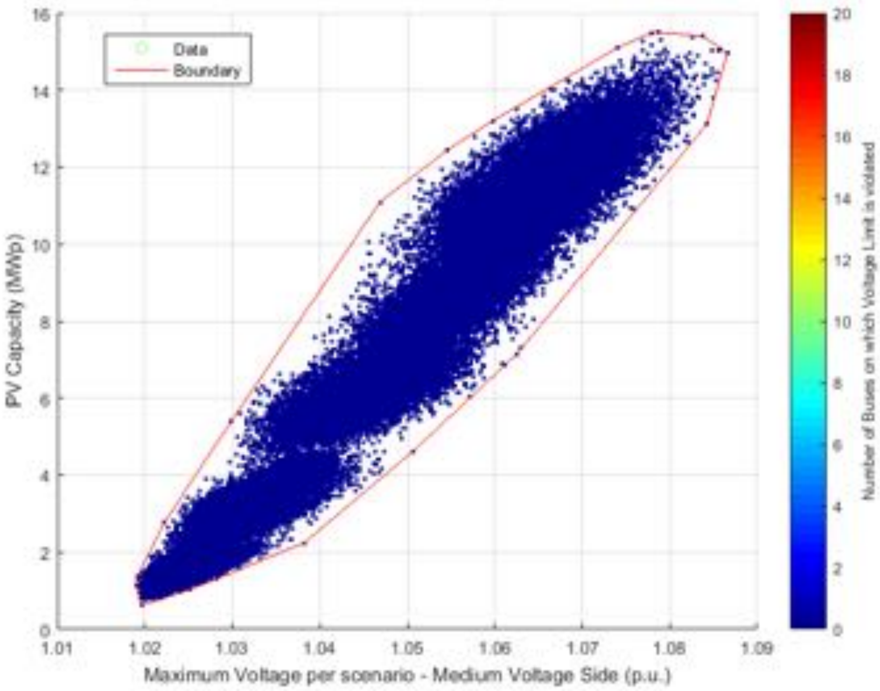


**Figure 112.** PV Capacity against Voltage – Medium voltage side - Power Factor cosφ(P).

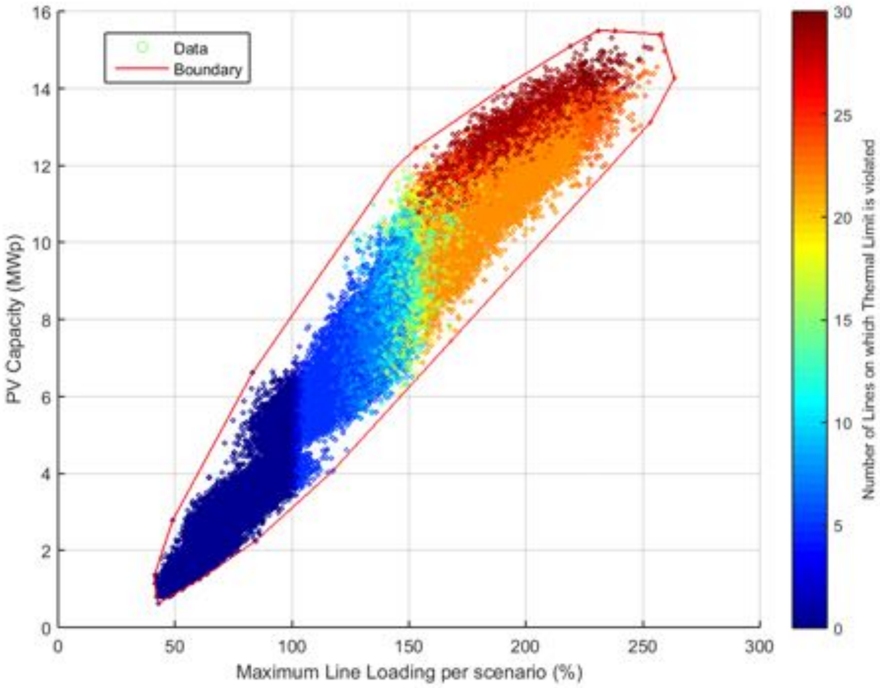


**Figure 113.** PV Capacity against Line Loading - Power Factor cosφ(P).

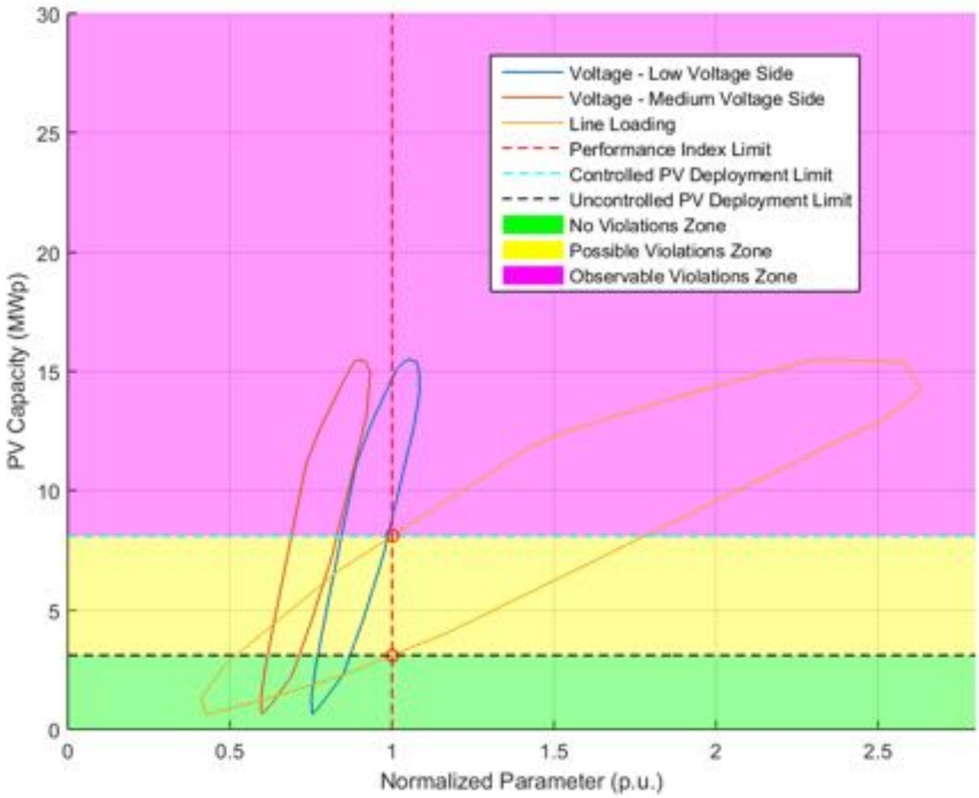


**Figure 114.** Normalized performance index parameters - Power Factor cosφ(P).

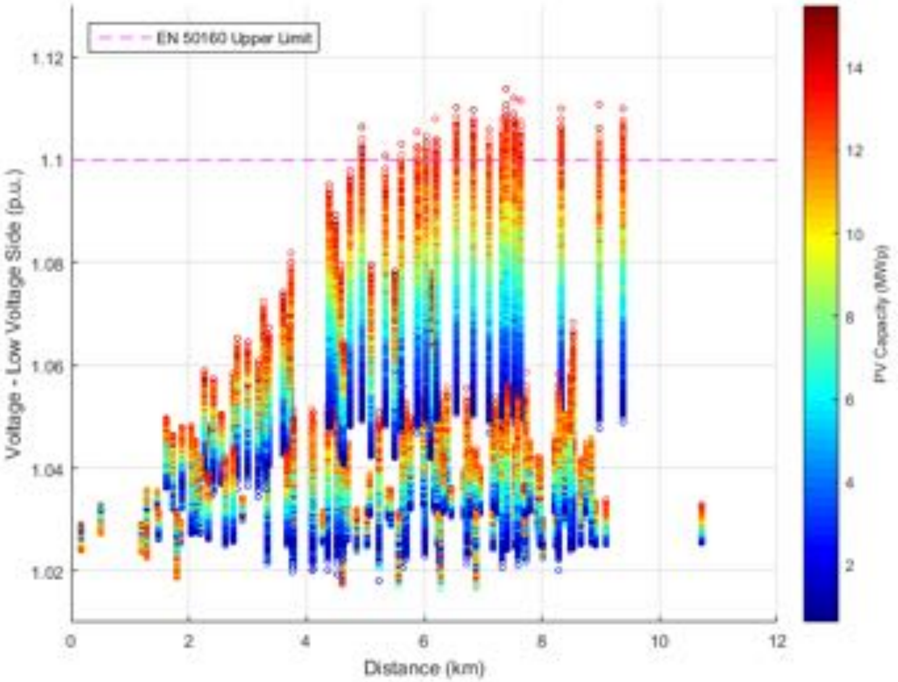


**Figure 115.** Voltage at low voltage side against distance from transmission substation - Power Factor cosφ(P).

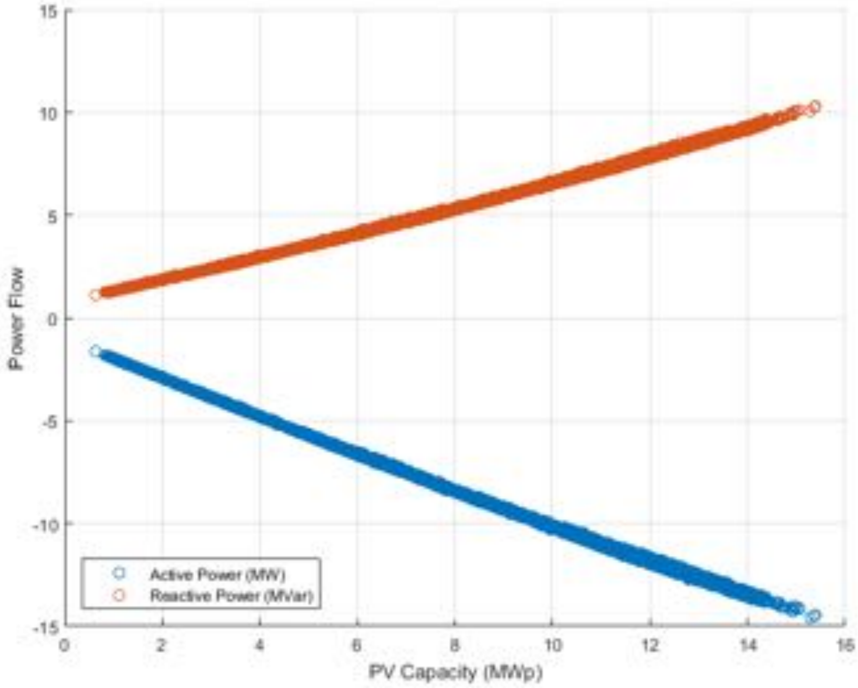


**Figure 116.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor cosφ(P).

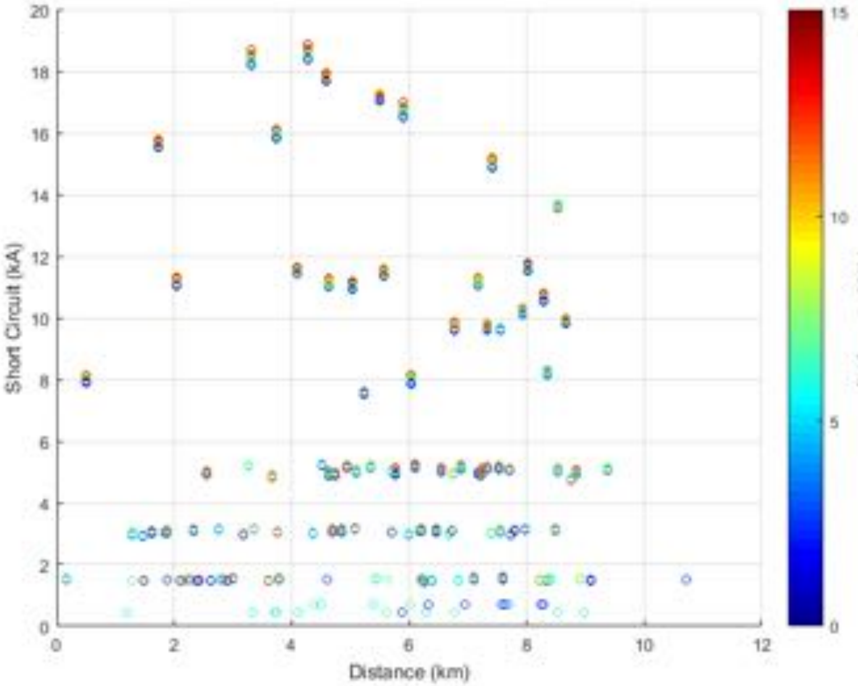


**Figure 117.** Short circuit current against distance - Power Factor cosφ(P).

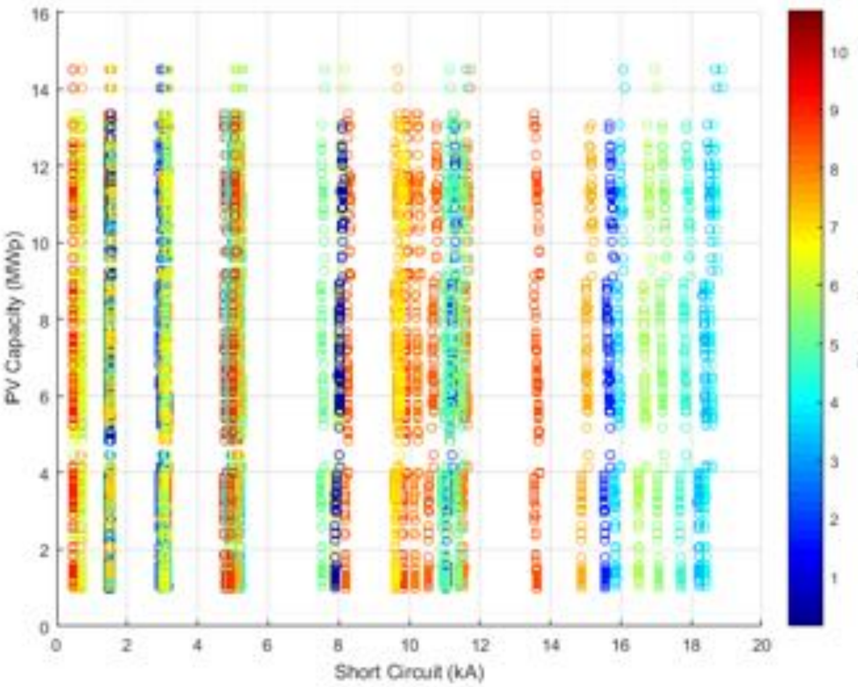


**Figure 118.** PV Capacity against short circuit current - Power Factor cosφ(P).

### B1.3.4 Summary – Monte Carlo Simulation

**Table 22.** Categorization of violations into zones.

| Scenario | No Violations Zone (MWp) | Possible Violations Zone (MWp) | Observable Violations Zone (MWp) |
|---|---|---|---|
| **Unity Power Factor** | below 3.22 | 3.22 – 8.85 | above 8.85 |
| **Power Factor equal to 0.95** | below 3.31 | 3.31 – 8.16 | above 8.16 |
| **Power Factor cosφ(P)** | below 3.10 | 3.10 – 8.09 | above 8.09 |

**Table 23.** Uncontrolled/Controlled PV Deployment Limit.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| **Unity Power Factor** | 3.22 | 9.17 | 7.77 | 14.20 | 3.81 | 8.85 |
| **Power Factor equal to 0.95** | 6.23 | 13.02 | 12.01 | 15.81 | 3.31 | 8.16 |
| **Power Factor cosφ(P)** | 8.82 | 14.68 | above 15.50 | above 15.50 | 3.10 | 8.09 |

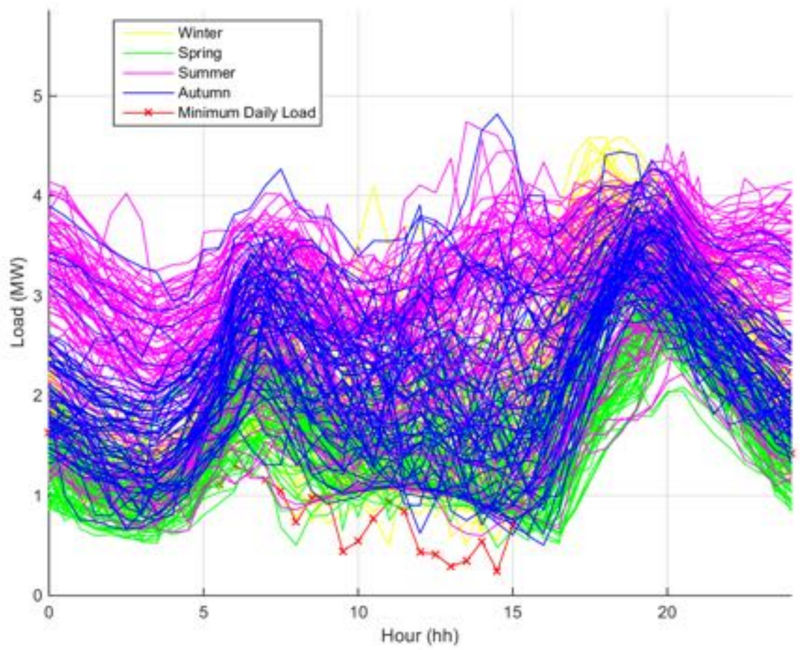


**Figure 119.** Athienou S/S - Minimum daily load.

# Appendix C

# C. Ypronas s/s - Executive Summary

The results of the PV hosting capacity for Ypsonas substation with two 10 MVA transmission transformers (with a total distribution transformer capacity of 52.850 MVA), 7 feeders, 251 distribution substations/transformers/busbars and 443 distribution lines either underground or overhead located in Nicosia district area, are presented and analysed in this Appendix. For this PV hosting capacity assessment, it was assumed that the inverter of PV systems is oversized by 10% (as imposed by newly formulated regulations).

## C.1 Results

### C1.1 Maximum Installed PV Capacity scenario

#### C1.1.1 Unity Power Factor Operation

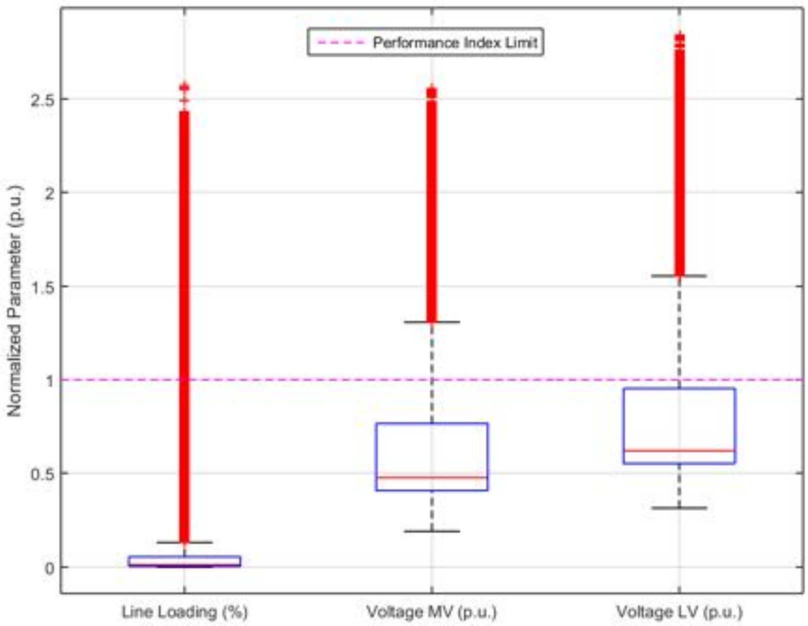


**Figure 120.** Performance Index parameters normalized to their limit – Unity Power Factor.

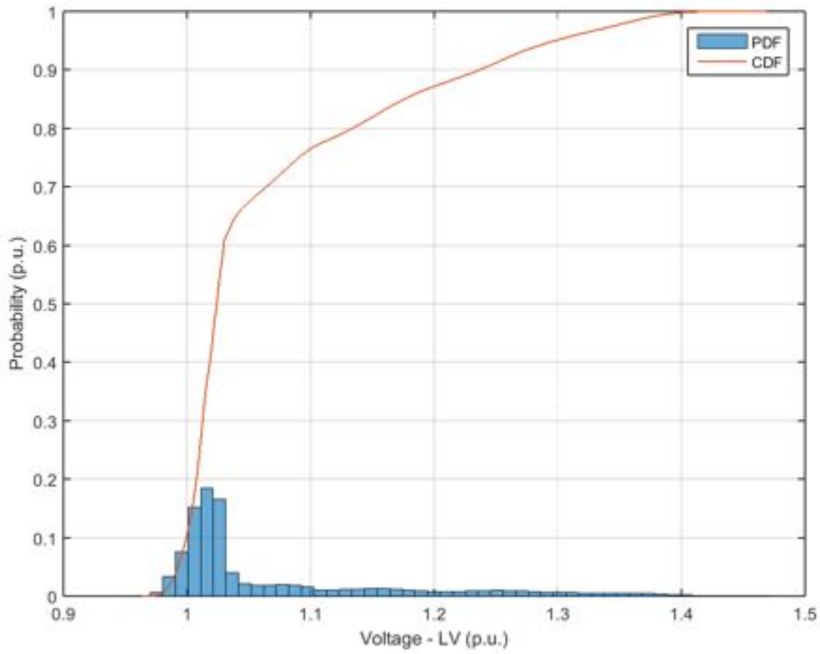


**Figure 121.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity power factor.

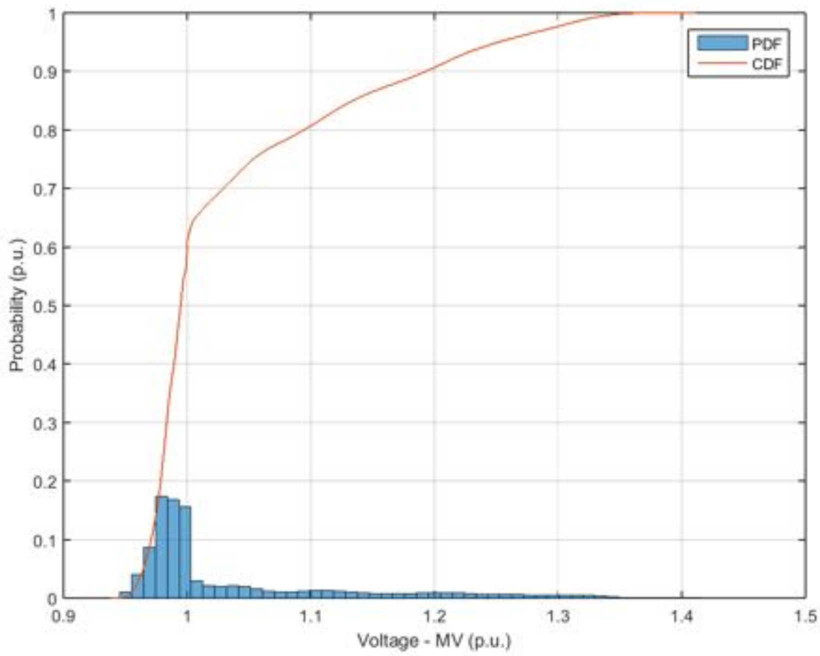


**Figure 122.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Unity power factor.

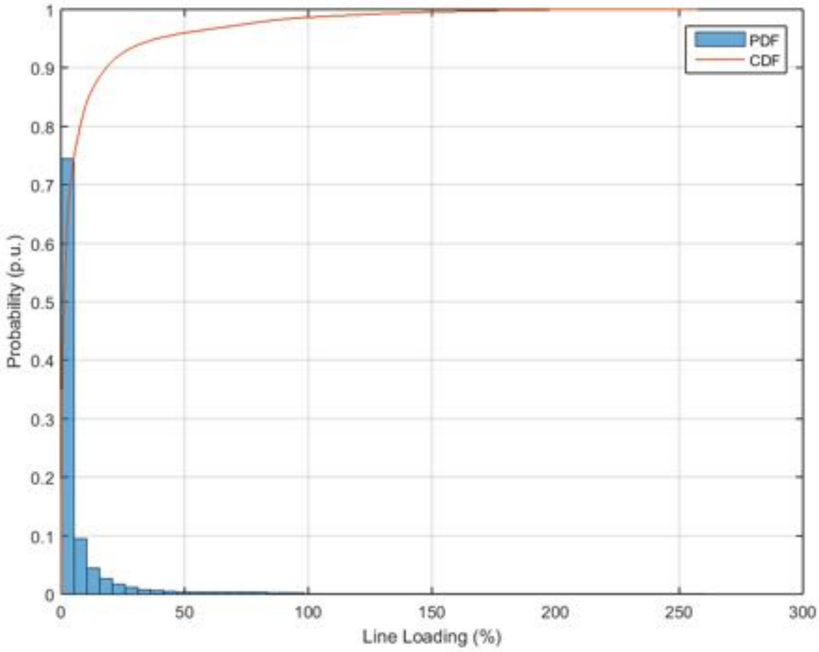


**Figure 123.** Probability distribution and cumulative probability distribution – Line Loading – Unity power factor.

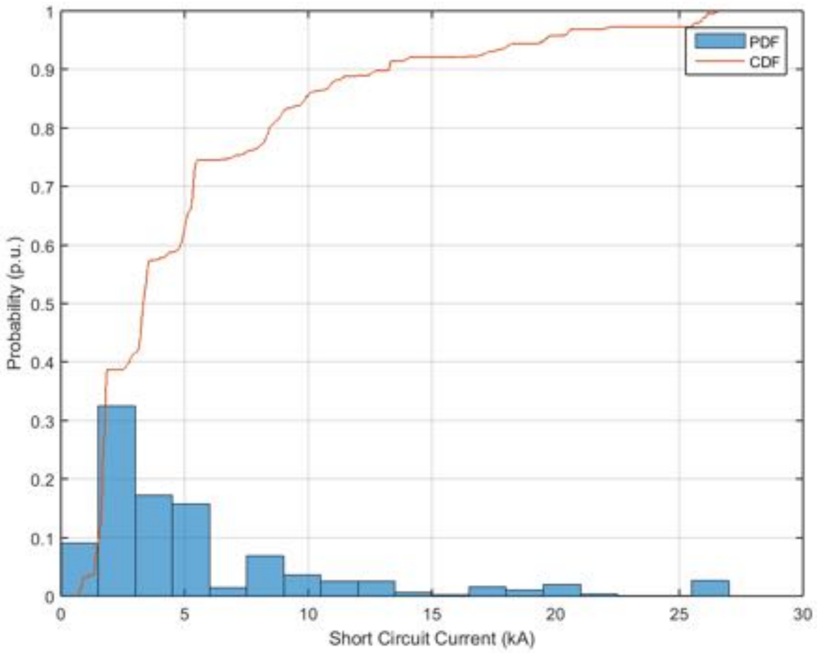


**Figure 124.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity power factor.

### C1.1.2 Power Factor equal to 0.95

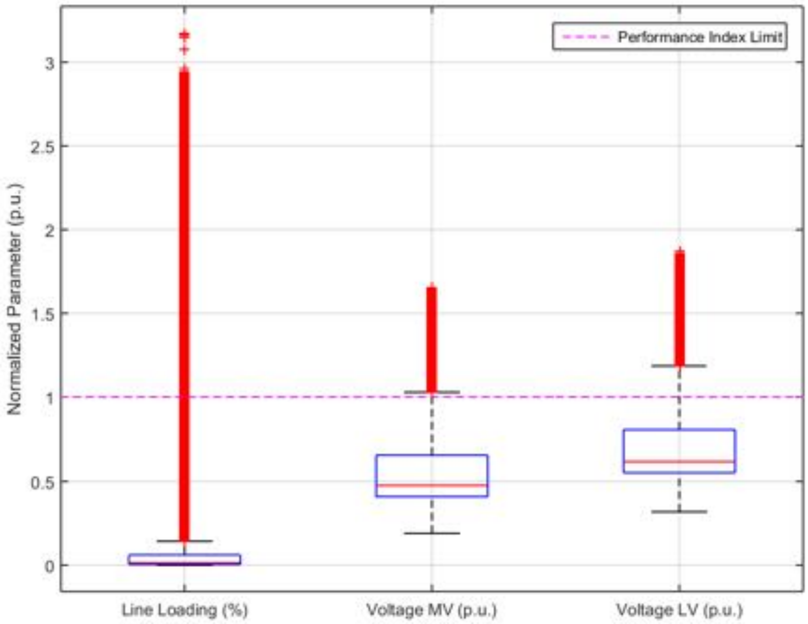


**Figure 125.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

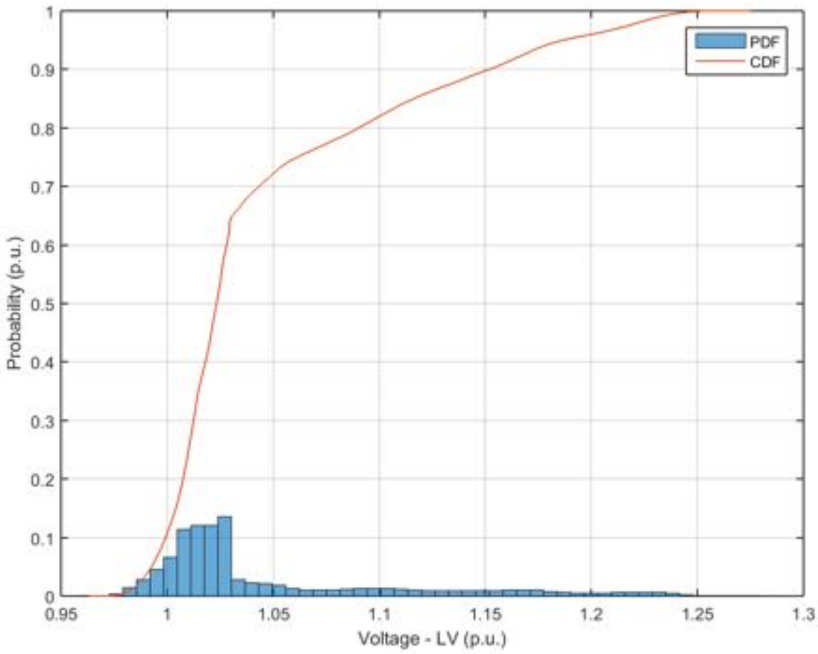


**Figure 126.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

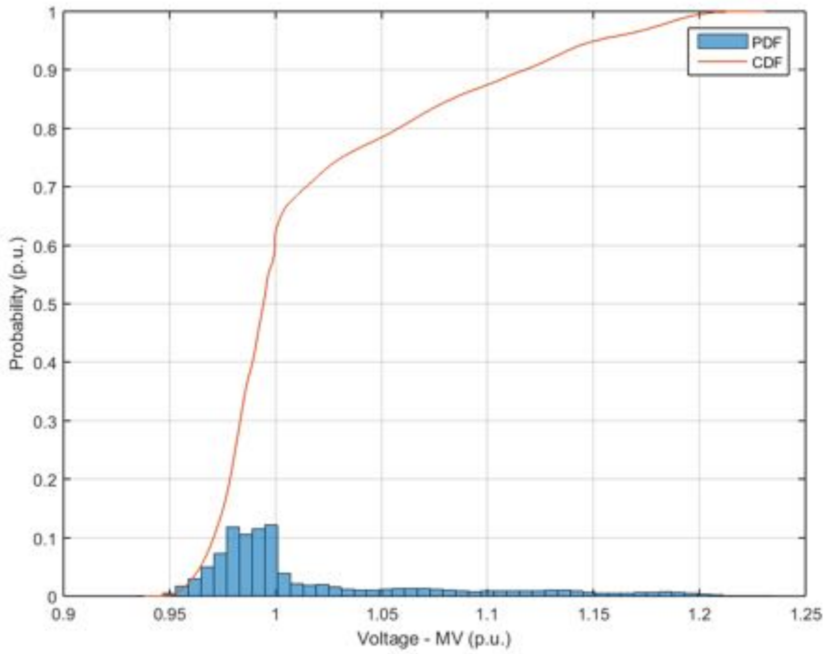


**Figure 127.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor equal to 0.95.

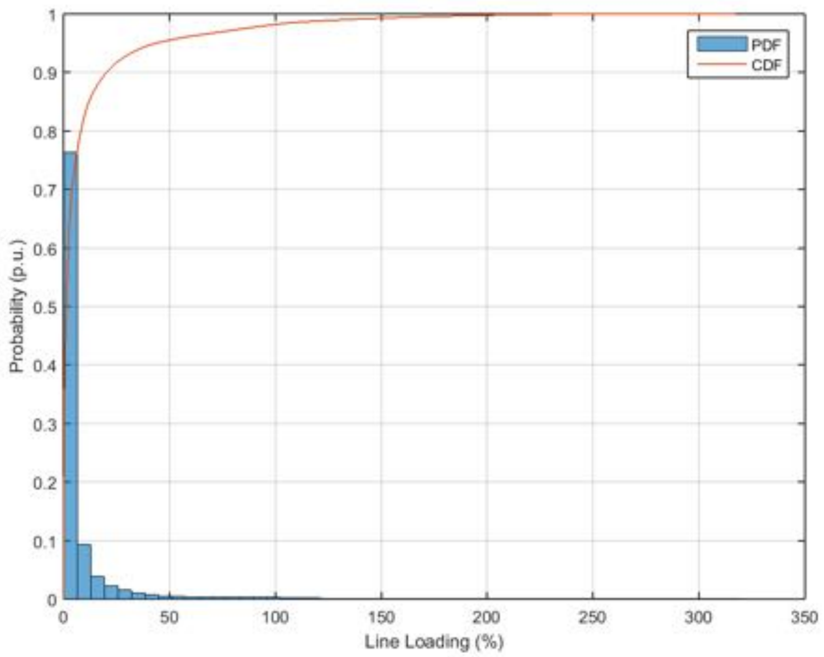


**Figure 128.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

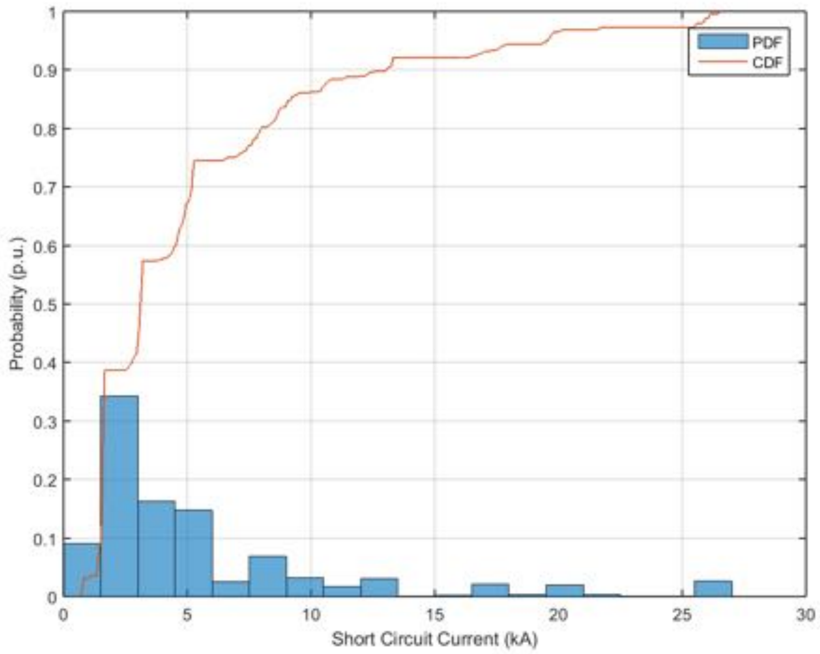


**Figure 129.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### C1.1.3 Power Factor cosφ(P)

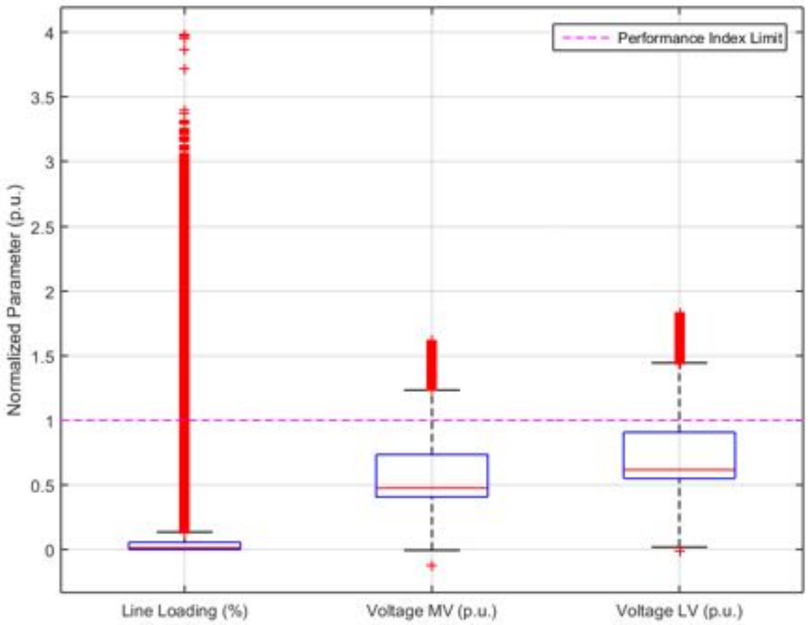


**Figure 130.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

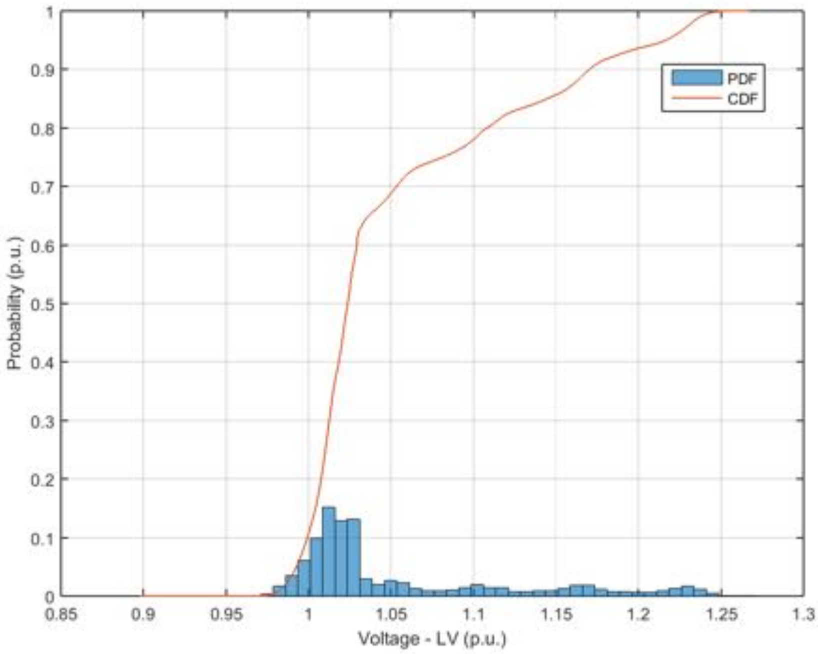


**Figure 131.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

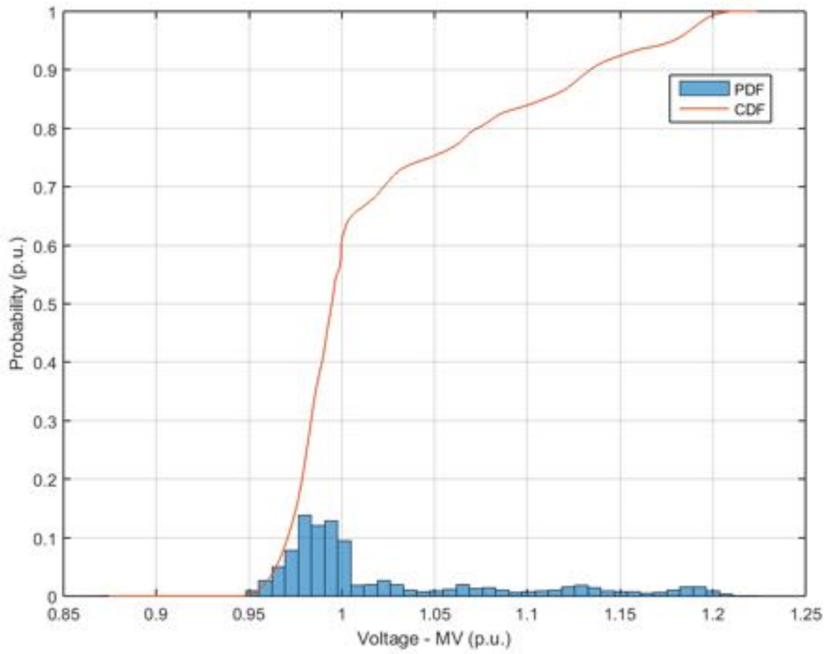


**Figure 132.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor cosφ(P).

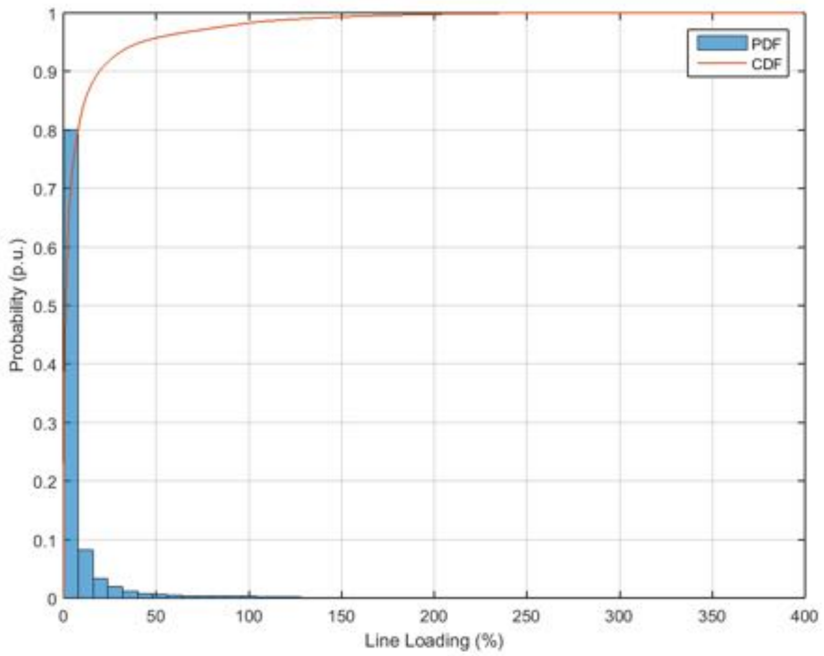


**Figure 133.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

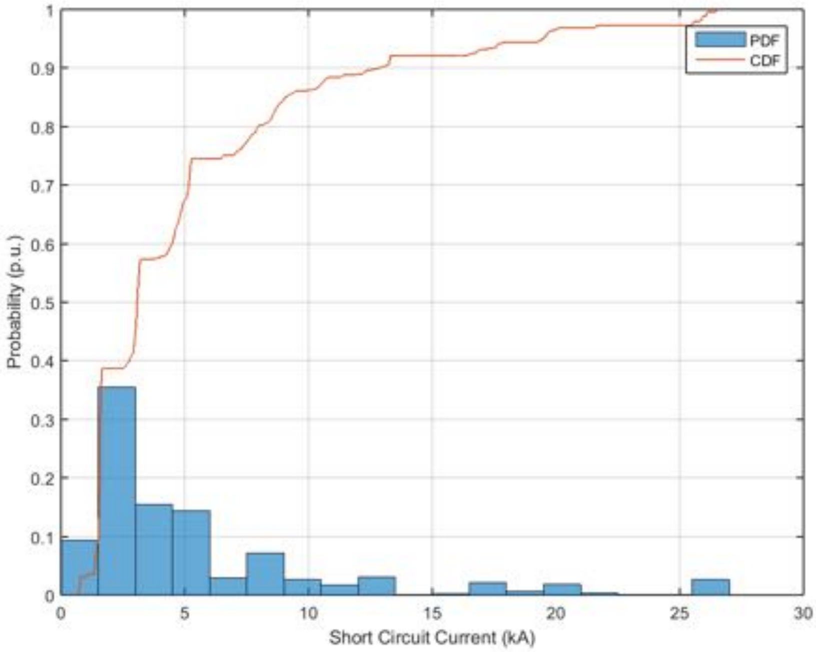


**Figure 134.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### C1.1.4 Summary and Discussion – Maximum Installed PV Capacity scenario

**Table 24.** Statistical analysis of PI parameters - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.315 | 0.315 | -0.012 |
| | 25th quantile | 0.551 | 0.551 | 0.551 |
| | Median | 0.620 | 0.617 | 0.619 |
| | Average | 0.845 | 0.737 | 0.769 |
| | Standard Deviation | 0.235 | 0.091 | 0.115 |
| | 75th quantile | 0.953 | 0.806 | 0.907 |
| | 95th quantile | 1.989 | 1.433 | 1.583 |
| | 99th quantile | 2.370 | 1.661 | 1.687 |
| | Maximum | 2.843 | 1.876 | 1.836 |
| **Number of elements of which the limit is violated** | | 225 out of 251 | 186 out of 251 | 181 out of 251 |
| **Voltage – Medium Voltage Side** | Minimum | 0.190 | 0.190 | -0.126 |
| | 25th quantile | 0.406 | 0.405 | 0.406 |
| | Median | 0.474 | 0.472 | 0.473 |
| | Average | 0.680 | 0.587 | 0.614 |
| | Standard Deviation | 0.206 | 0.084 | 0.104 |
| | 75th quantile | 0.767 | 0.656 | 0.737 |
| | 95th quantile | 1.759 | 1.255 | 1.394 |
| | 99th quantile | 2.120 | 1.469 | 1.488 |
| | Maximum | 2.558 | 1.655 | 1.619 |
| **Number of elements of which the limit is violated** | | 193 out of 251 | 148 out of 251 | 143 out of 251 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.002 | 0.002 | 0.002 |
| | Median | 0.013 | 0.014 | 0.013 |
| | Average | 0.079 | 0.089 | 0.086 |
| | Standard Deviation | 0.043 | 0.057 | 0.055 |
| | 75th quantile | 0.054 | 0.058 | 0.055 |
| | 95th quantile | 0.388 | 0.438 | 0.418 |
| | 99th quantile | 1.161 | 1.315 | 1.282 |
| | Maximum | 2.573 | 3.174 | 3.986 |
| | CDF-100% loading | 98.64% | 98.20% | 98.27% |
| **Number of elements of which the limit is violated** | | 59 out of 443 | 68 out of 443 | 70 out of 443 |

**Table 25.** Statistical analysis of Short Circuit Values - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 0.652 | 0.652 | 0.652 |
| | 25th quantile | 1.714 | 1.592 | 1.578 |
| | Median | 3.325 | 3.108 | 3.077 |
| | Average | 5.514 | 5.320 | 5.297 |
| | Standard Deviation | 5.664 | 5.619 | 5.615 |
| | 75th quantile | 6.922 | 6.601 | 6.557 |
| | 95th quantile | 19.558 | 19.552 | 19.416 |
| | 99th quantile | 26.080 | 26.064 | 26.064 |
| | Maximum | 26.516 | 26.506 | 26.504 |

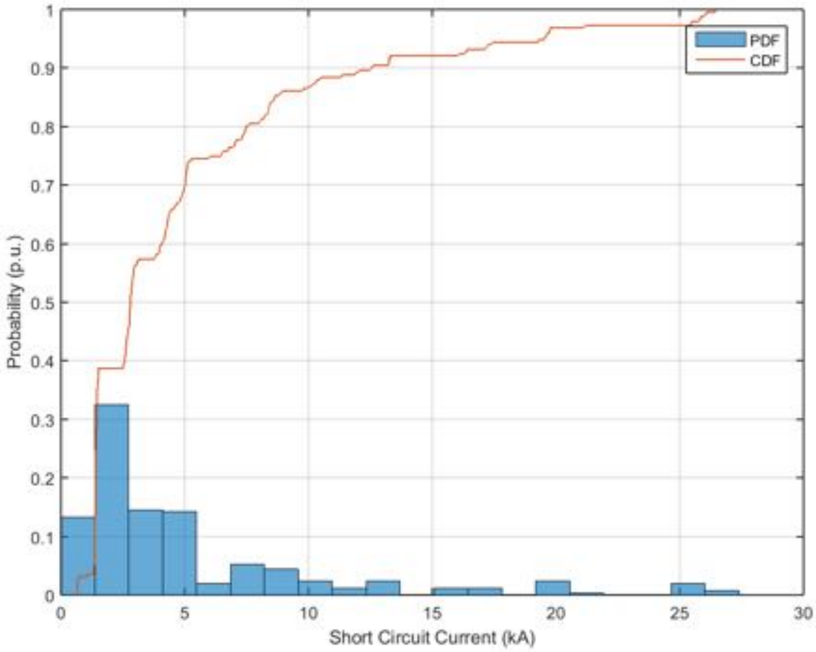


**Figure 135.** Probability distribution and cumulative probability distribution – Short Circuit Current – No PV.

## C1.2 Maximum PV Capacity per Distribution Substation

### C1.2.1 Unity Power Factor Scheme

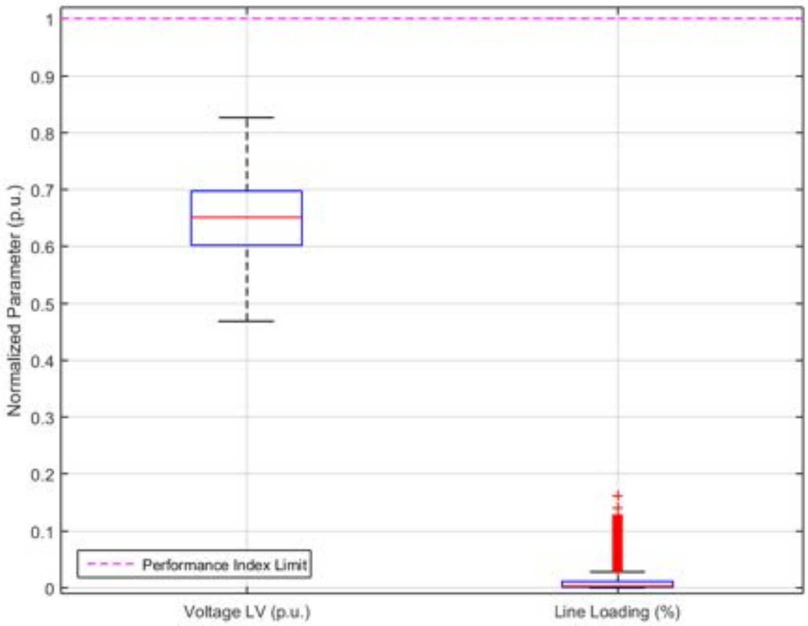


**Figure 136.** Performance Index parameters normalized to their limit – Unity Power Factor.

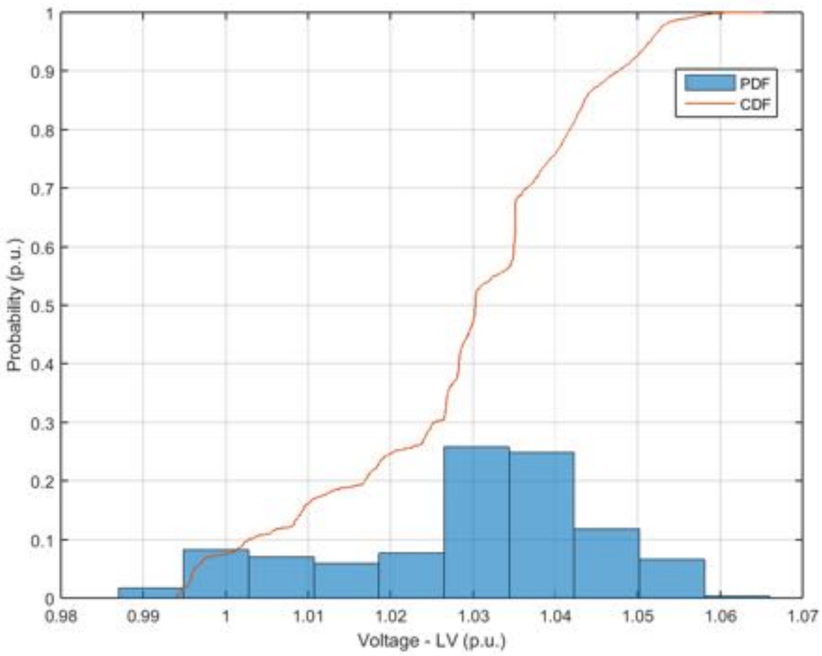


**Figure 137.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity Power Factor.

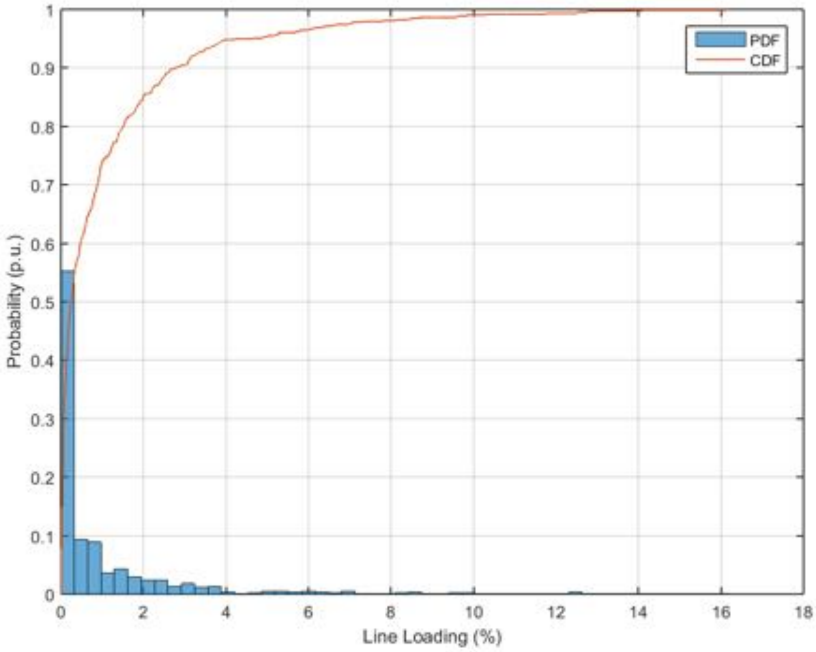


**Figure 138.** Probability distribution and cumulative probability distribution – Line Loading – Unity Power Factor.

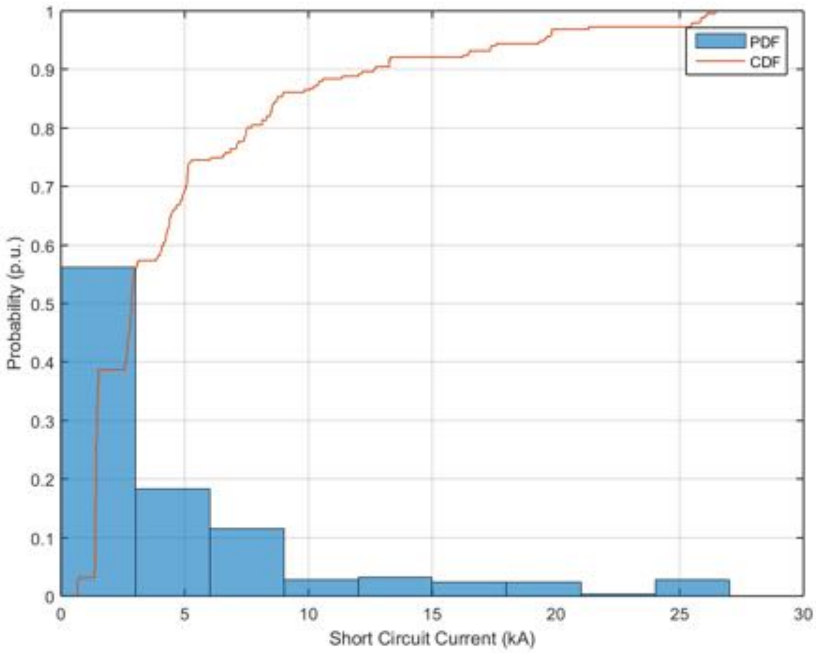


**Figure 139.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity Power Factor.

### C1.2.2 Power Factor equal to 0.95

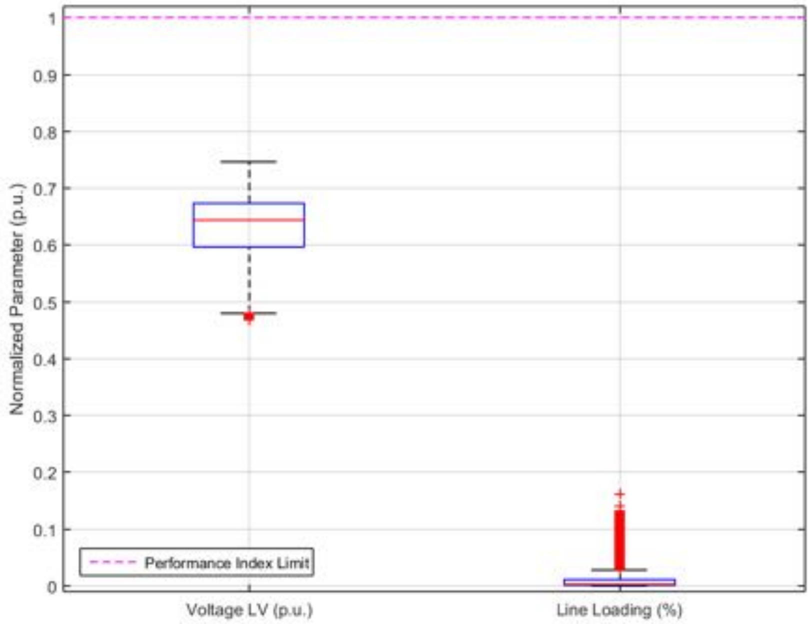


**Figure 140.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

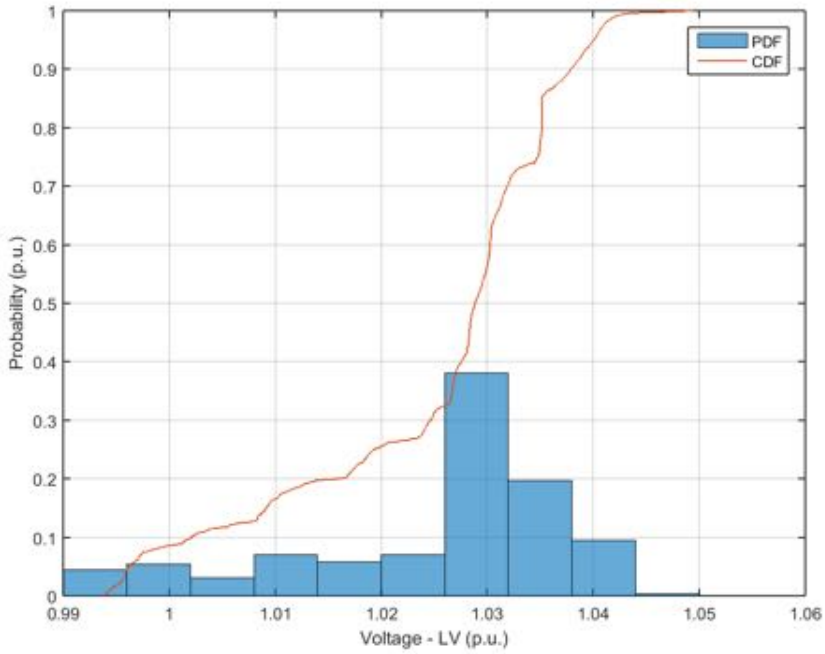


**Figure 141.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

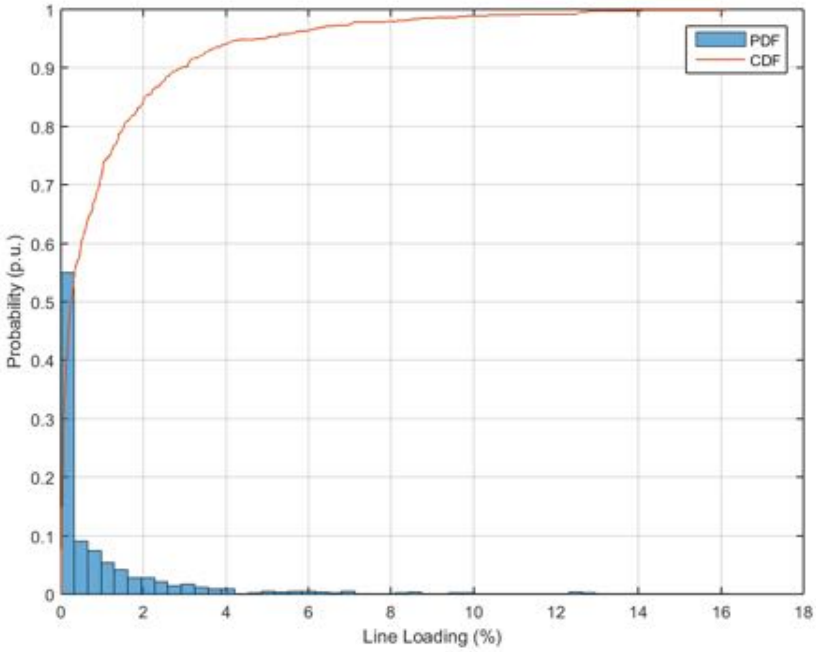


**Figure 142.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

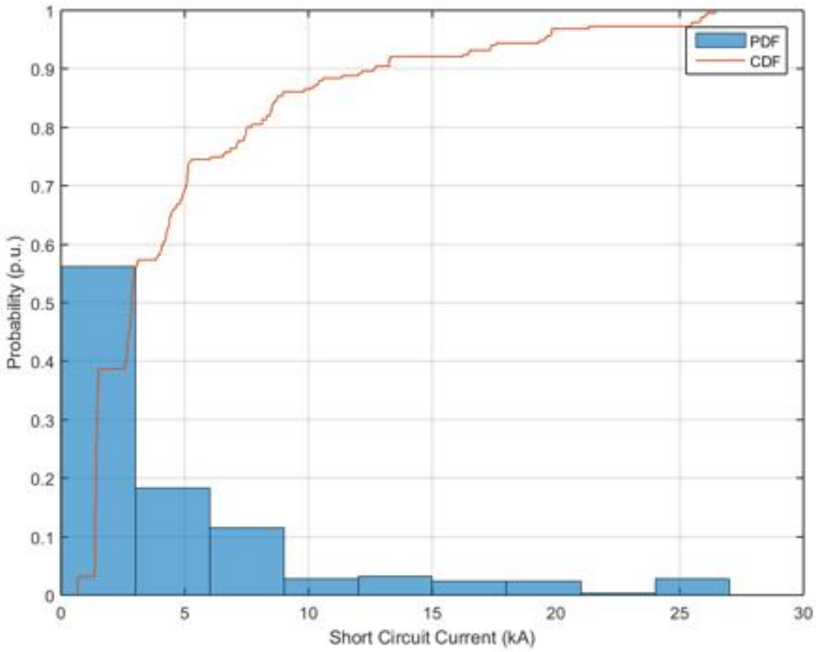


**Figure 143.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### C1.2.3 Power Factor cosφ(P)

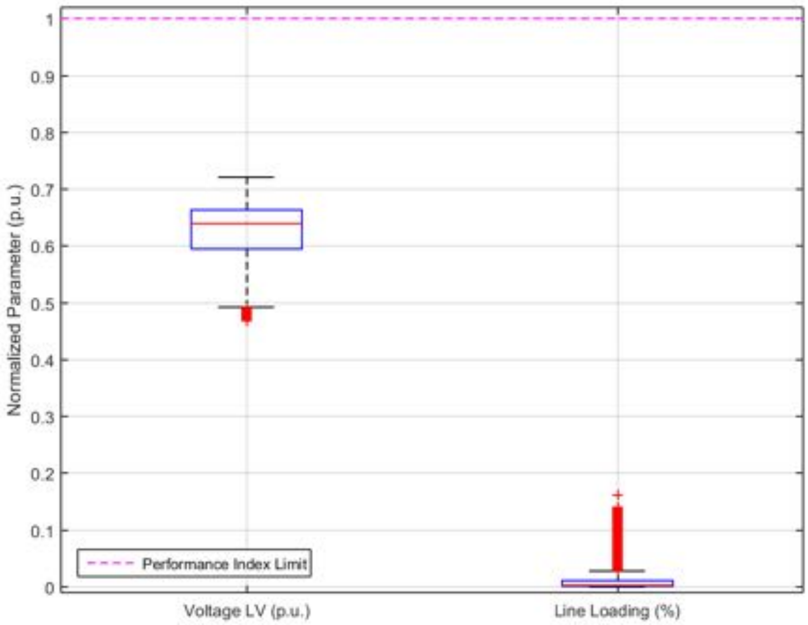


**Figure 144.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

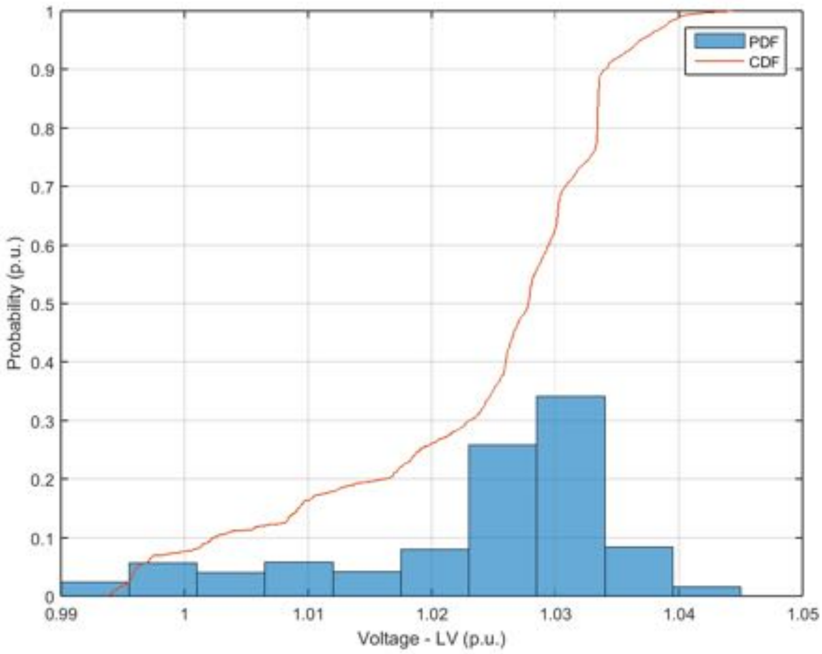


**Figure 145.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

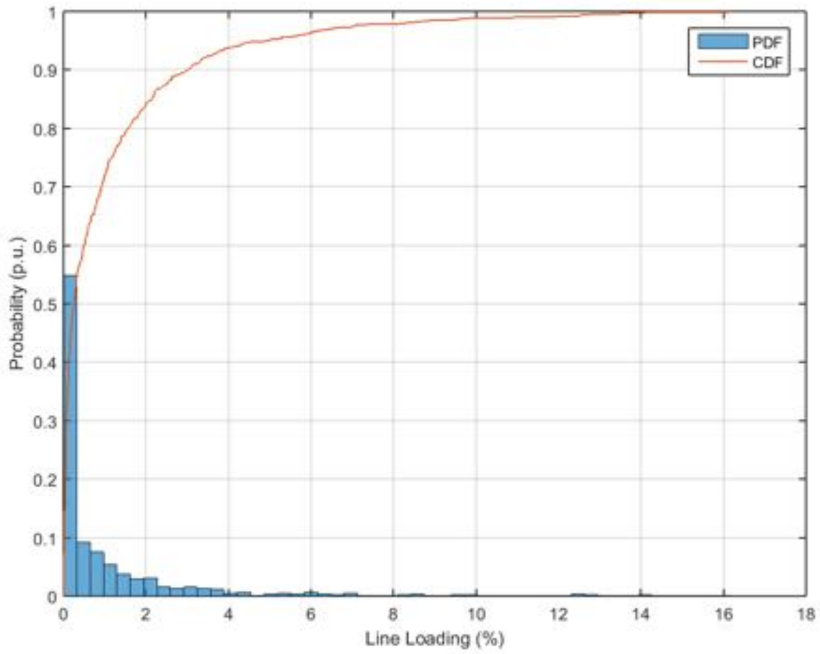


**Figure 146.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

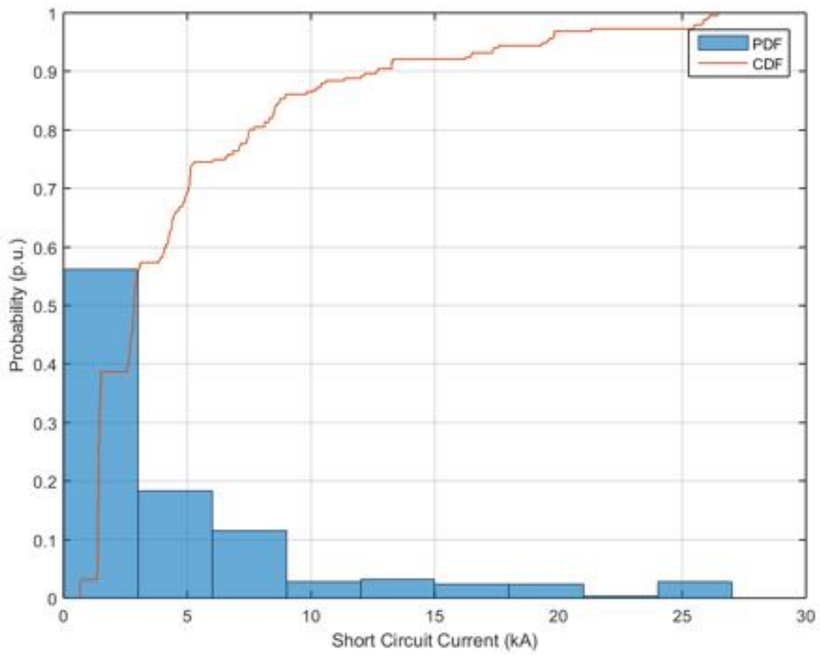


**Figure 147.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### C1.2.4 Summary and Discussion – Maximum PV Capacity per Distribution Substation

**Table 26.** Statistical analysis of PI parameters - Maximum PV Capacity per Distribution Substation.

| | | **Scenario** | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.469 | 0.469 | 0.469 |
| | 25th quantile | 0.602 | 0.597 | 0.595 |
| | Median | 0.651 | 0.644 | 0.639 |
| | Average | 0.644 | 0.626 | 0.620 |
| | Standard Deviation | 0.006 | 0.004 | 0.003 |
| | 75th quantile | 0.697 | 0.674 | 0.664 |
| | 95th quantile | 0.758 | 0.700 | 0.685 |
| | 99th quantile | 0.780 | 0.710 | 0.701 |
| | Maximum | 0.826 | 0.747 | 0.722 |
| **Number of elements of which the limit is violated** | | 0 out of 251 | 0 out of 251 | 0 out of 251 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.001 | 0.001 | 0.001 |
| | Median | 0.002 | 0.002 | 0.002 |
| | Average | 0.010 | 0.011 | 0.011 |
| | Standard Deviation | 0.000 | 0.000 | 0.000 |
| | 75th quantile | 0.012 | 0.012 | 0.012 |
| | 95th quantile | 0.046 | 0.049 | 0.049 |
| | 99th quantile | 0.099 | 0.106 | 0.113 |
| | Maximum | 0.162 | 0.162 | 0.162 |
| **Number of elements of which the limit is violated** | | 0 out of 443 | 0 out of 443 | 0 out of 443 |

**Table 27.** Statistical analysis of Short Circuit Values - Maximum PV Capacity per Distribution Substation.

| | | **Scenario** | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 0.668 | 0.668 | 0.668 |
| | 25th quantile | 1.423 | 1.423 | 1.423 |
| | Median | 2.834 | 2.834 | 2.834 |
| | Average | 5.122 | 5.122 | 5.122 |
| | Standard Deviation | 5.632 | 5.632 | 5.632 |
| | 75th quantile | 6.425 | 6.425 | 6.425 |
| | 95th quantile | 19.519 | 19.519 | 19.519 |
| | 99th quantile | 26.008 | 26.008 | 26.008 |
| | Maximum | 26.464 | 26.464 | 26.464 |

## C1.3 Assessing PV Capacity using Monte Carlo method

### C1.3.1 Unity Power Factor Operation

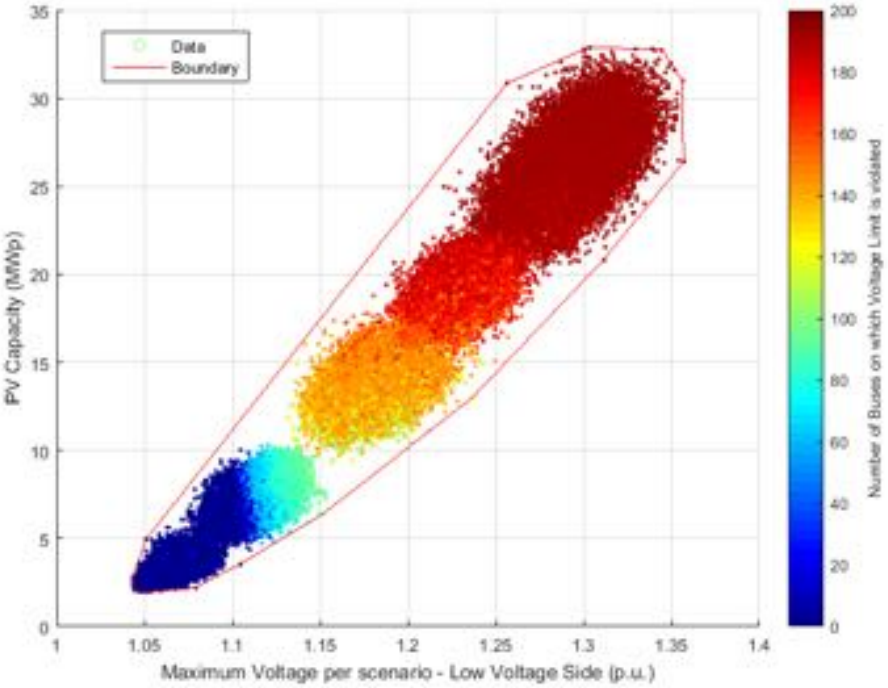


**Figure 148.** PV Capacity against Voltage – Low voltage side - Unity Power Factor.

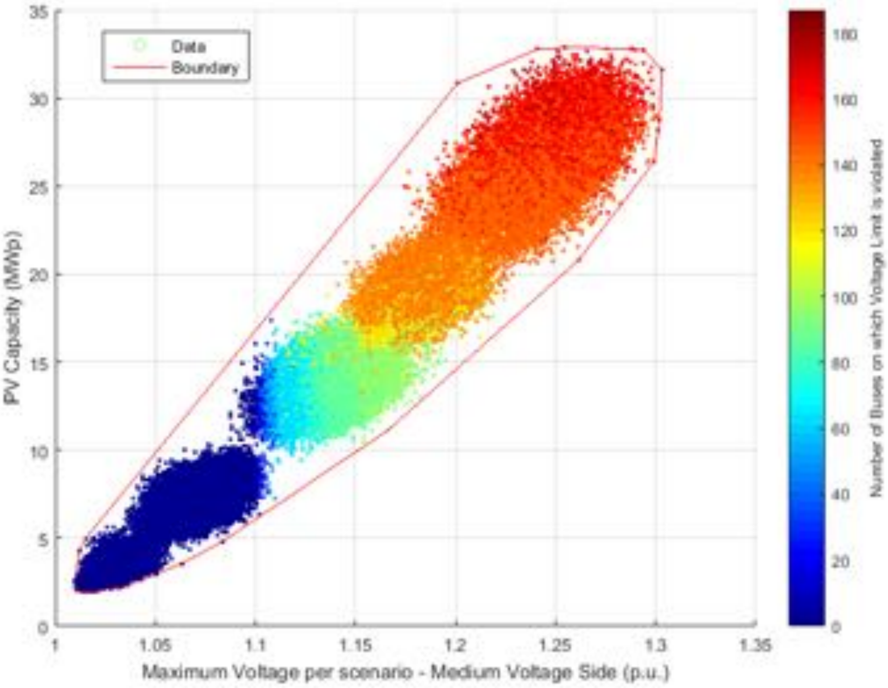


**Figure 149.** PV Capacity against Voltage – Medium voltage side - Unity Power Factor.

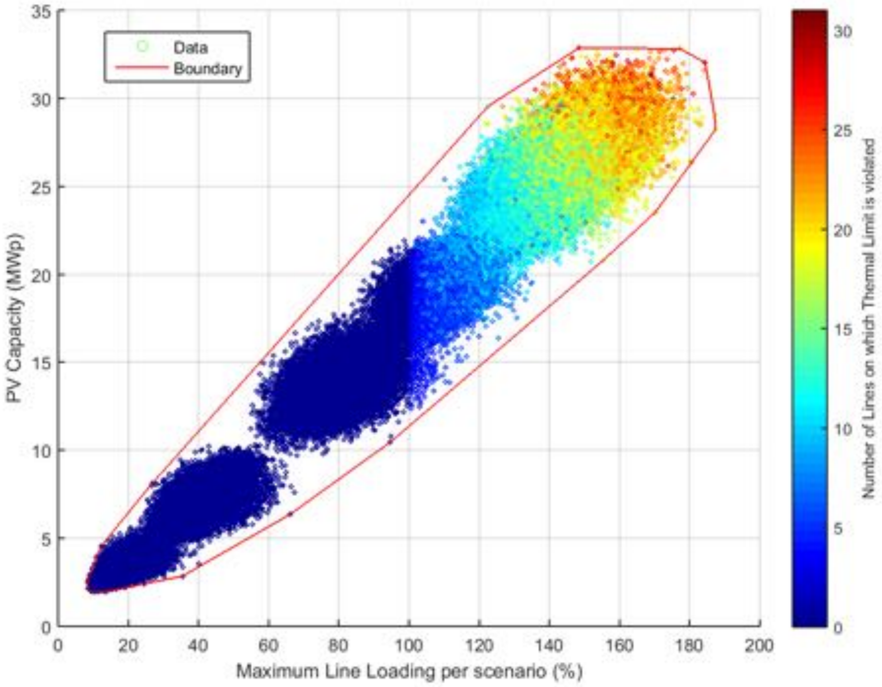


**Figure 150.** PV Capacity against Line Loading - Unity Power Factor.

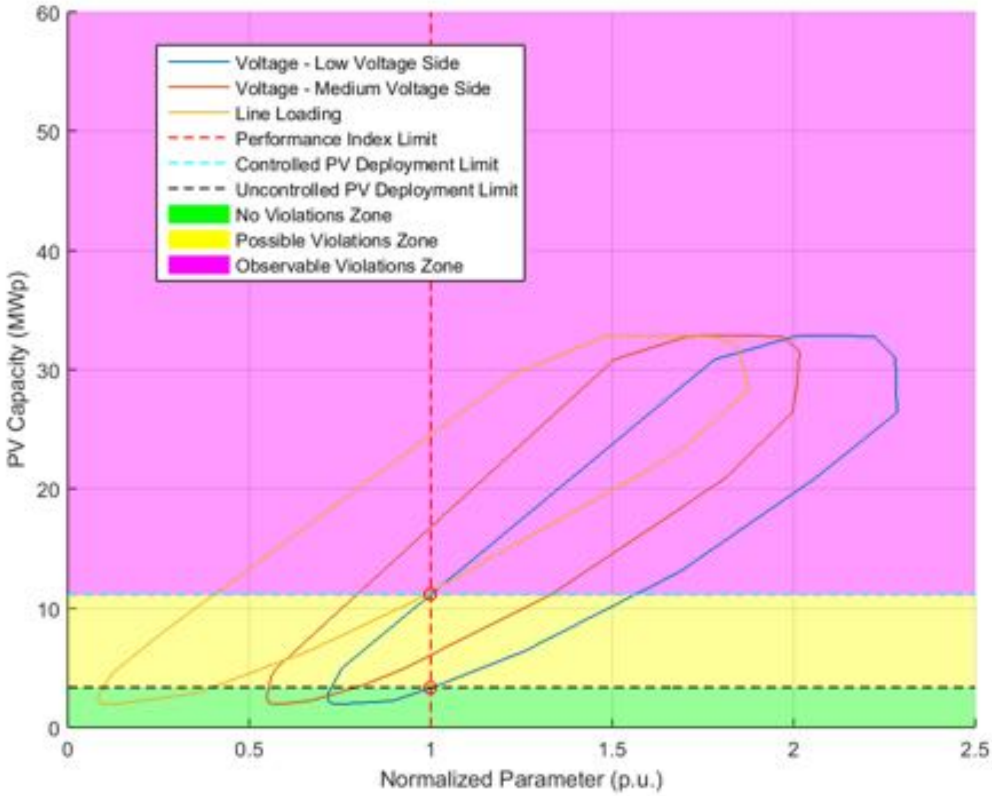


**Figure 151.** Normalized performance index parameters - Unity Power Factor.

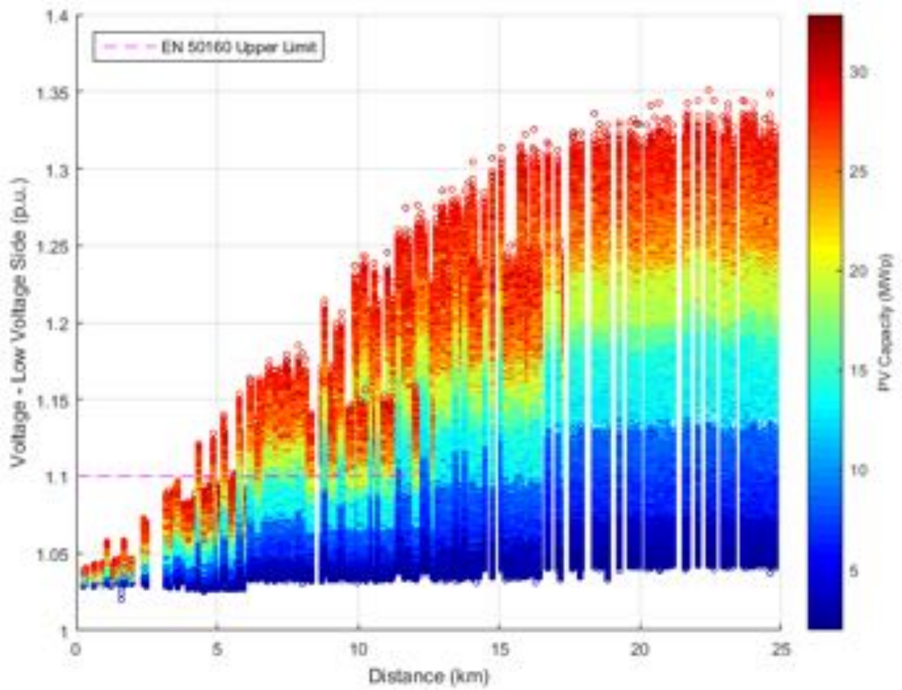


**Figure 152.** Voltage at low voltage side against distance from transmission substation - Unity Power Factor.

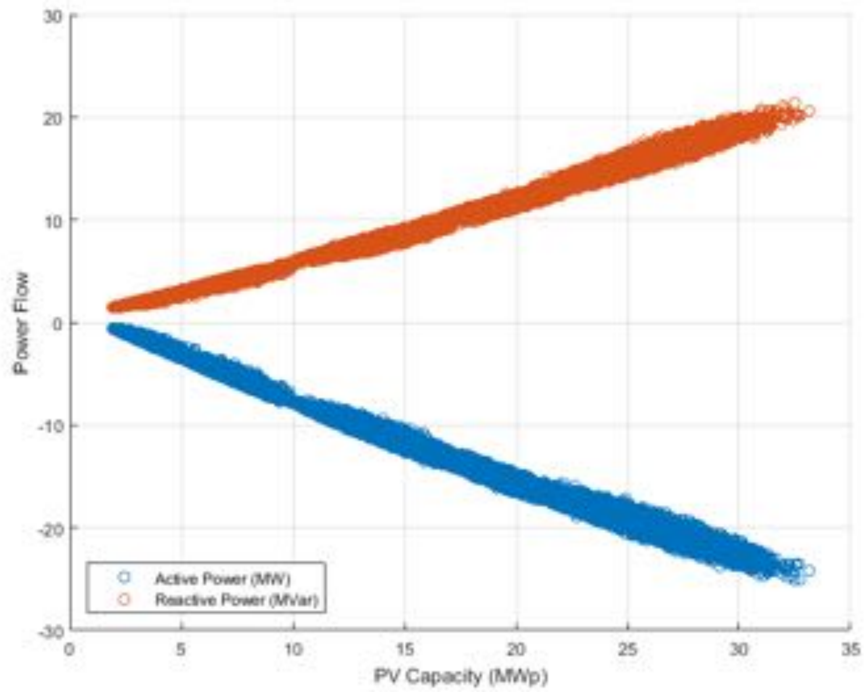


**Figure 153.** Power flow at PCC (connection of the reference substation with HV network) against PV capacity - Unity Power Factor (negative sign denotes reverse power flow).

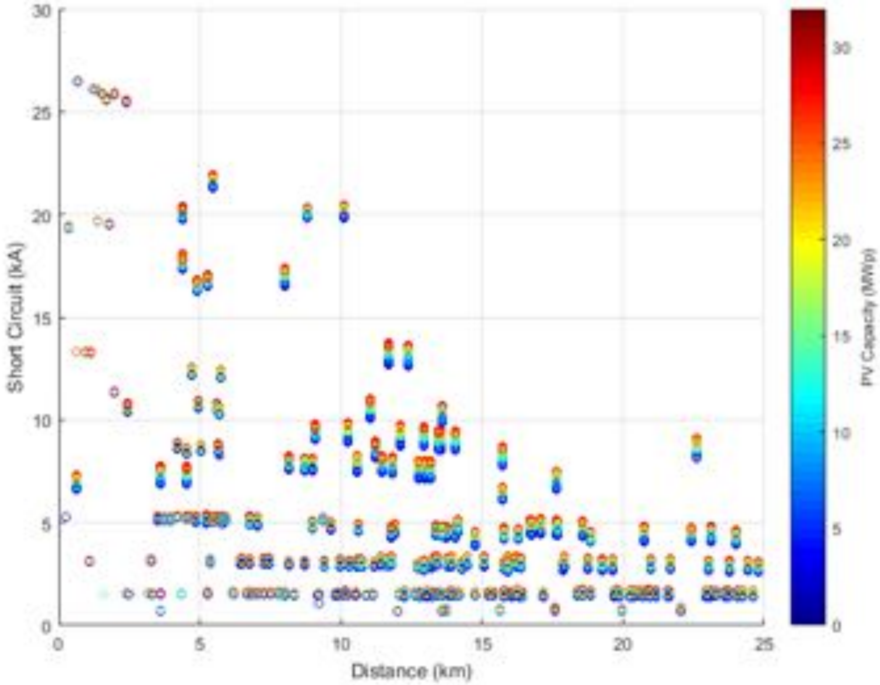


**Figure 154.** Short circuit current against distance - Unity Power Factor.

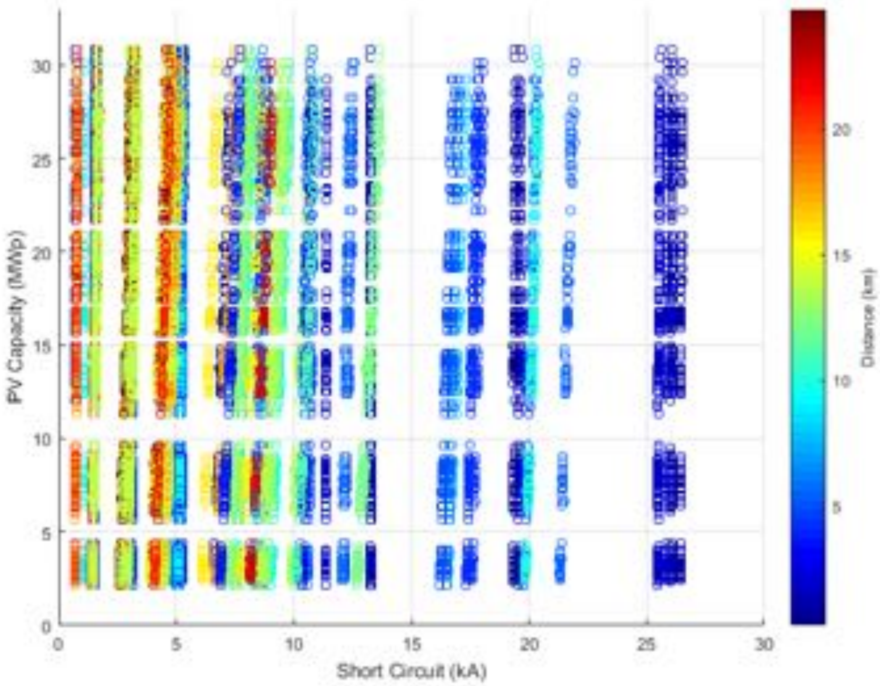


**Figure 155.** PV Capacity against Short circuit current - Unity Power Factor

### C1.3.2 Power Factor equal to 0.95

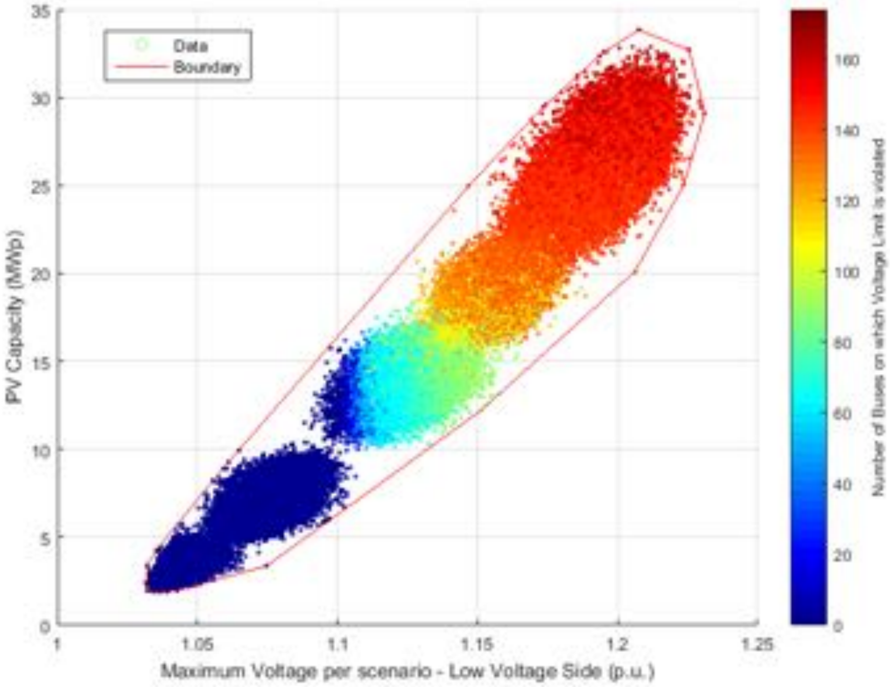


**Figure 156.** PV Capacity against Voltage – Low voltage side - Power Factor equal to 0.95.

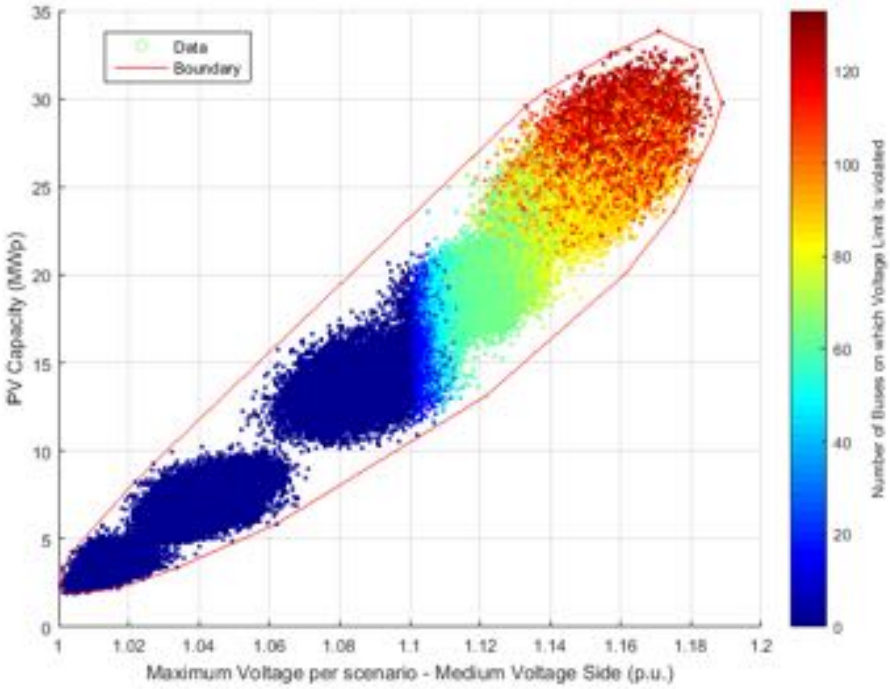


**Figure 157.** PV Capacity against Voltage – Medium voltage side - Power Factor equal to 0.95.

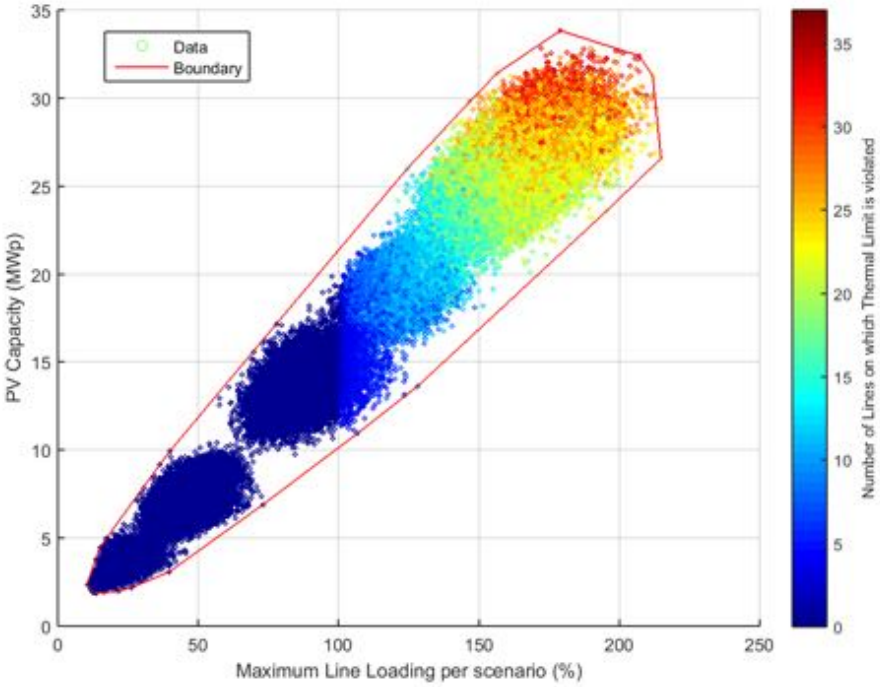


**Figure 158.** PV Capacity against Line Loading - Power Factor equal to 0.95.

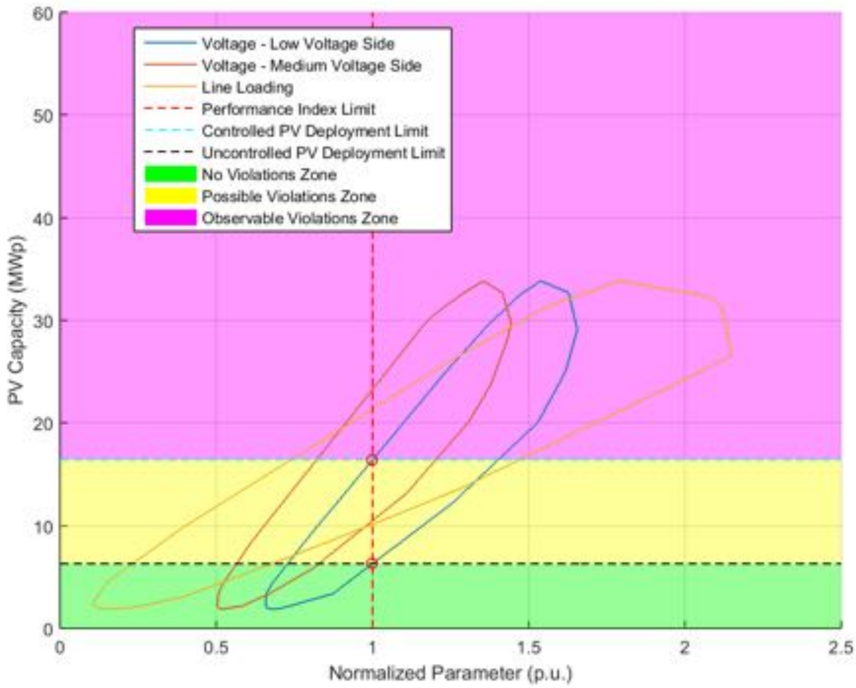


**Figure 159.** Normalized performance index parameters - Power Factor equal to 0.95.

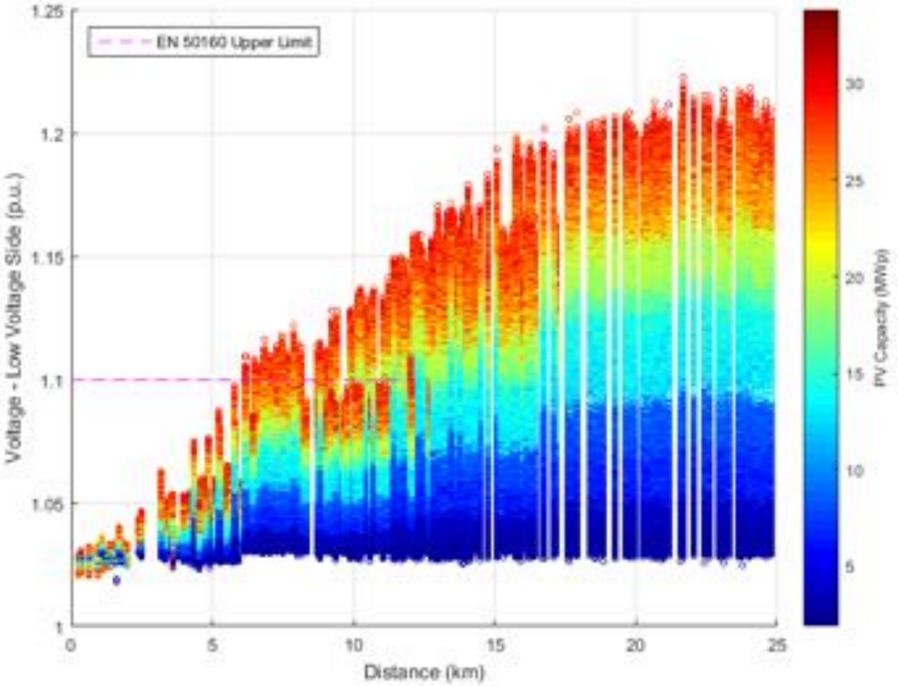


**Figure 160.** Voltage at low voltage side against Distance from transmission substation - Power Factor equal to 0.95.

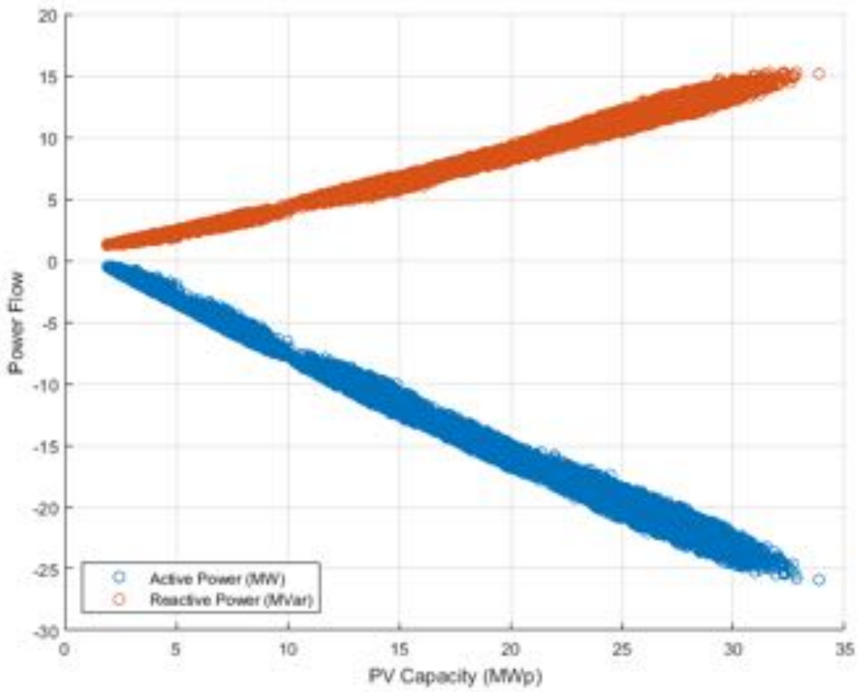


**Figure 161.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor equal to 0.95.

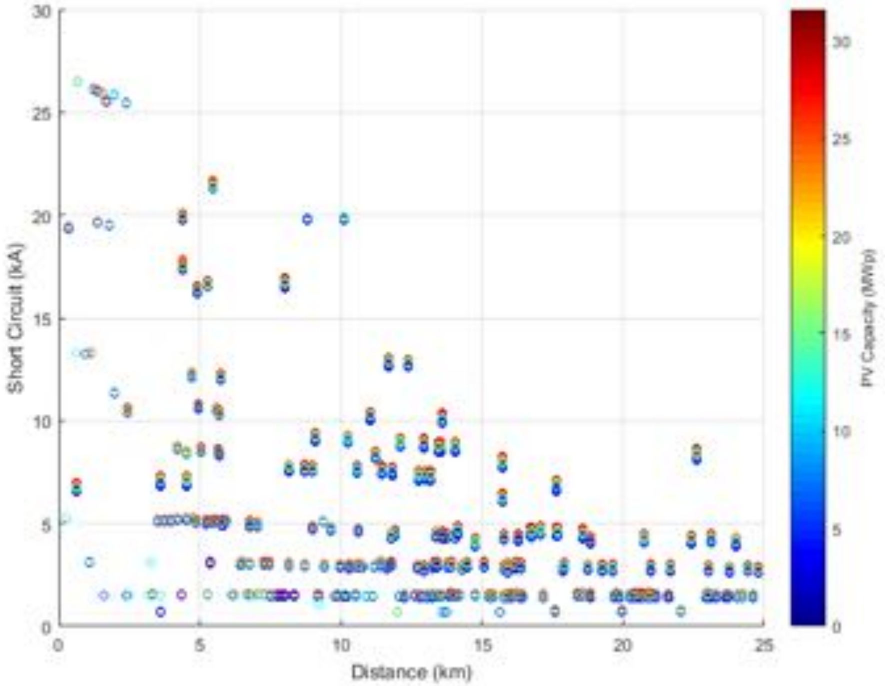


**Figure 162.** Short circuit current against Distance - Power Factor equal to 0.95.

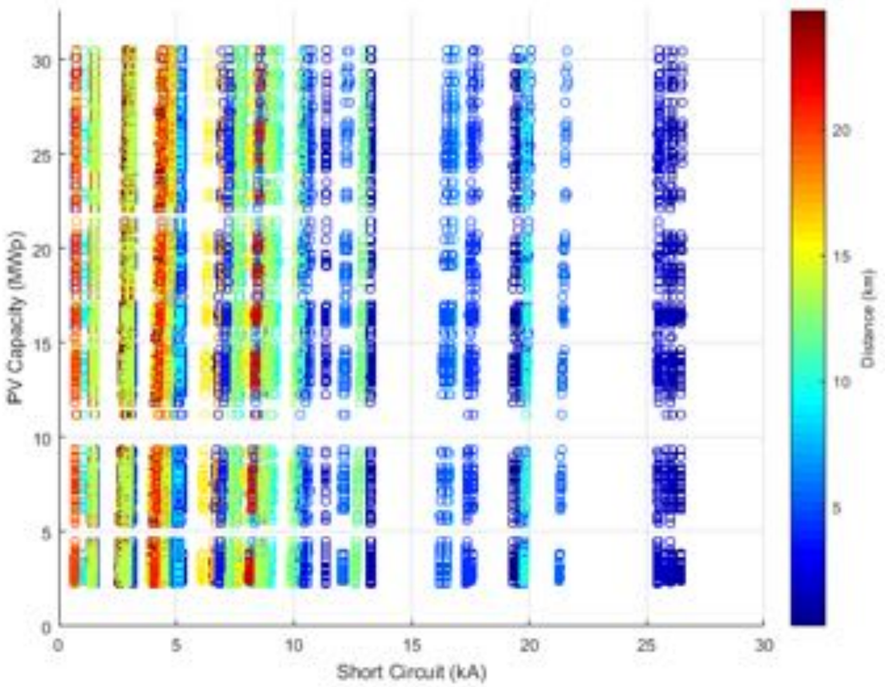


**Figure 163.** PV Capacity against Short Circuit current - Power Factor equal to 0.95.

### C1.3.3 Power Factor cosφ(P)

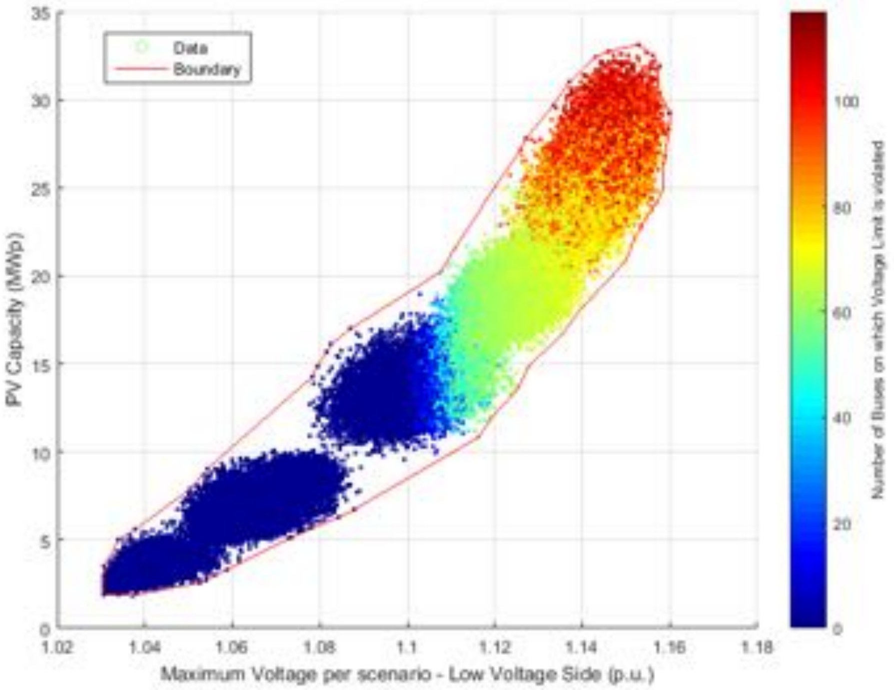


**Figure 164.** PV Capacity against Voltage – Low voltage side - Power Factor cosφ(P).

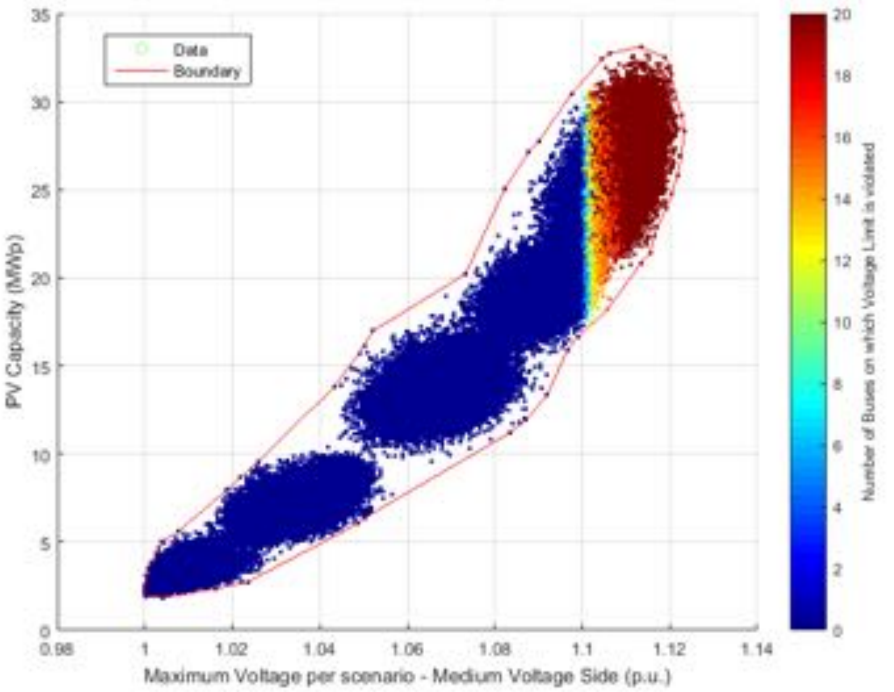


**Figure 165.** PV Capacity against Voltage – Medium voltage side - Power Factor cosφ(P).

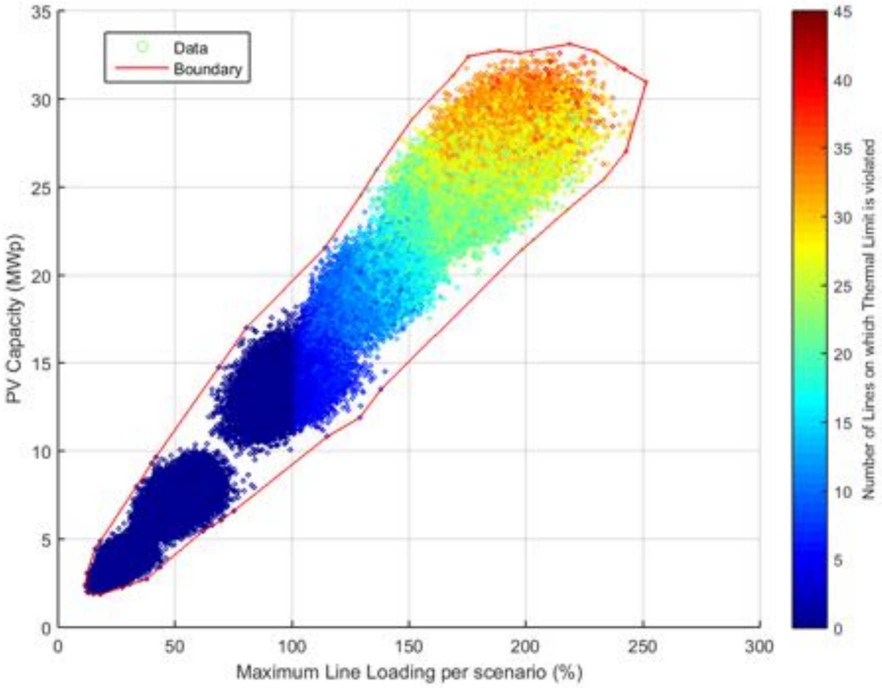


**Figure 166.** PV Capacity against Line Loading - Power Factor cosφ(P).

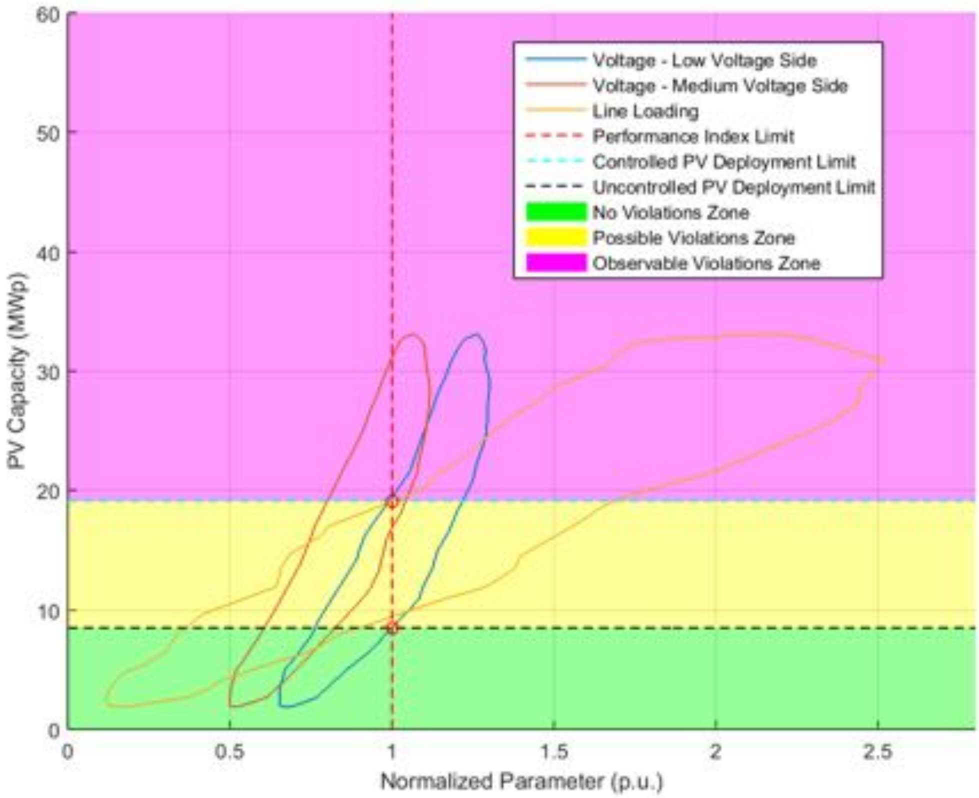


**Figure 167.** Normalized performance index parameters - Power Factor cosφ(P).

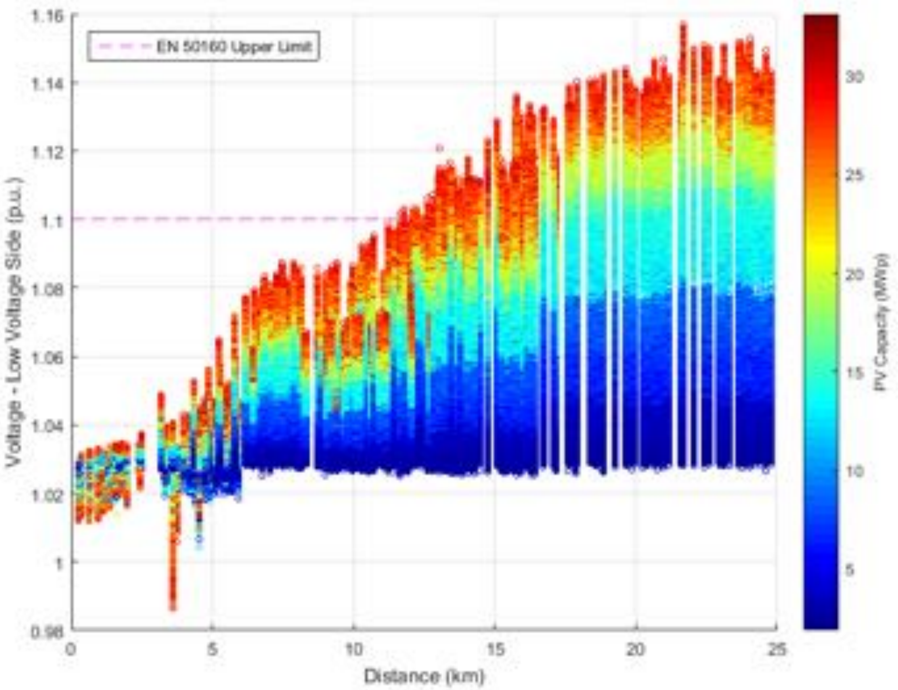


**Figure 168.** Voltage at low voltage side against distance from transmission substation - Power Factor cosφ(P).

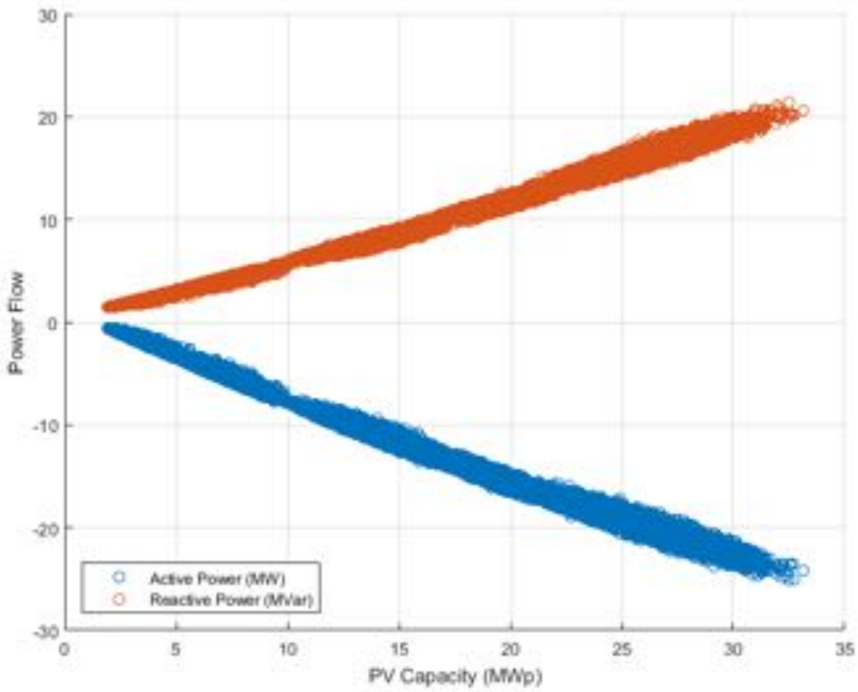


**Figure 169.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor cosφ(P).

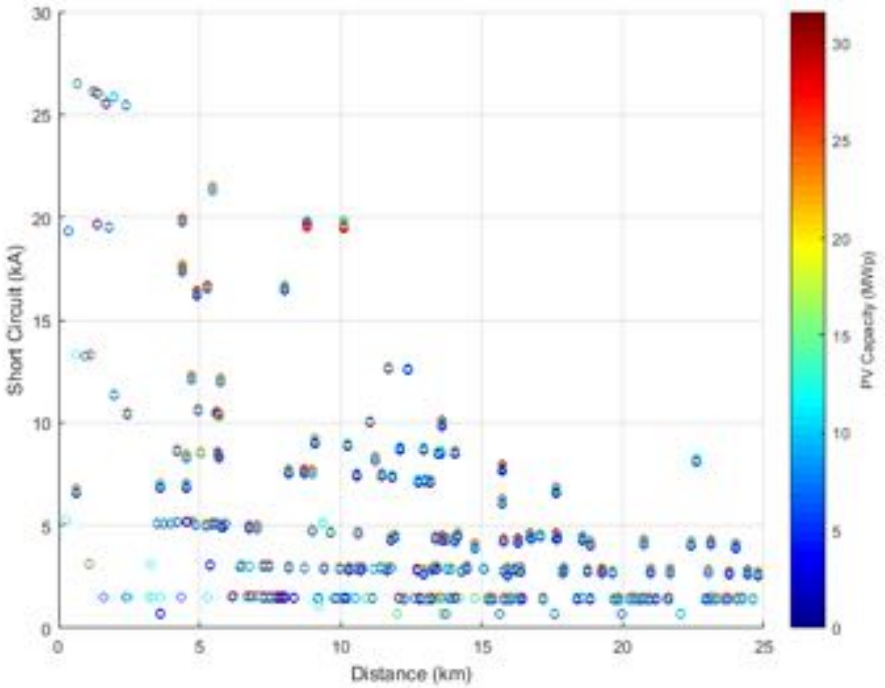


**Figure 170.** Short circuit current against distance - Power Factor cosφ(P).

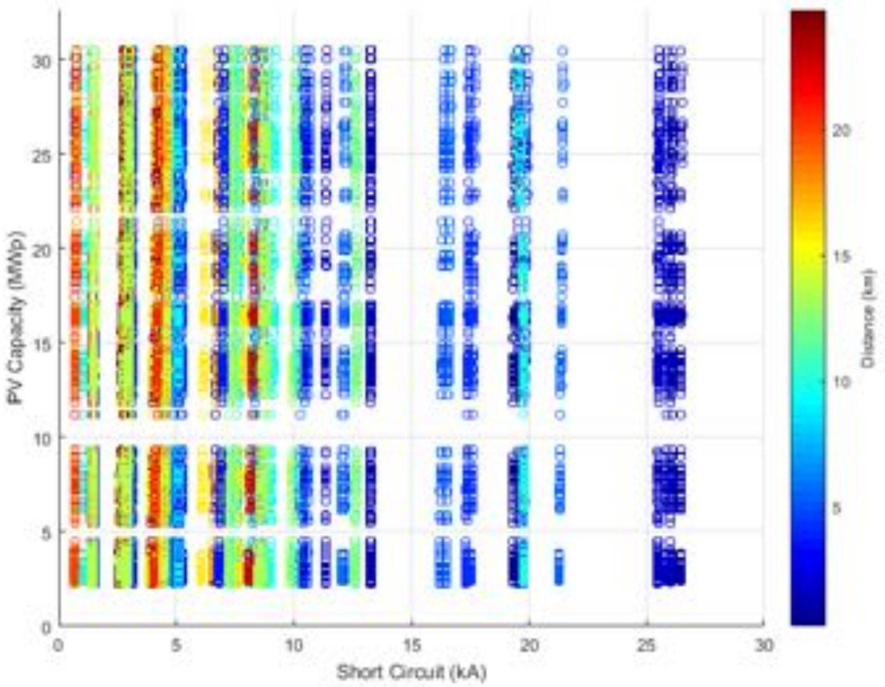


**Figure 171.** PV Capacity against short circuit current - Power Factor cosφ(P).

### C1.3.4 Summary – Monte Carlo Simulation

**Table 28.** Categorization of violations into zones.

| Scenario | No Violations Zone | Possible Violations Zone | Observable Violations Zone |
|---|---|---|---|
| Unity Power Factor | below 3.31 | 3.31 – 11.13 | above 11.13 |
| Power Factor equal to 0.95 | below 6.29 | 6.29 – 16.40 | above 16.40 |
| Power Factor cosφ(P) | below 8.49 | 8.49 – 19.09 | above 19.09 |

**Table 29.** Uncontrolled/Controlled PV Deployment Limit.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit(MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| Unity Power Factor | 3.31 | 11.13 | 6.07 | 16.79 | 11.37 | 24.50 |
| Power Factor equal to 0.95 | 6.30 | 16.40 | 10.48 | 23.27 | 10.14 | 21.36 |
| Power Factor cosφ(P) | 8.49 | 19.48 | 16.88 | 31.13 | 9.44 | 19.09 |

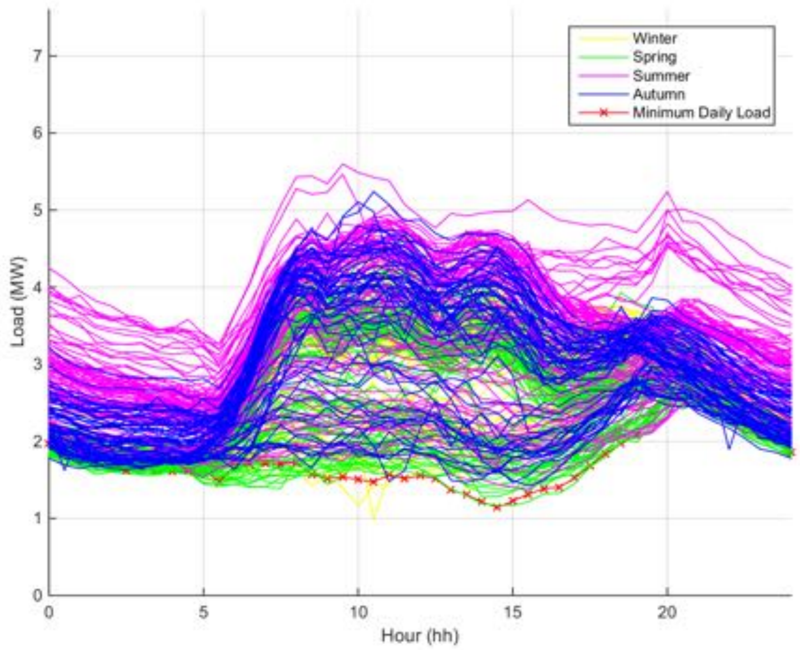


**Figure 172.** Ypronas S/S - Minimum daily load.

# Appendix D

# D. Renos Prentzas s/s - Executive Summary

The results of the PV hosting capacity for Renos Prentzas substation with three 40 MVA transmission transformers (with a total distribution transformer capacity of 126.100 MVA), 24 feeders, 155 distribution substations/transformers/busbars and 252 distribution lines either underground or overhead located in Nicosia district area, are presented and analysed in this Appendix. For this PV hosting capacity assessment, it was assumed that the inverter of PV systems is oversized by 10% (as imposed by newly formulated regulations).

## D.1 Results

### D1.1 Maximum Installed PV Capacity scenario

#### D1.1.1 Unity Power Factor Operation

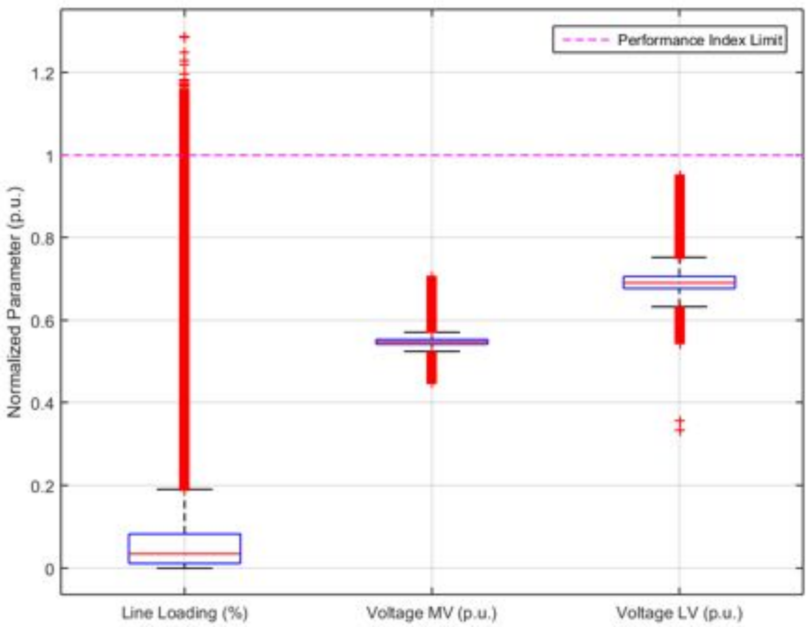


**Figure 173.** Performance Index parameters normalized to their limit – Unity Power Factor.

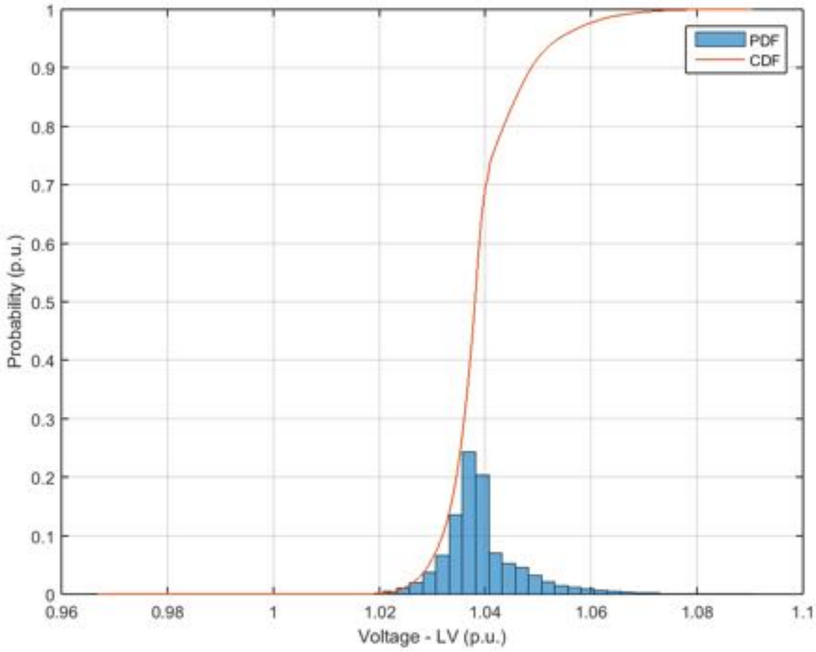


**Figure 174.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity power factor.

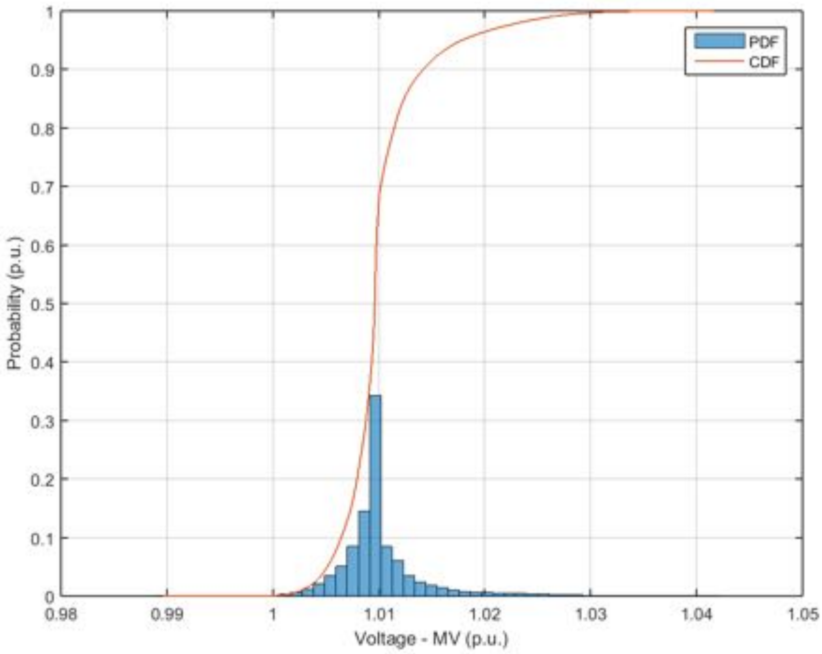


**Figure 175.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Unity power factor.

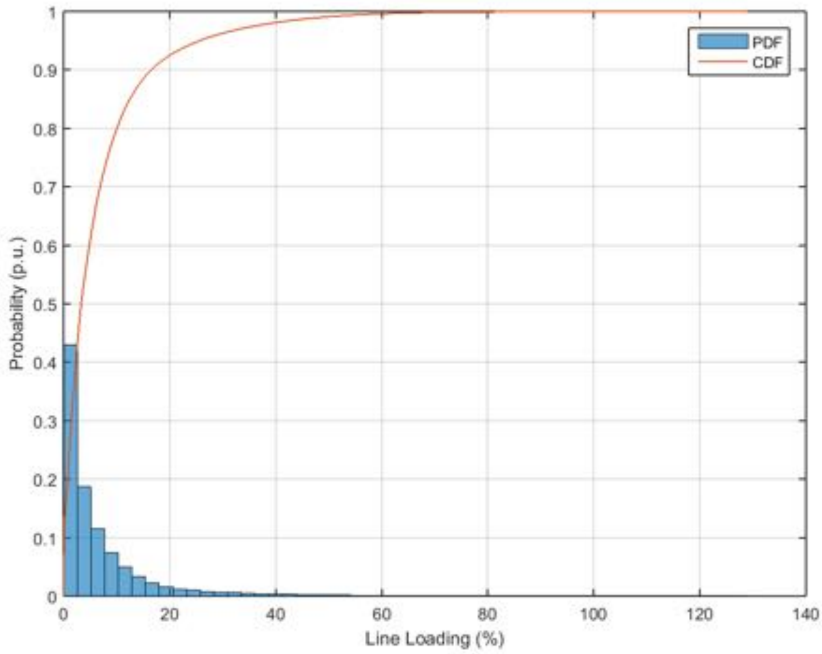


**Figure 176.** Probability distribution and cumulative probability distribution – Line Loading – Unity power factor.

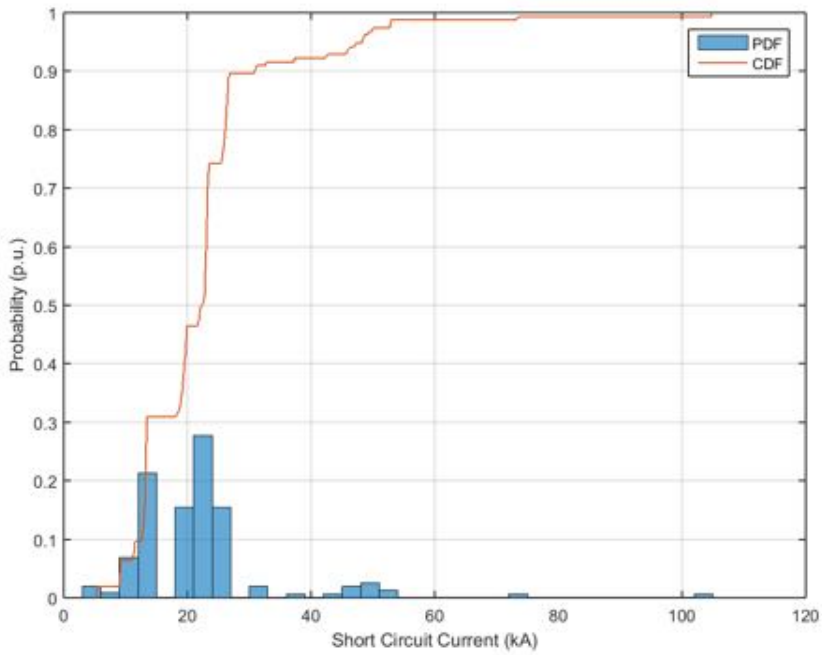


**Figure 177.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity power factor.

### D1.1.2 Power Factor equal to 0.95

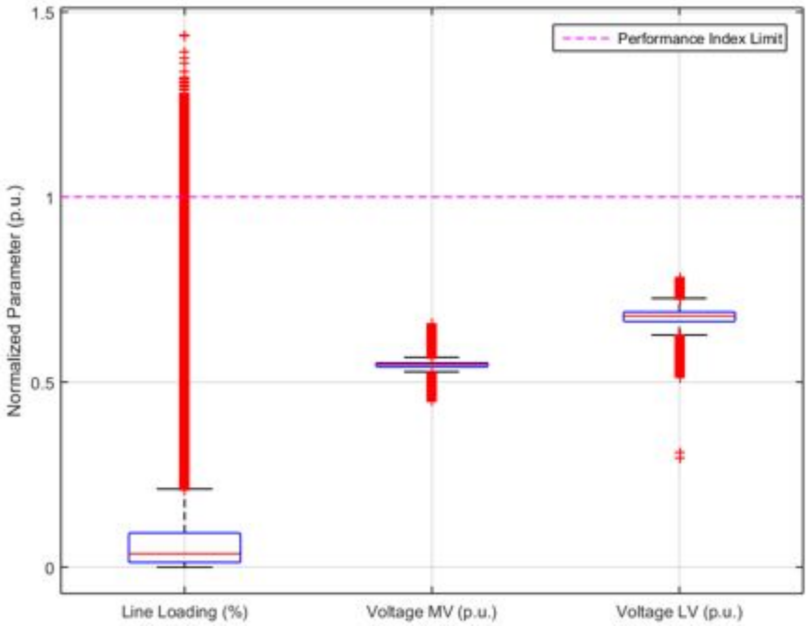


**Figure 178.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

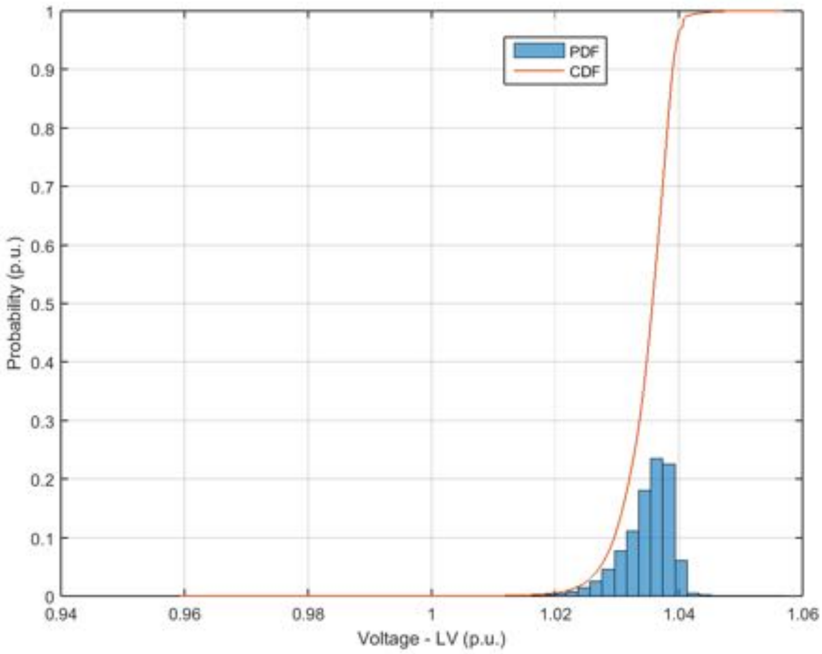


**Figure 179.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

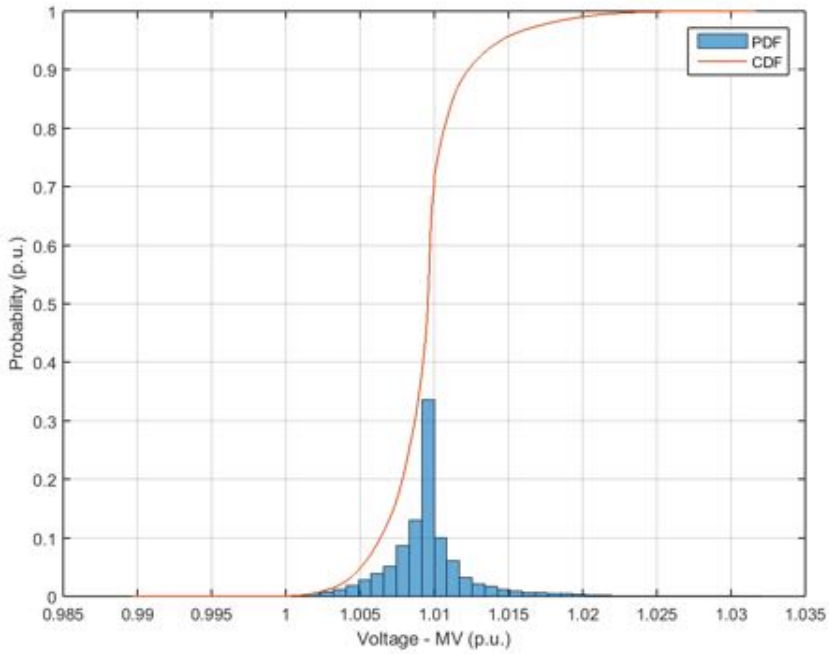


**Figure 180.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor equal to 0.95.

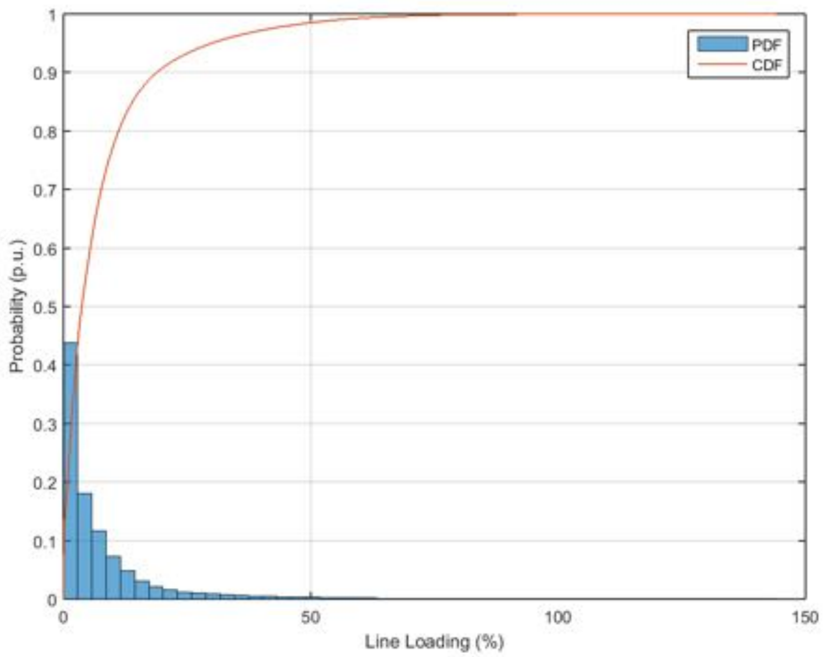


**Figure 181.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

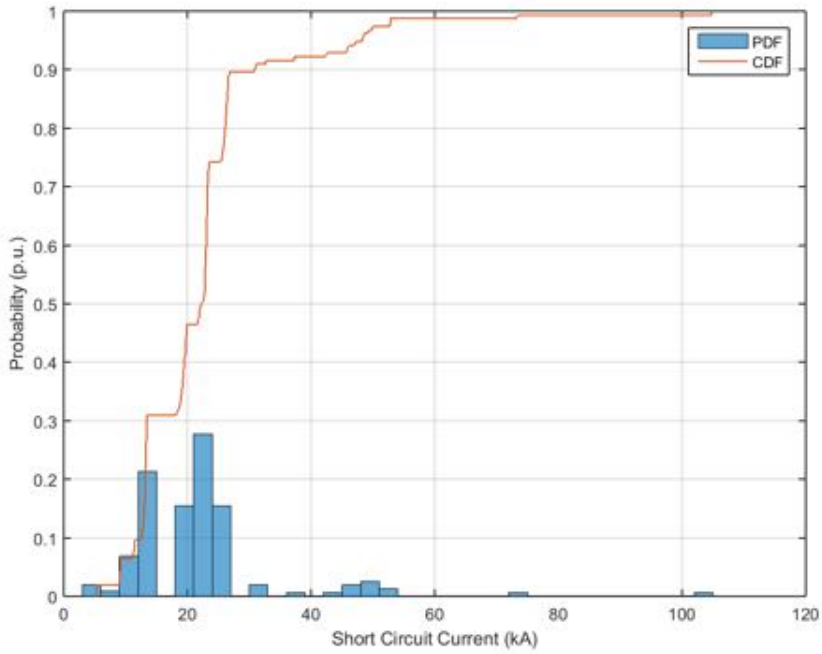


**Figure 182.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### D1.1.3 Power Factor cosφ(P)

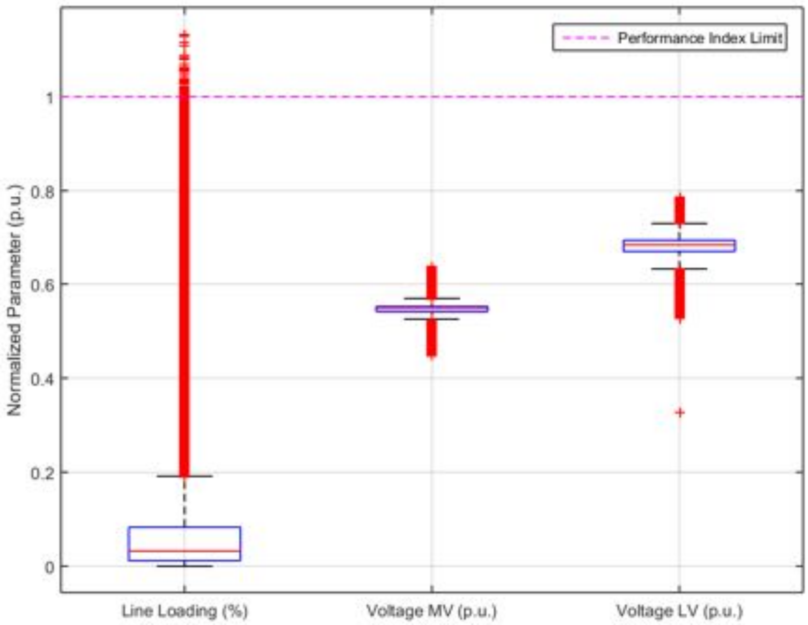


**Figure 183.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

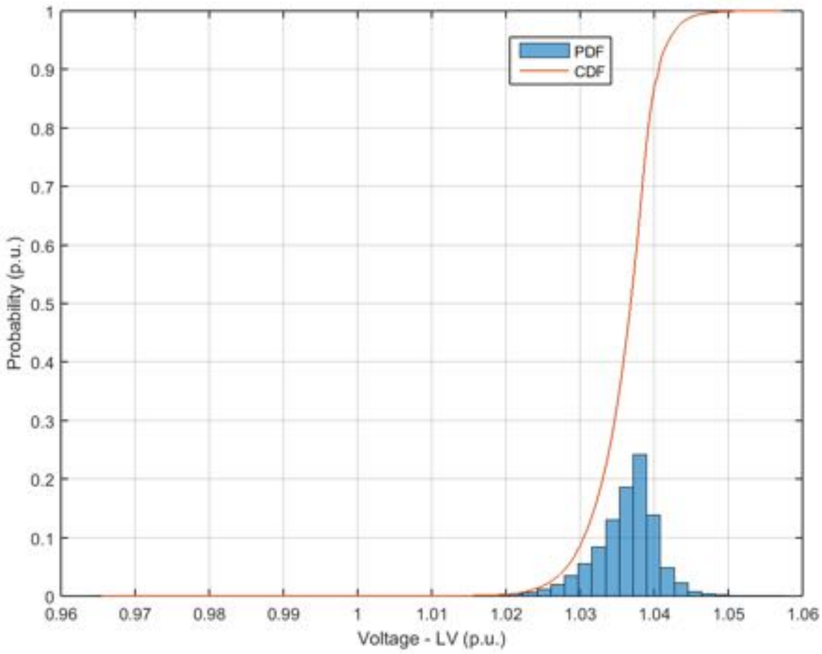


**Figure 184.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

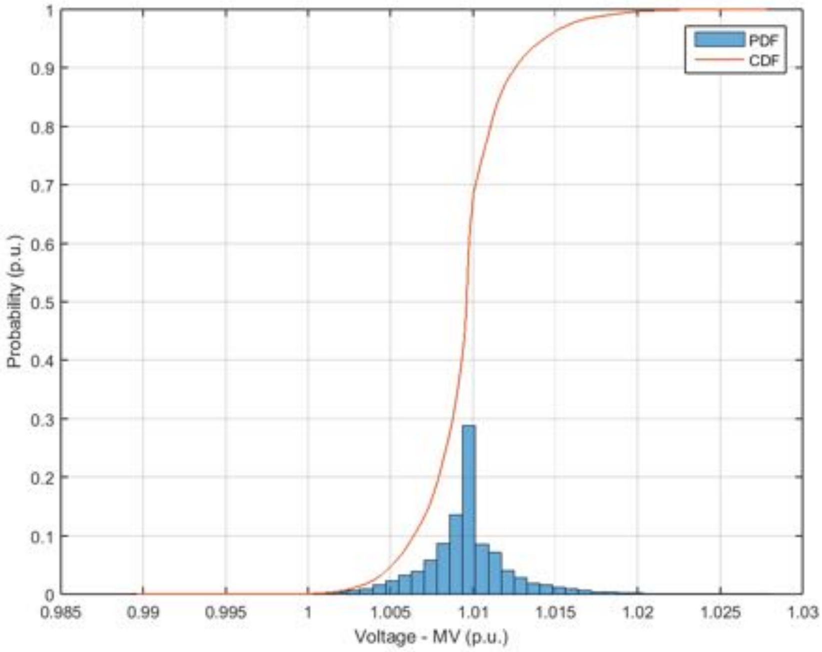


**Figure 185.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor cosφ(P).

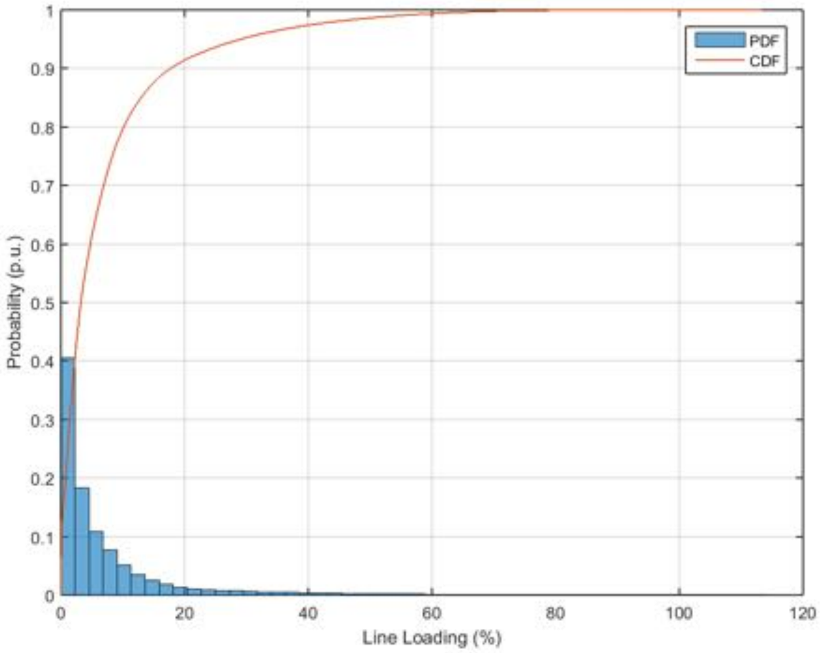


**Figure 186.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

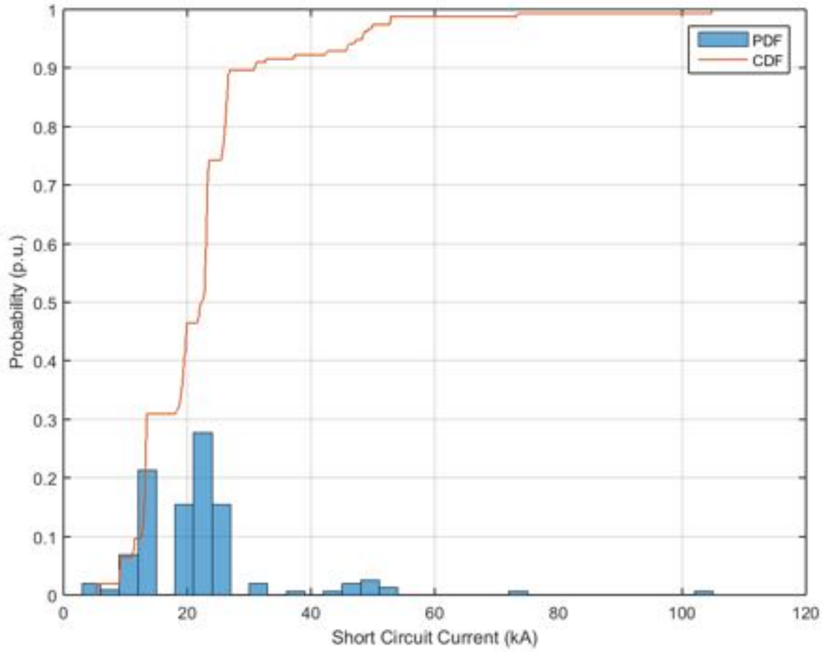


**Figure 187.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### D1.1.4 Summary and Discussion – Maximum Installed PV Capacity scenario

**Table 30.** Statistical analysis of PI parameters - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.334 | 0.296 | 0.328 |
| | 25th quantile | 0.677 | 0.664 | 0.670 |
| | Median | 0.690 | 0.679 | 0.684 |
| | Average | 0.696 | 0.675 | 0.681 |
| | Standard Deviation | 0.001 | 0.000 | 0.000 |
| | 75th quantile | 0.707 | 0.689 | 0.694 |
| | 95th quantile | 0.769 | 0.699 | 0.710 |
| | 99th quantile | 0.826 | 0.705 | 0.725 |
| | Maximum | 0.952 | 0.784 | 0.787 |
| **Number of elements of which the limit is violated** | | 0 out of 155 | 0 out of 155 | 0 out of 155 |
| **Voltage – Medium Voltage Side** | Minimum | 0.448 | 0.448 | 0.448 |
| | 25th quantile | 0.542 | 0.542 | 0.542 |
| | Median | 0.548 | 0.548 | 0.548 |
| | Average | 0.551 | 0.548 | 0.548 |
| | Standard Deviation | 0.000 | 0.000 | 0.000 |
| | 75th quantile | 0.554 | 0.551 | 0.553 |
| | 95th quantile | 0.589 | 0.572 | 0.572 |
| | 99th quantile | 0.631 | 0.599 | 0.591 |
| | Maximum | 0.708 | 0.658 | 0.639 |
| **Number of elements of which the limit is violated** | | 0 out of 155 | 0 out of 155 | 0 out of 155 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.011 | 0.012 | 0.011 |
| | Median | 0.033 | 0.037 | 0.032 |
| | Average | 0.067 | 0.076 | 0.071 |
| | Standard Deviation | 0.009 | 0.012 | 0.011 |
| | 75th quantile | 0.083 | 0.092 | 0.083 |
| | 95th quantile | 0.257 | 0.300 | 0.291 |
| | 99th quantile | 0.487 | 0.557 | 0.542 |
| | Maximum | 1.288 | 1.440 | 1.133 |
| | CDF-100% loading | 99.99% | 99.97% | 100.00% |
| **Number of elements of which the limit is violated** | | 3 out of 252 | 5 out of 252 | 7 out of 252 |

**Table 31.** Statistical analysis of Short Circuit Values - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 5.282 | 5.281 | 5.283 |
| | 25th quantile | 13.306 | 13.293 | 13.293 |
| | Median | 22.246 | 22.215 | 22.211 |
| | Average | 22.221 | 22.211 | 22.213 |
| | Standard Deviation | 12.125 | 12.123 | 12.123 |
| | 75th quantile | 25.577 | 25.573 | 25.576 |
| | 95th quantile | 48.296 | 48.296 | 48.296 |
| | 99th quantile | 73.254 | 73.253 | 73.253 |
| | Maximum | 104.885 | 104.861 | 104.866 |

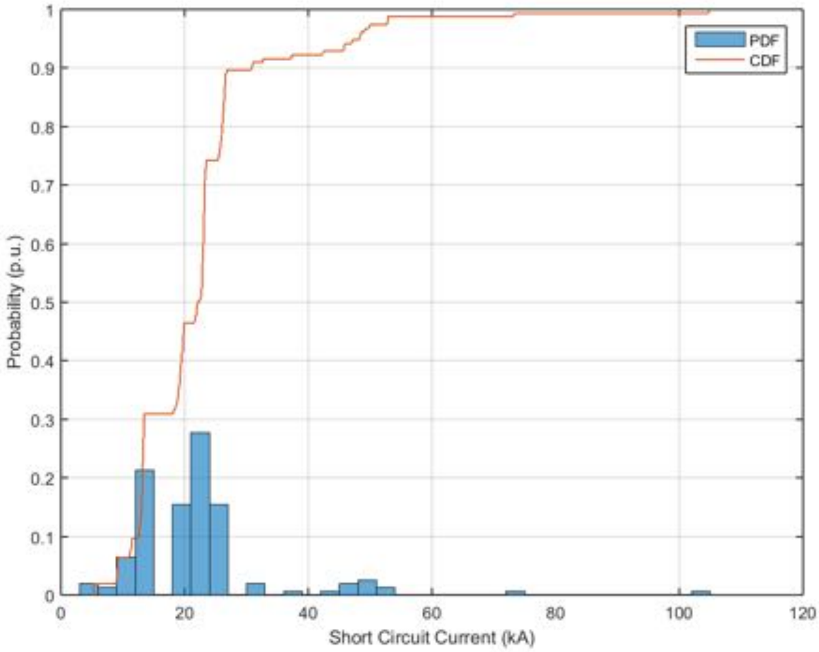


**Figure 188.** Probability distribution and cumulative probability distribution – Short Circuit Current – No PV.

## D1.2 Maximum PV Capacity per Distribution Substation

### D1.2.1 Unity Power Factor Scheme

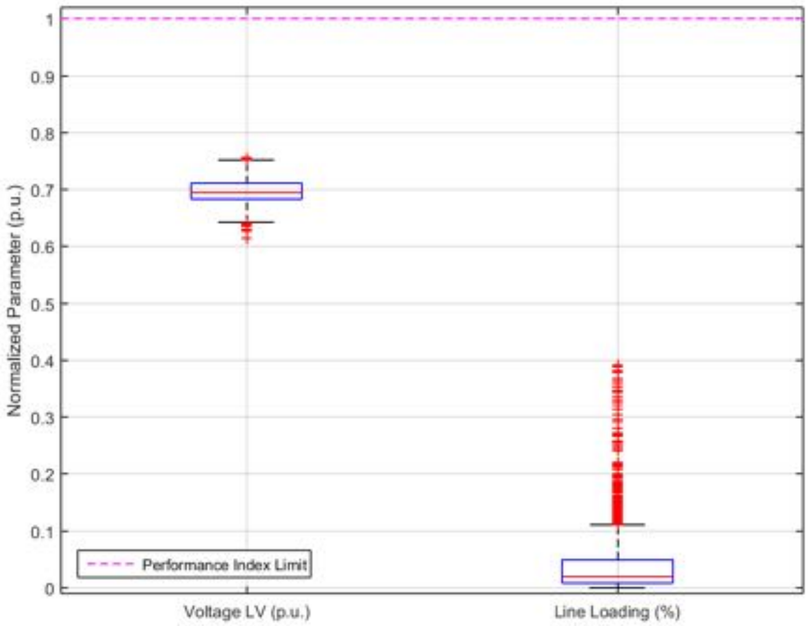


**Figure 189.** Performance Index parameters normalized to their limit – Unity Power Factor.

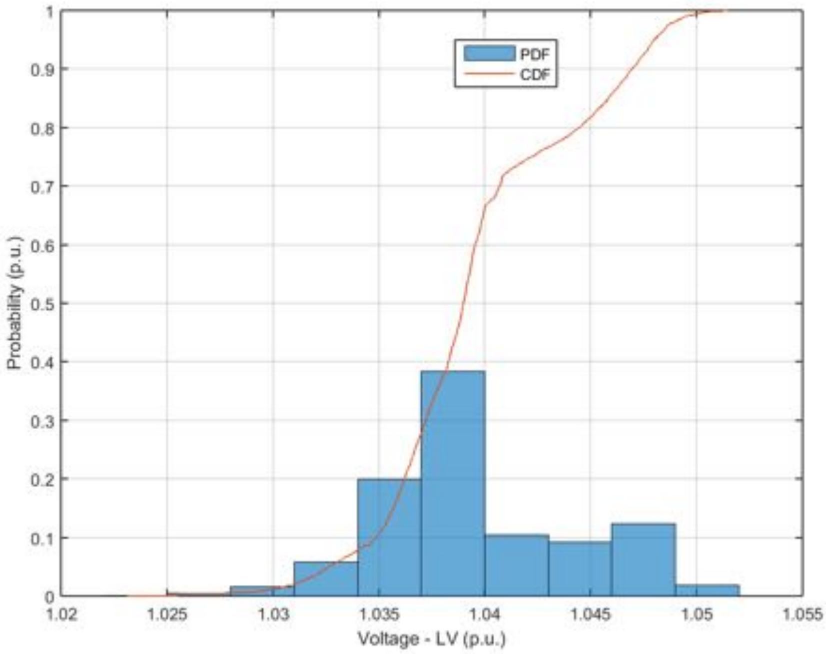


**Figure 190.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity Power Factor.

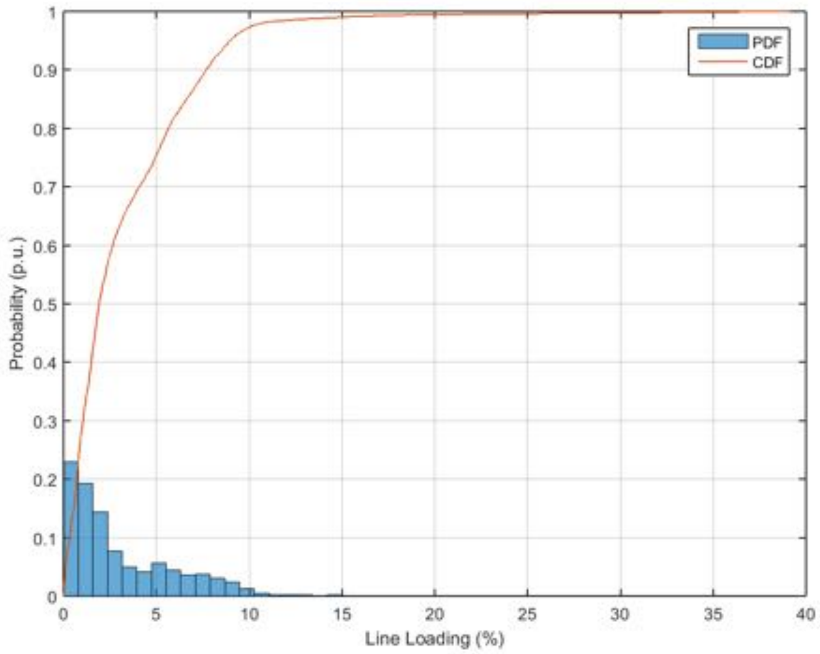


**Figure 191.** Probability distribution and cumulative probability distribution – Line Loading – Unity Power Factor.

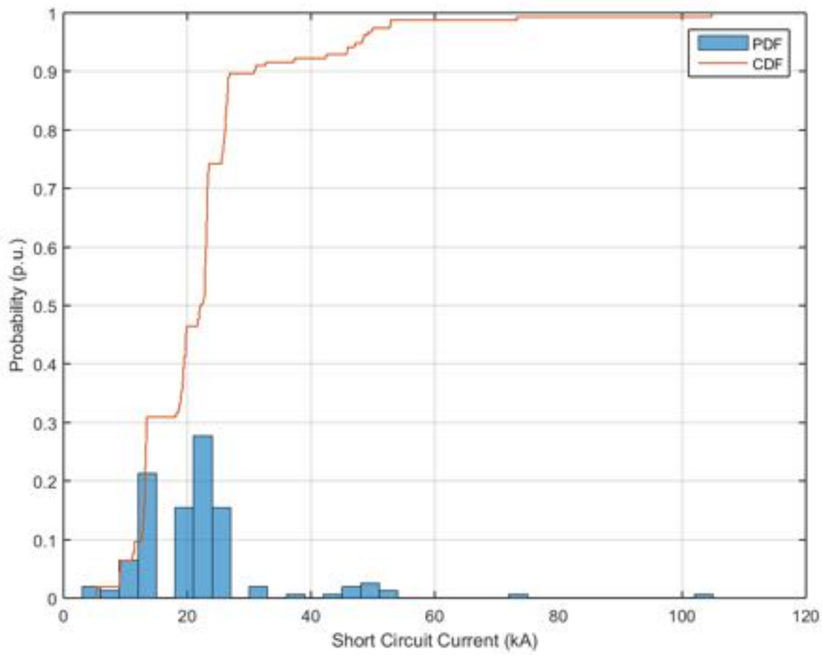


**Figure 192.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity Power Factor.

### D1.2.2 Power Factor equal to 0.95

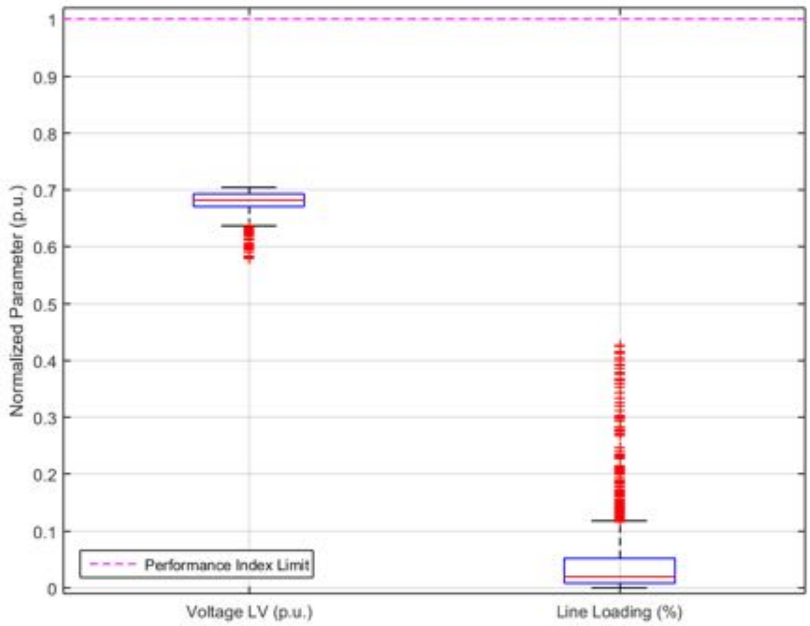


**Figure 193.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

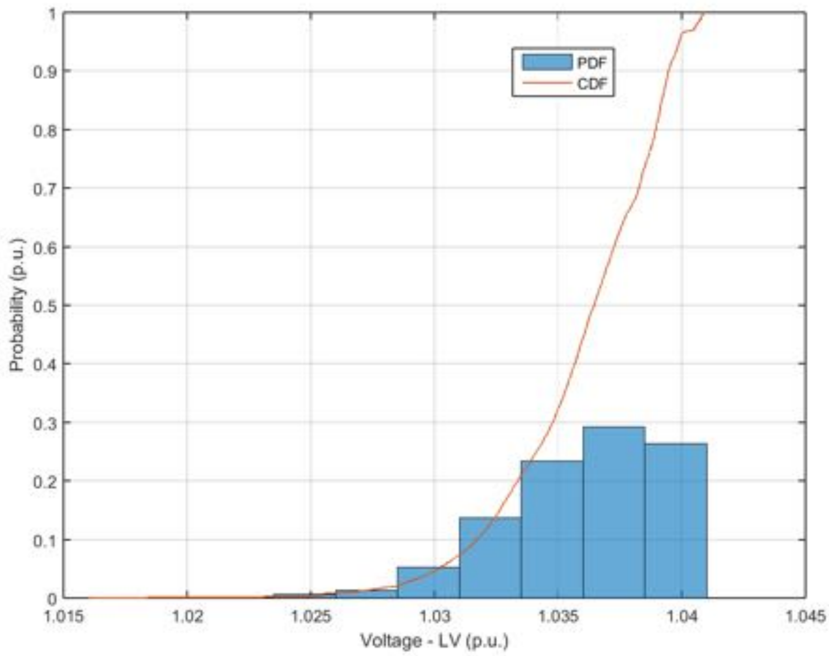


**Figure 194.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

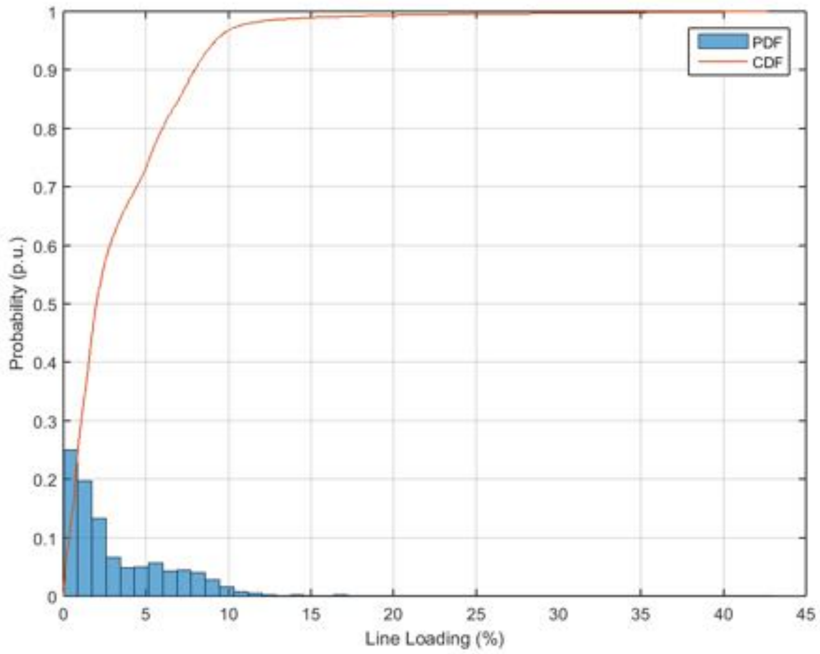


**Figure 195.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

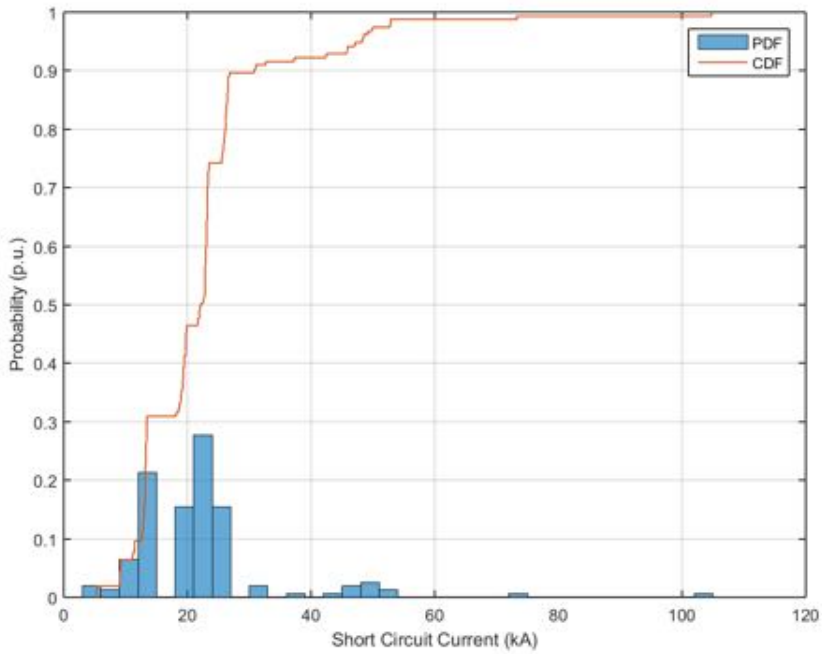


**Figure 196.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### D1.2.3 Power Factor cosφ(P)

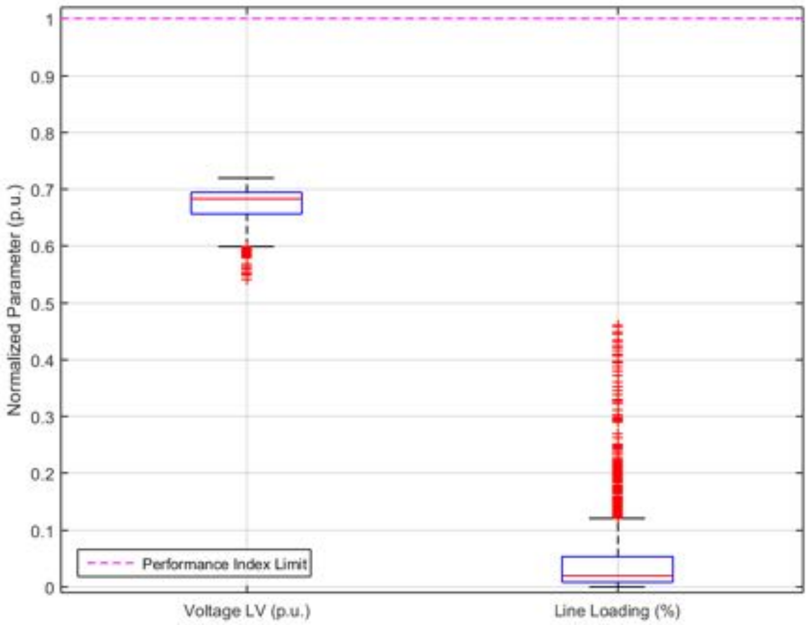


**Figure 197.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

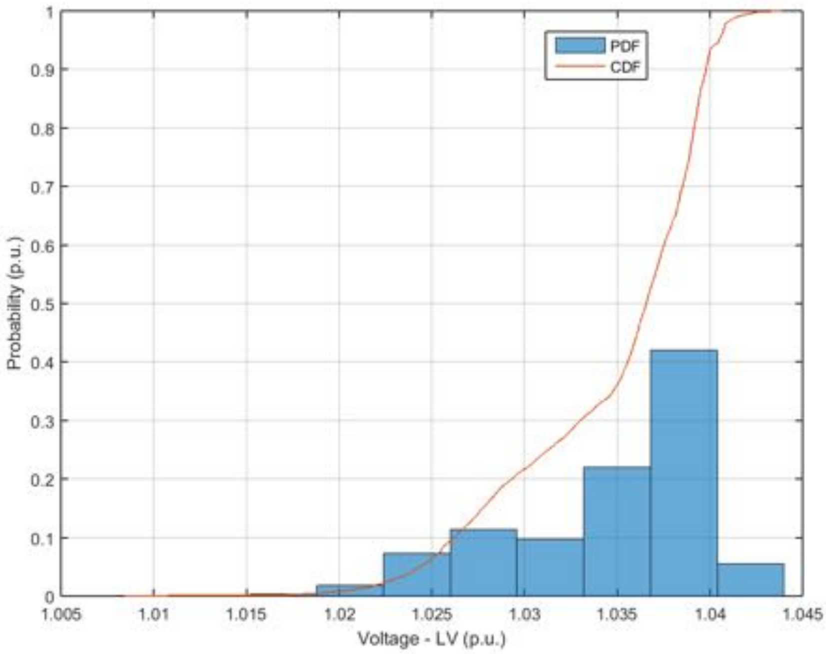


**Figure 198.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

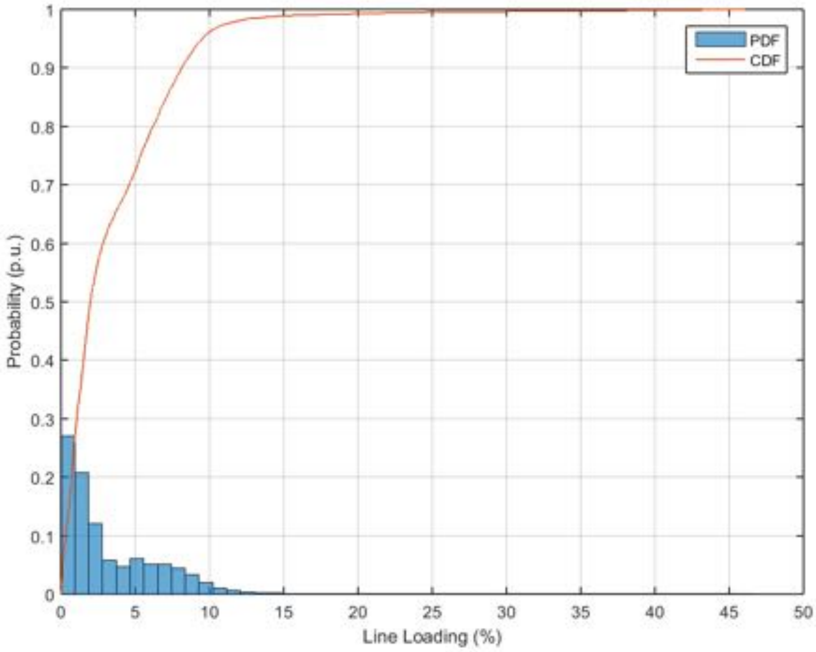


**Figure 199.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

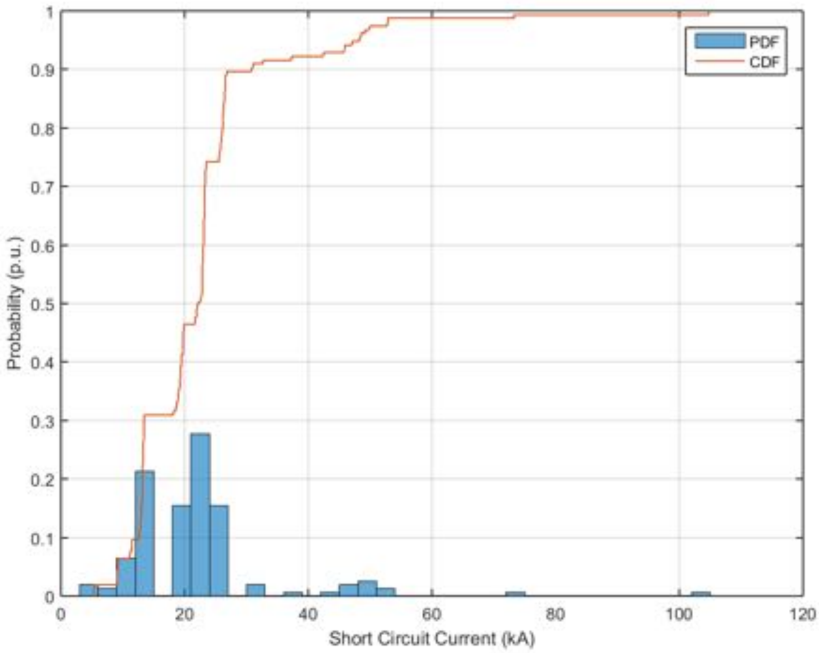


**Figure 200.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### D1.2.4 Summary and Discussion–Maximum PV Capacity per Distribution Substation

**Table 32.** Statistical analysis of PI parameters - Maximum PV Capacity per Distribution Substation.

| | | Scenario | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.616 | 0.580 | 0.542 |
| | 25th quantile | 0.684 | 0.671 | 0.656 |
| | Median | 0.695 | 0.682 | 0.683 |
| | Average | 0.698 | 0.680 | 0.674 |
| | Standard Deviation | 0.001 | 0.001 | 0.001 |
| | 75th quantile | 0.711 | 0.693 | 0.694 |
| | 95th quantile | 0.740 | 0.699 | 0.703 |
| | 99th quantile | 0.747 | 0.704 | 0.708 |
| | Maximum | 0.757 | 0.704 | 0.719 |
| **Number of elements of which the limit is violated** | | 0 out of 155 | 0 out of 155 | 0 out of 155 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.009 | 0.009 | 0.009 |
| | Median | 0.019 | 0.020 | 0.020 |
| | Average | 0.032 | 0.034 | 0.035 |
| | Standard Deviation | 0.001 | 0.001 | 0.002 |
| | 75th quantile | 0.049 | 0.052 | 0.054 |
| | 95th quantile | 0.090 | 0.092 | 0.095 |
| | 99th quantile | 0.149 | 0.156 | 0.159 |
| | Maximum | 0.391 | 0.427 | 0.461 |
| **Number of elements of which the limit is violated** | | 0 out of 251 | 0 out of 251 | 0 out of 251 |

**Table 33.** Statistical analysis of Short Circuit Values - Maximum PV Capacity per Distribution Substation.

| | | Scenario | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 5.301 | 5.301 | 5.301 |
| | 25th quantile | 13.285 | 13.285 | 13.285 |
| | Median | 22.210 | 22.210 | 22.210 |
| | Average | 22.201 | 22.201 | 22.201 |
| | Standard Deviation | 12.160 | 12.160 | 12.160 |
| | 75th quantile | 25.556 | 25.556 | 25.556 |
| | 95th quantile | 47.995 | 47.995 | 47.995 |
| | 99th quantile | 72.238 | 72.238 | 72.238 |
| | Maximum | 104.783 | 104.783 | 104.783 |

## D1.3 Assessing PV Capacity using Monte Carlo method

### D1.3.1 Unity Power Factor Operation

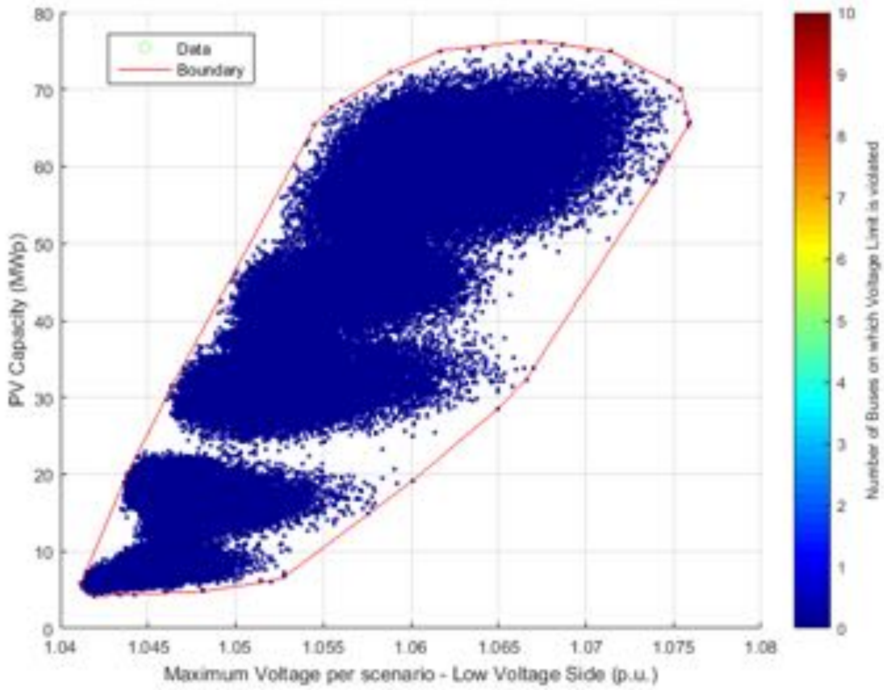


**Figure 201.** PV Capacity against Voltage – Low voltage side - Unity Power Factor.

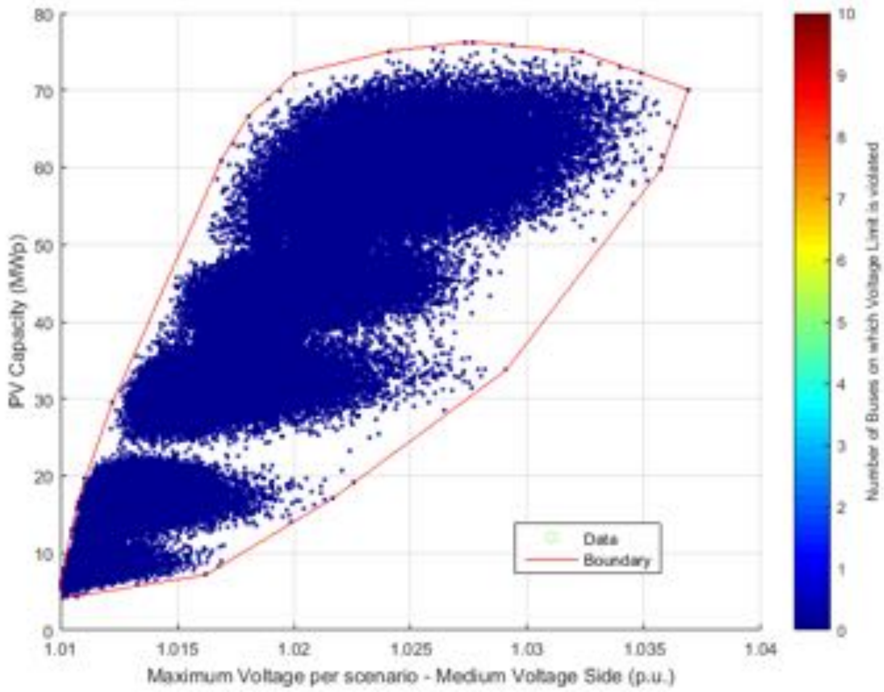


**Figure 202.** PV Capacity against Voltage – Medium voltage side - Unity Power Factor.

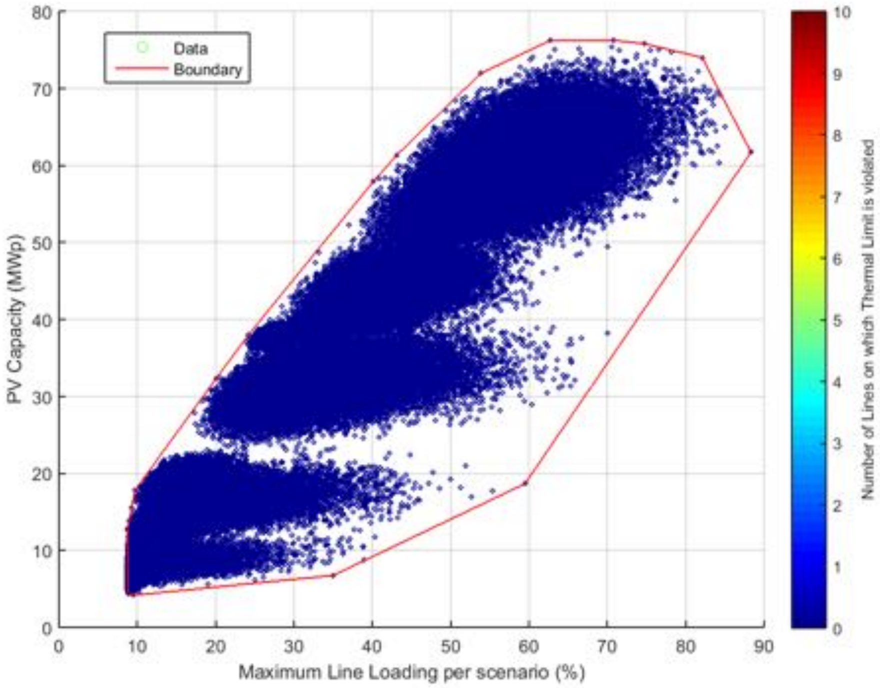


**Figure 203.** PV Capacity against Line Loading - Unity Power Factor.

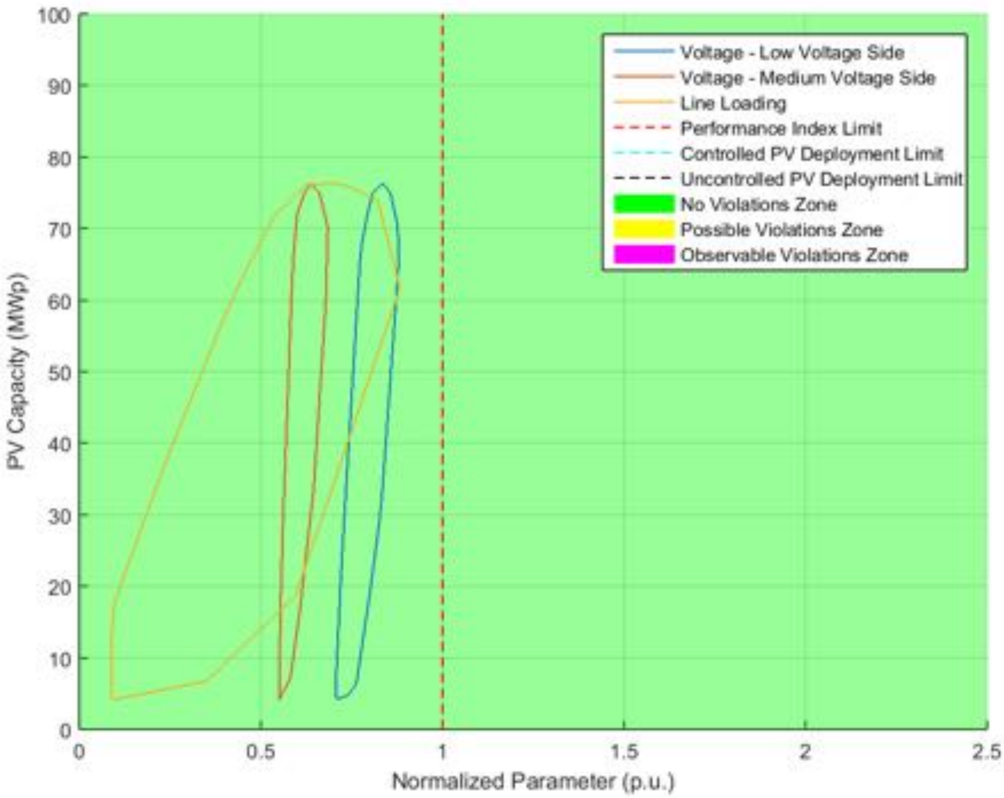


**Figure 204.** Normalized performance index parameters - Unity Power Factor.

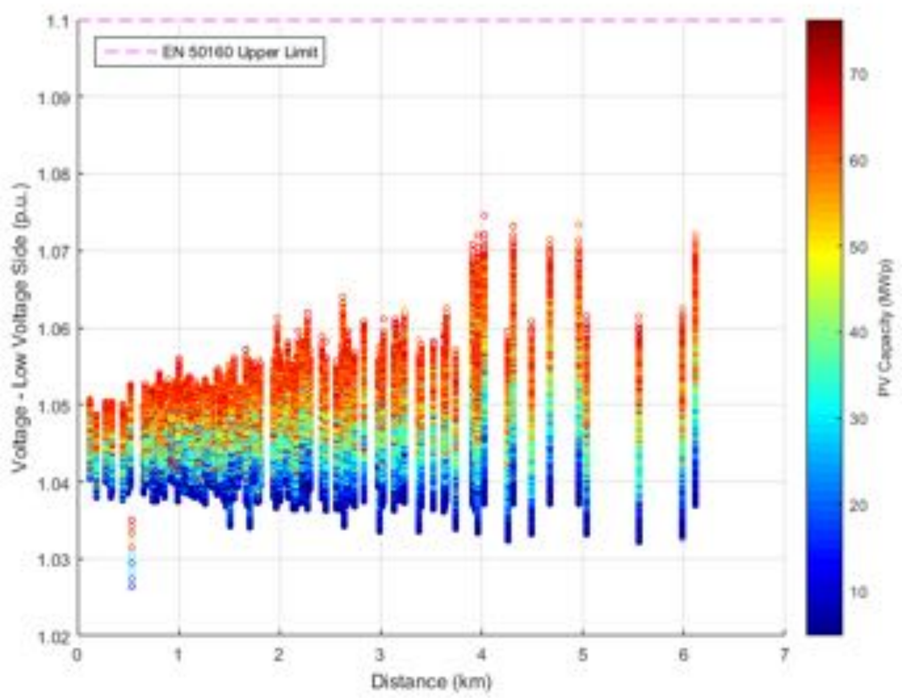


**Figure 205.** Voltage at low voltage side against distance from transmission substation - Unity Power Factor.

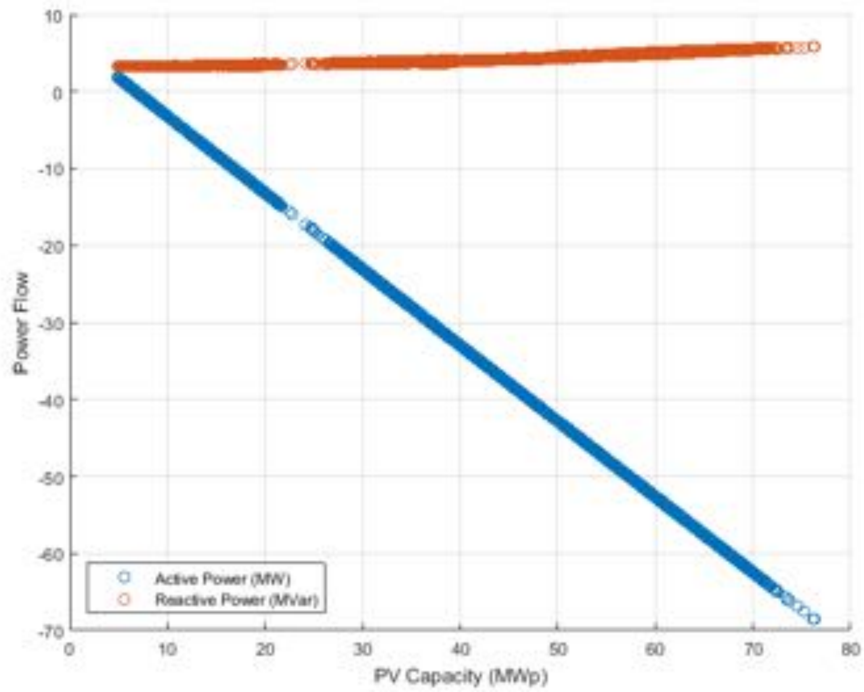


**Figure 206.** Power flow at PCC (connection of the reference substation with HV network) against PV capacity - Unity Power Factor (negative sign denotes reverse power flow).

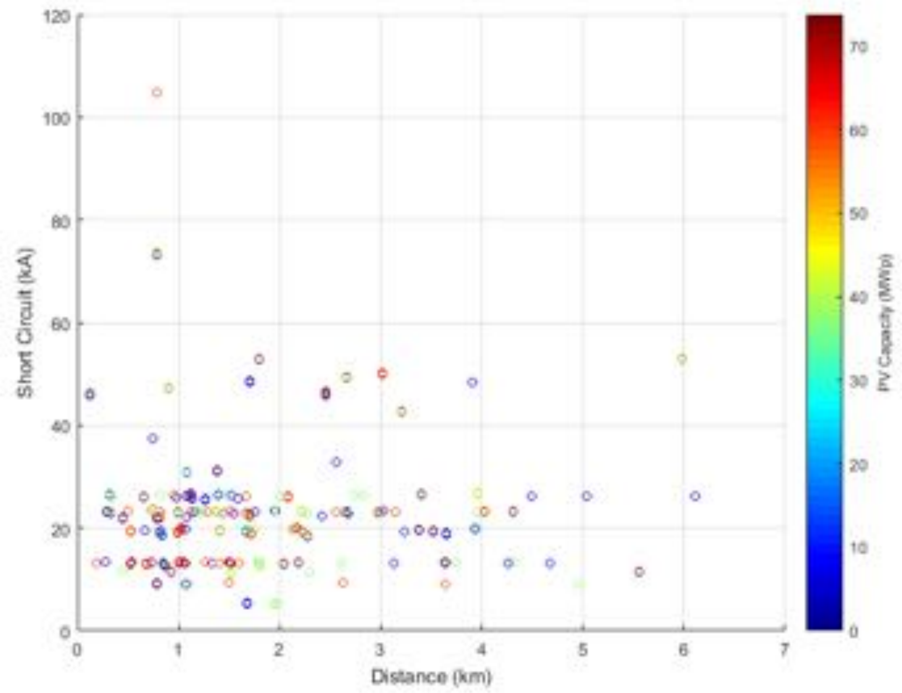


**Figure 207.** Short circuit current against distance - Unity Power Factor.

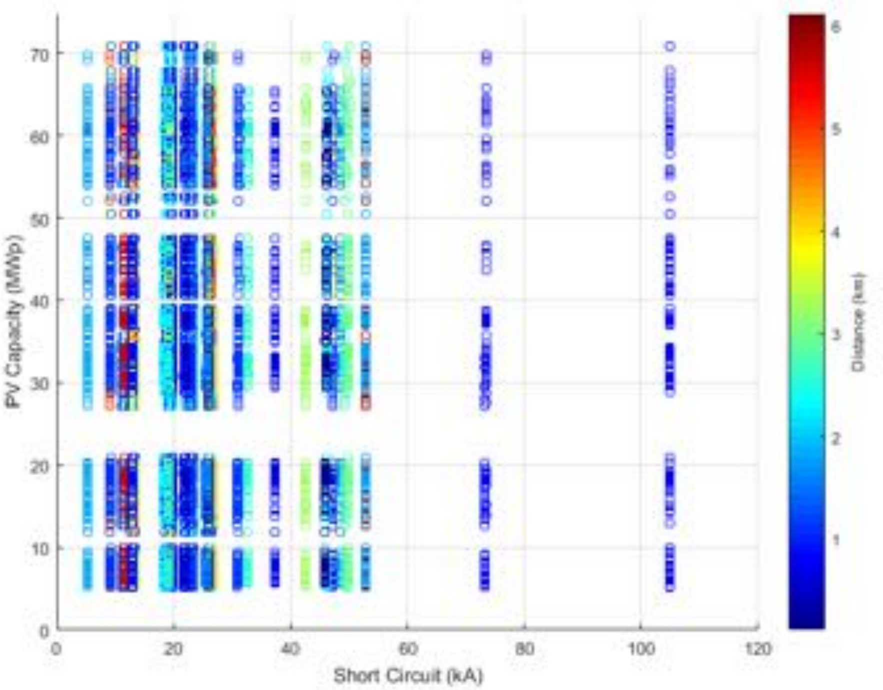


**Figure 208.** PV Capacity against Short circuit current - Unity Power Factor

### D1.3.2 Power Factor equal to 0.95

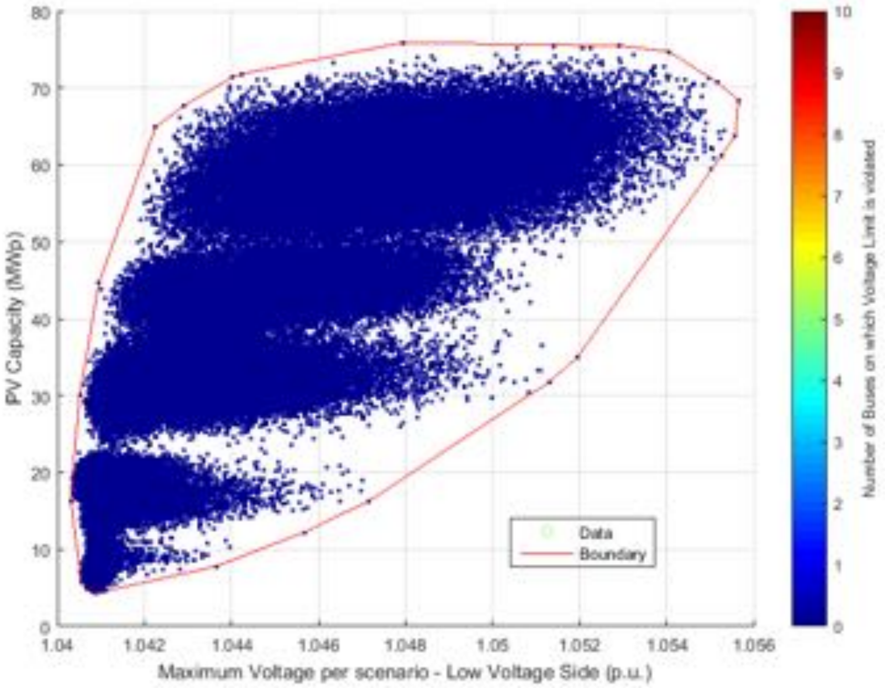


**Figure 209.** PV Capacity against Voltage – Low voltage side - Power Factor equal to 0.95.

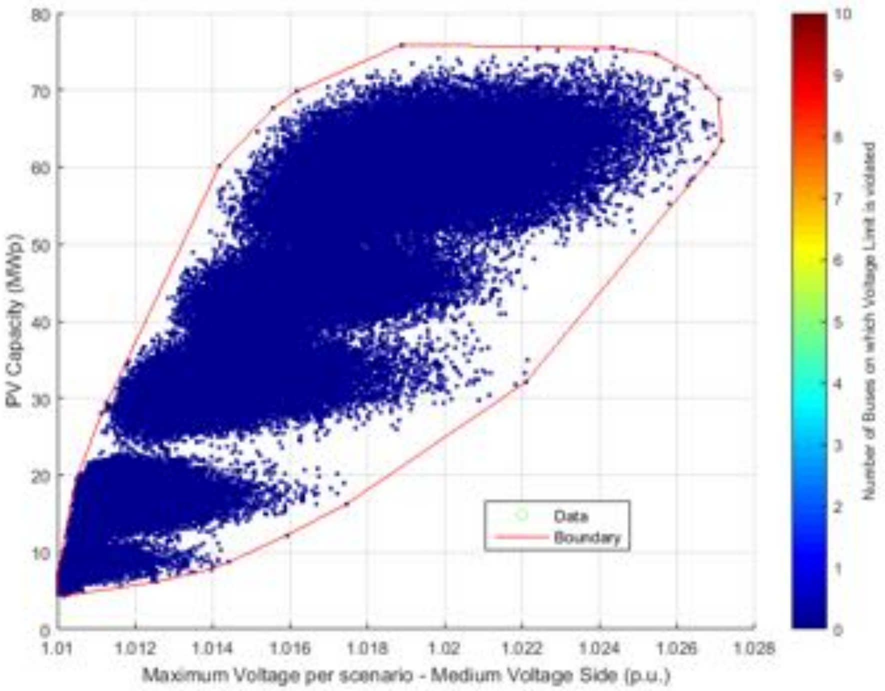


**Figure 210.** PV Capacity against Voltage – Medium voltage side - Power Factor equal to 0.95.

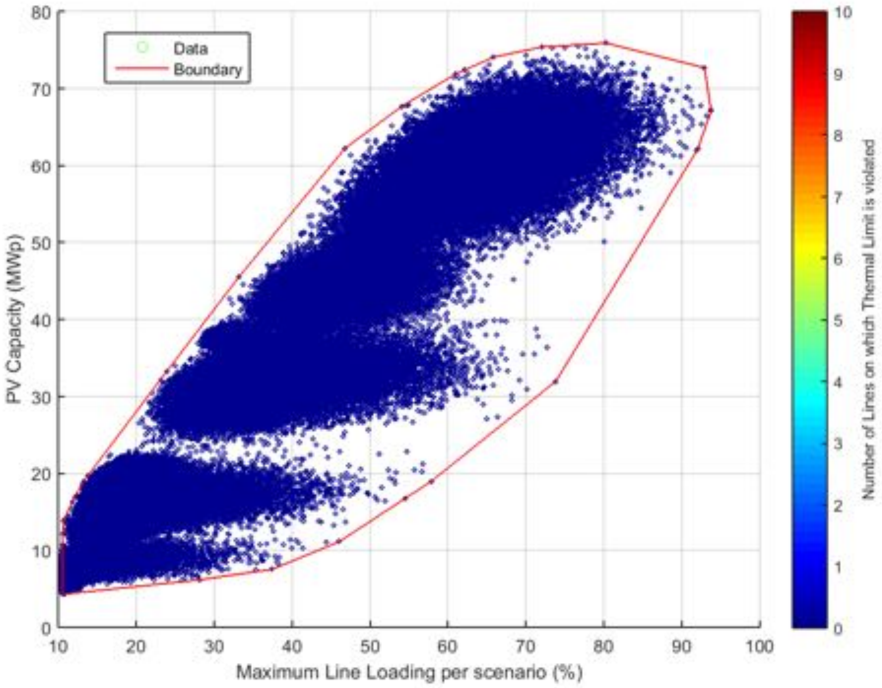


**Figure 211.** PV Capacity against Line Loading - Power Factor equal to 0.95.

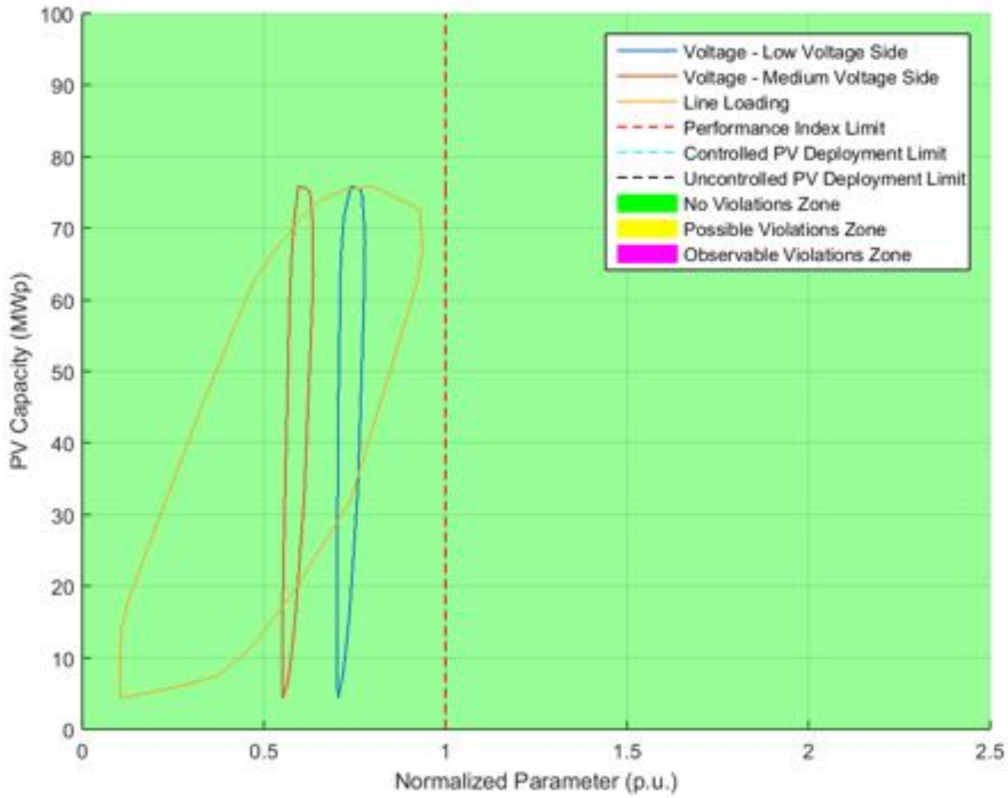


**Figure 212.** Normalized performance index parameters - Power Factor equal to 0.95.

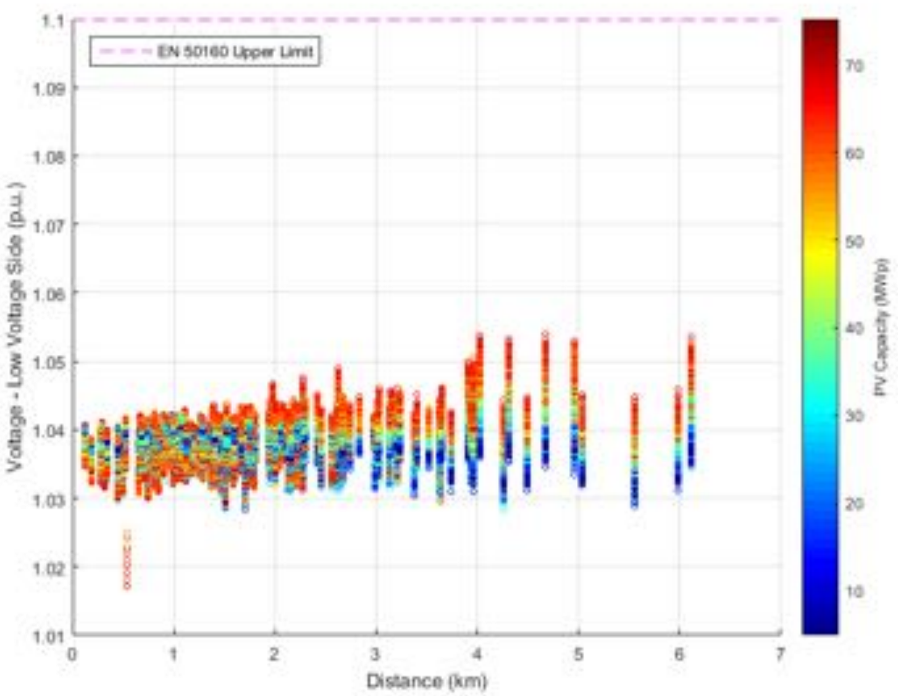


**Figure 213.** Voltage at low voltage side against Distance from transmission substation - Power Factor equal to 0.95.

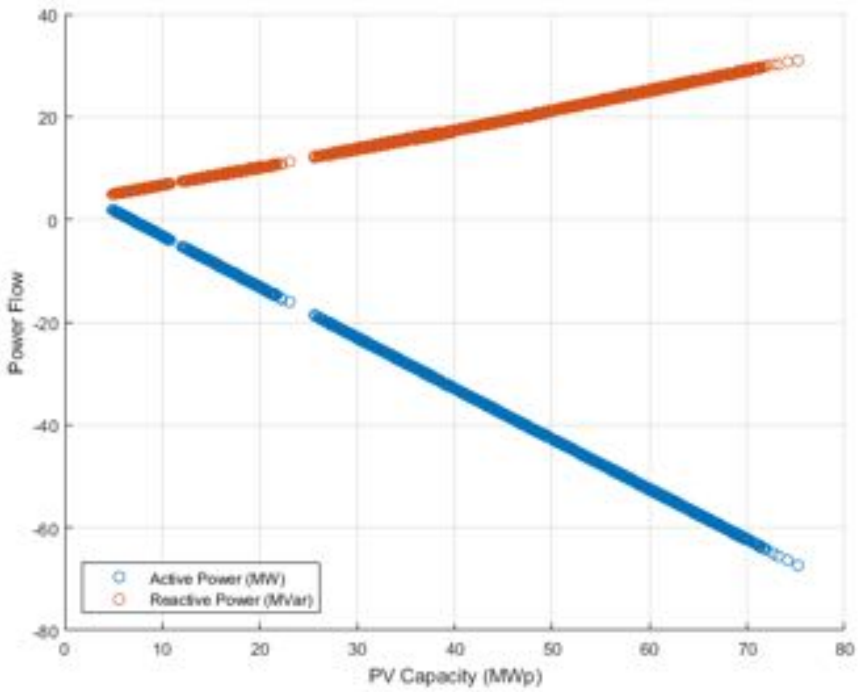


**Figure 214.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor equal to 0.95.

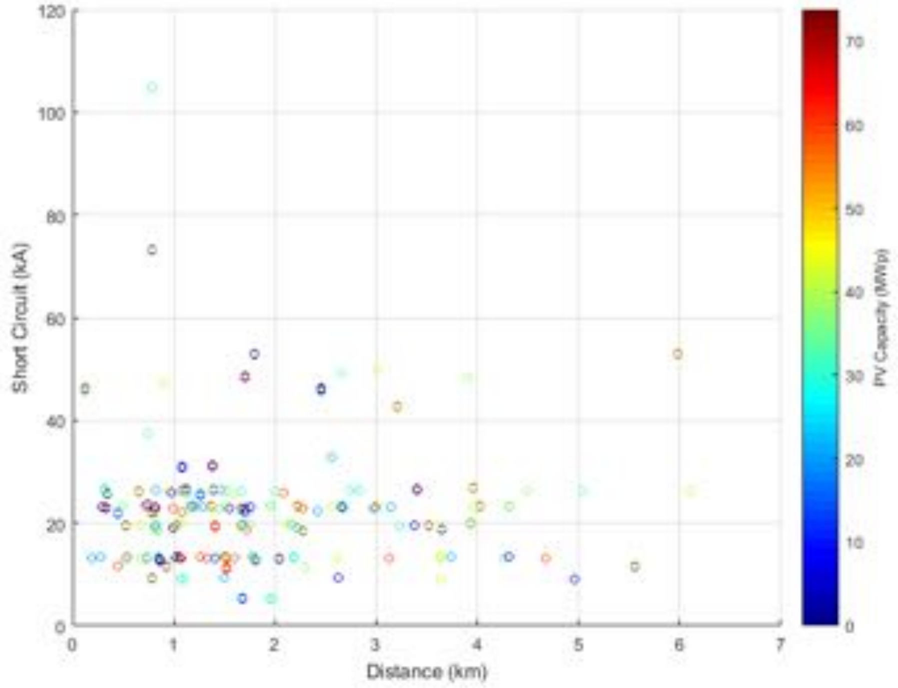


**Figure 215.** Short circuit current against Distance - Power Factor equal to 0.95.

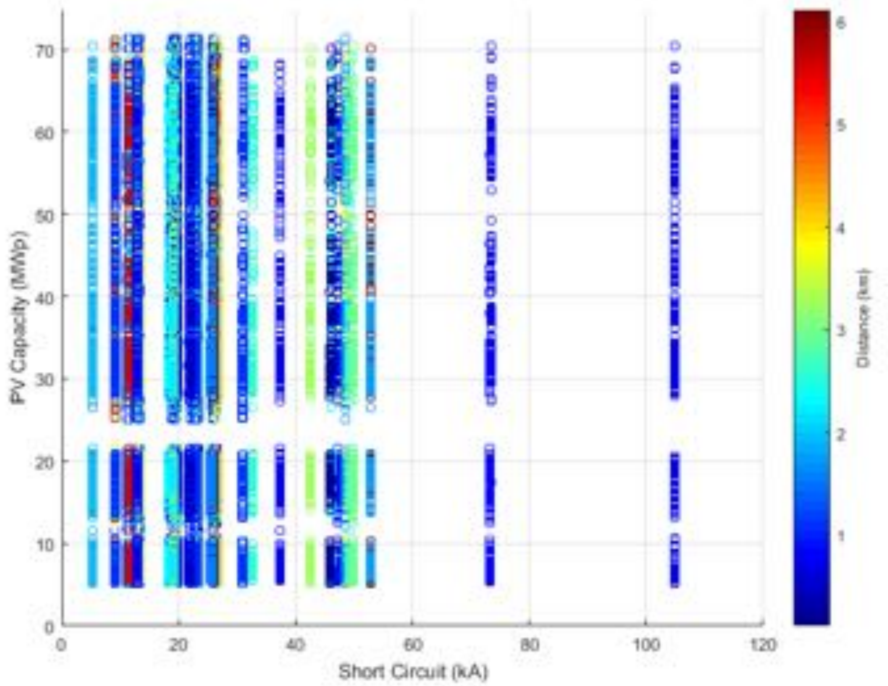


**Figure 216.** PV Capacity against Short Circuit current - Power Factor equal to 0.95.

### D1.3.3 Power Factor cosφ(P)

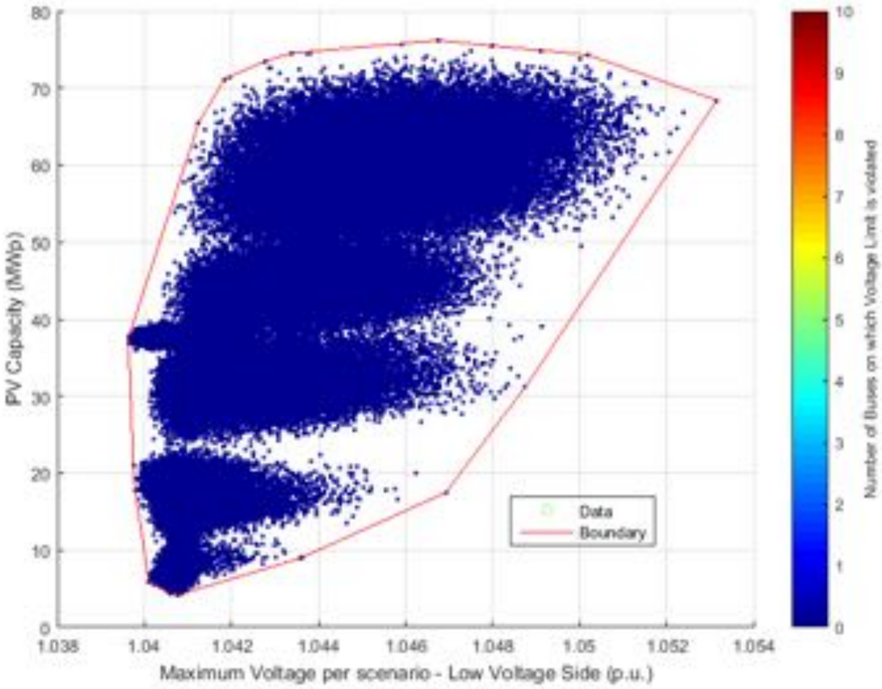


**Figure 217.** PV Capacity against Voltage – Low voltage side - Power Factor cosφ(P).

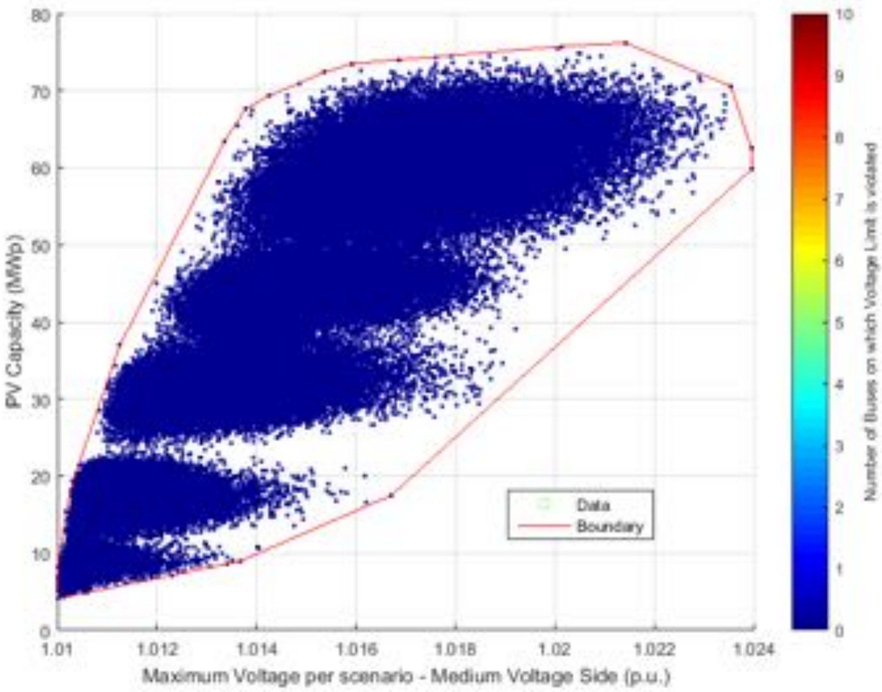


**Figure 218.** PV Capacity against Voltage – Medium voltage side - Power Factor cosφ(P).

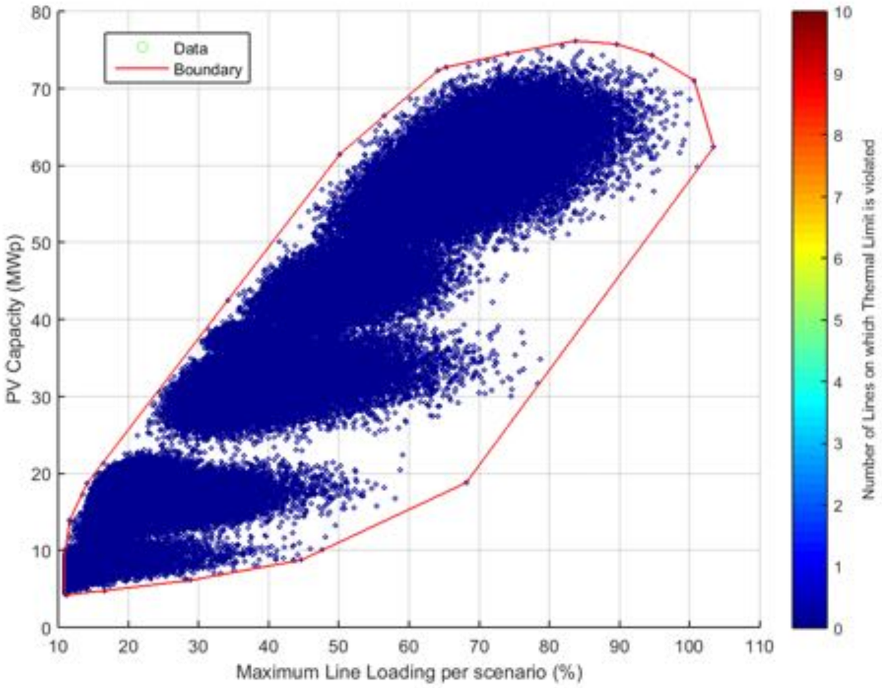


**Figure 219.** PV Capacity against Line Loading - Power Factor cosφ(P).

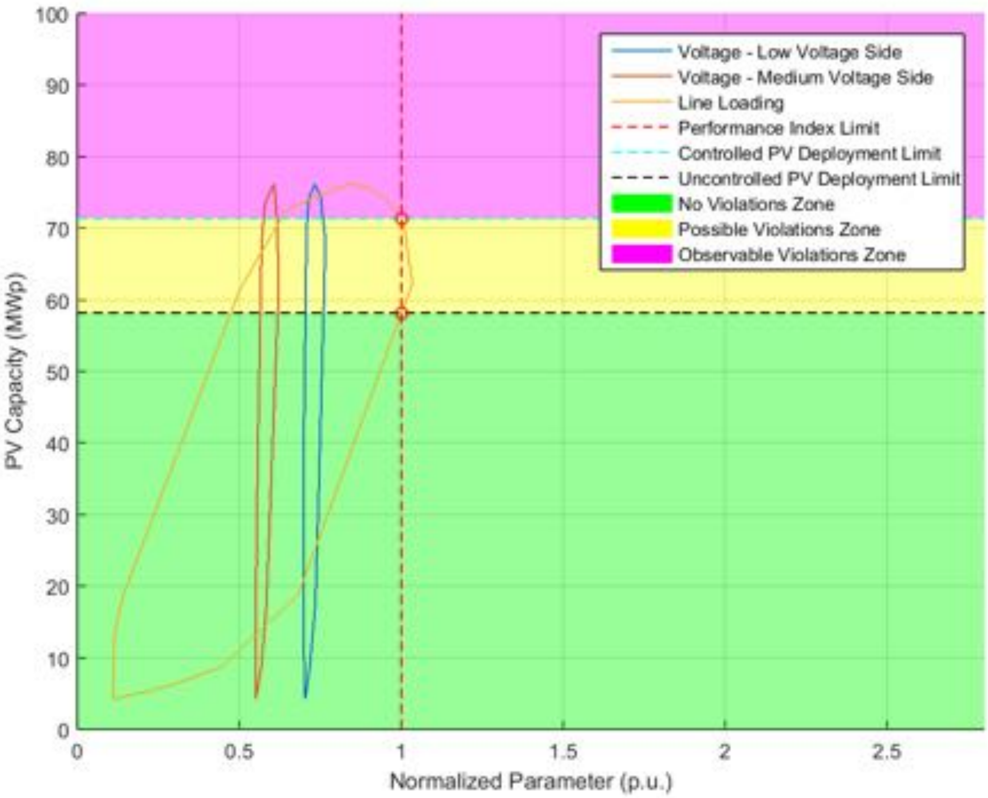


**Figure 220.** Normalized performance index parameters - Power Factor cosφ(P).

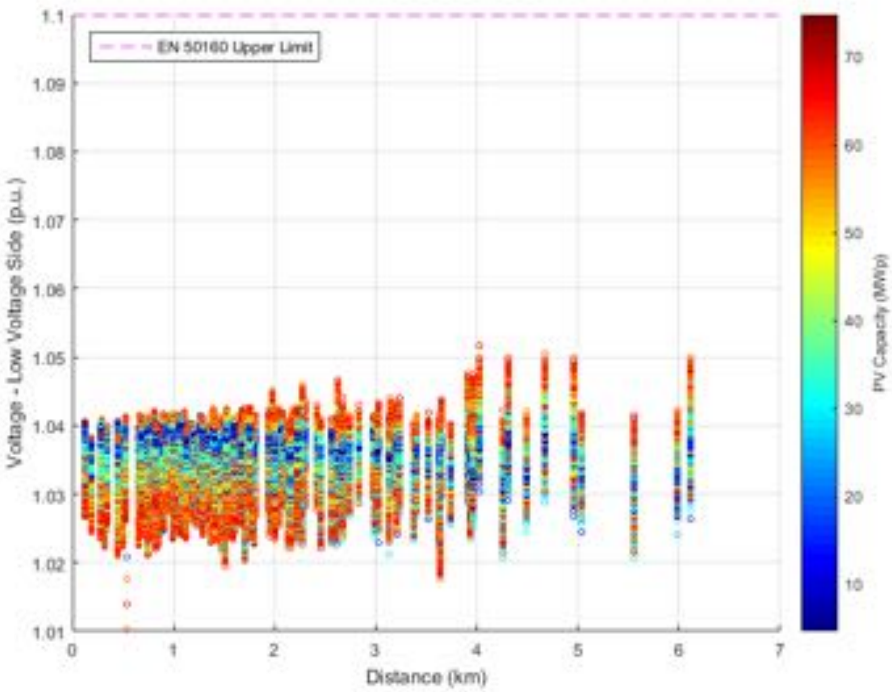


**Figure 221.** Voltage at low voltage side against distance from transmission substation - Power Factor cosφ(P).

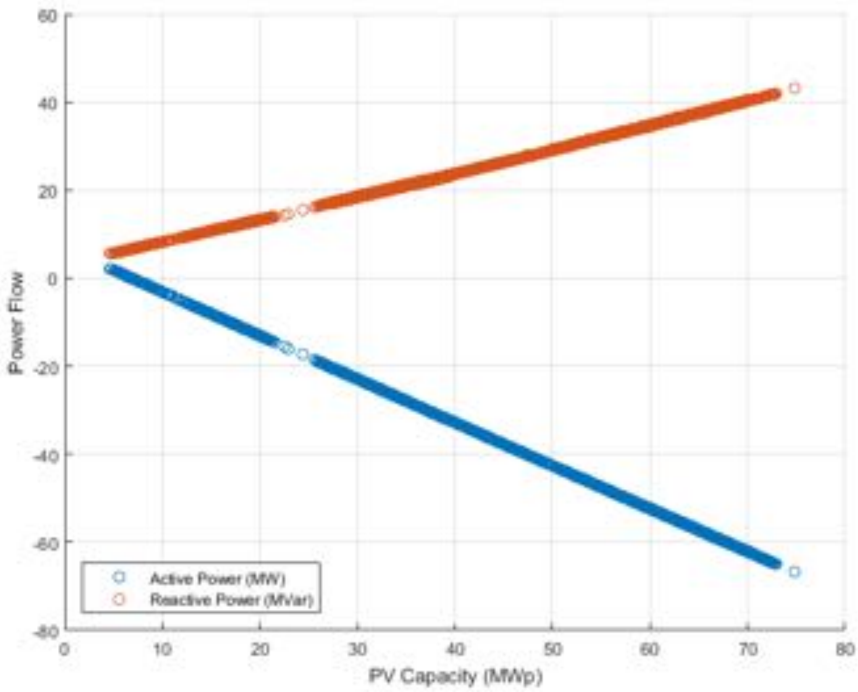


**Figure 222.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor cosφ(P).

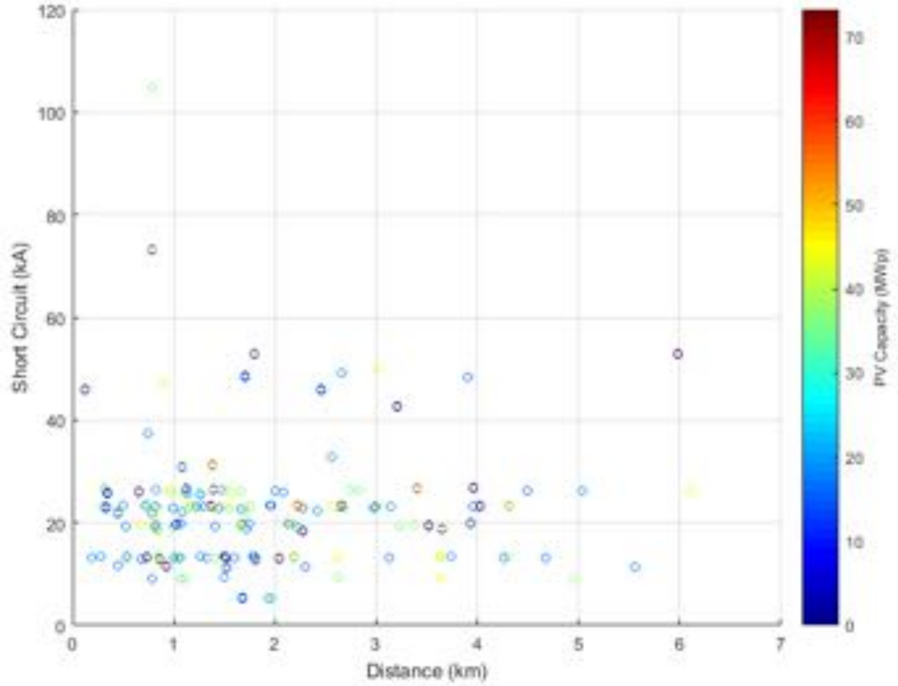


**Figure 223.** Short circuit current against distance - Power Factor cosφ(P).

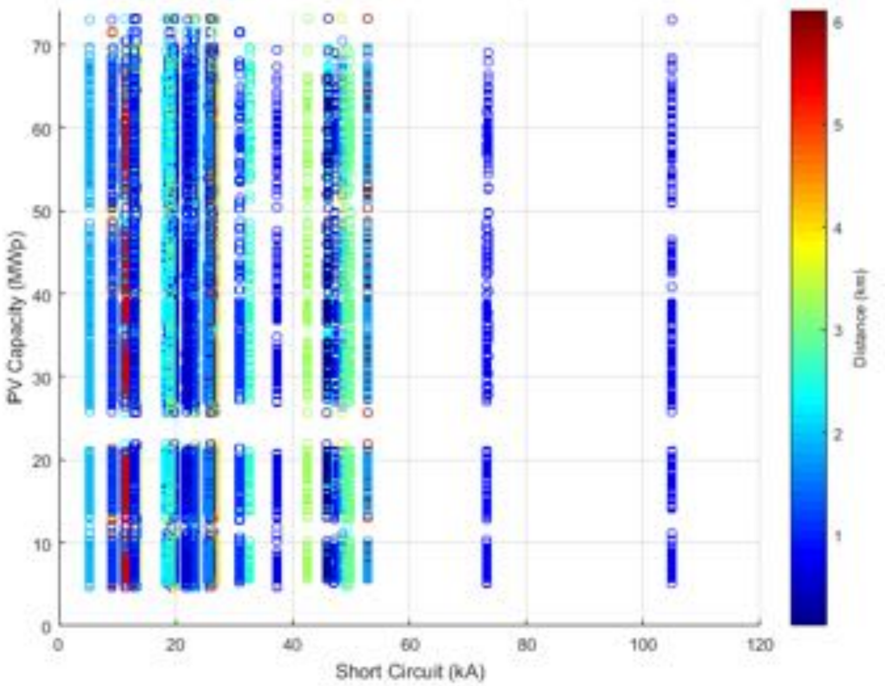


**Figure 224.** PV Capacity against short circuit current - Power Factor cosφ(P).

## D1.3.4 Summary – Monte Carlo Simulation

**Table 34.** Categorization of violations into zones.

| Scenario | No Violations Zone (MWp) | Possible Violations Zone (MWp) | Observable Violations Zone (MWp) |
|---|---|---|---|
| Unity Power Factor | above 76.2 | above 76.2 | above 76.2 |
| Power Factor equal to 0.95 | above 75.9 | above 75.9 | above 75.9 |
| Power Factor cosφ(P) | below 58.12 | 58.12 - 71.38 | above 71.38 |

**Table 35.** Uncontrolled/Controlled PV Deployment Limit.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| Unity Power Factor | above 76.2 | above 76.2 | above 76.2 | above 76.2 | above 76.2 | above 76.2 |
| Power Factor equal to 0.95 | above 75.9 | above 75.9 | above 75.9 | above 75.9 | above 75.9 | above 75.9 |
| Power Factor cosφ(P) | above 76.17 | above 76.17 | above 76.17 | above 76.17 | 58.12 | 71.38 |

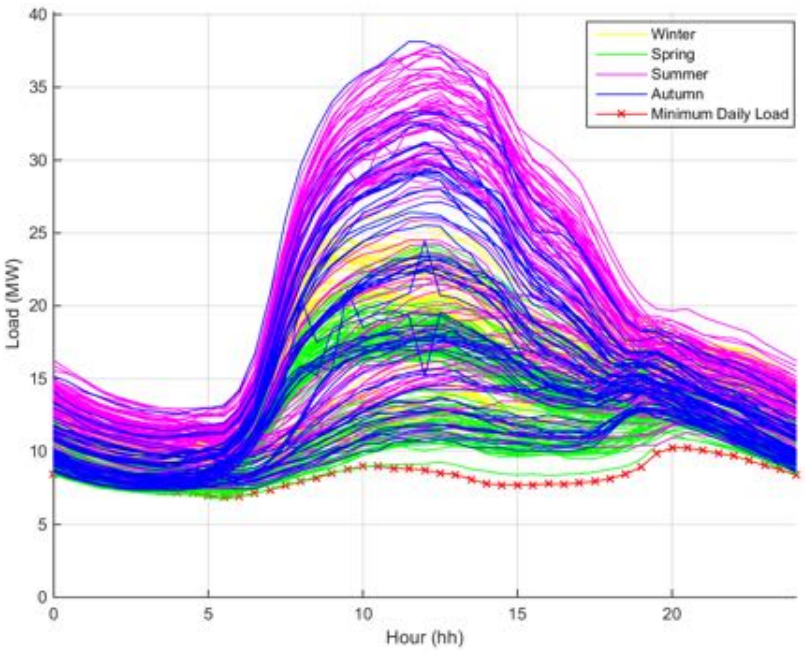


**Figure 225.** Renos Prentzas S/S - Minimum daily load.

# Appendix E

## E. Alambra s/s - Executive Summary

The results of the PV hosting capacity for Alambra substation with two 15 MVA and one 16 MVA transmission transformers (with a total distribution transformer capacity of 121.475 MVA), 10 feeders, 736 distribution substations/transformers/busbars and 1293 distribution lines either underground or overhead located in Nicosia district area, are presented and analysed in this Appendix. For this PV hosting capacity assessment, it was assumed that the inverter of PV systems is oversized by 10% (as imposed by newly formulated regulations).

# E.1 Results

## E1.1 Maximum Installed PV Capacity scenario

### E1.1.1 Unity Power Factor Operation

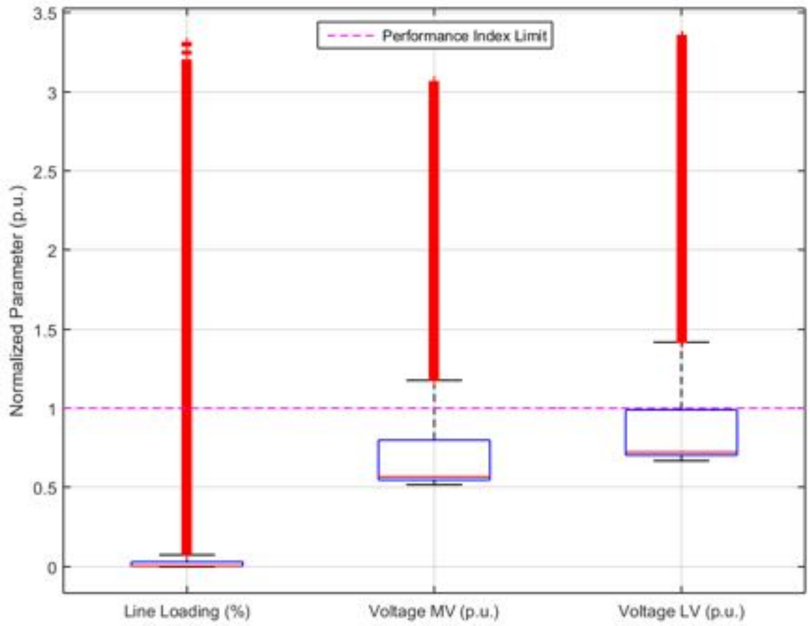


**Figure 226.** Performance Index parameters normalized to their limit – Unity Power Factor.

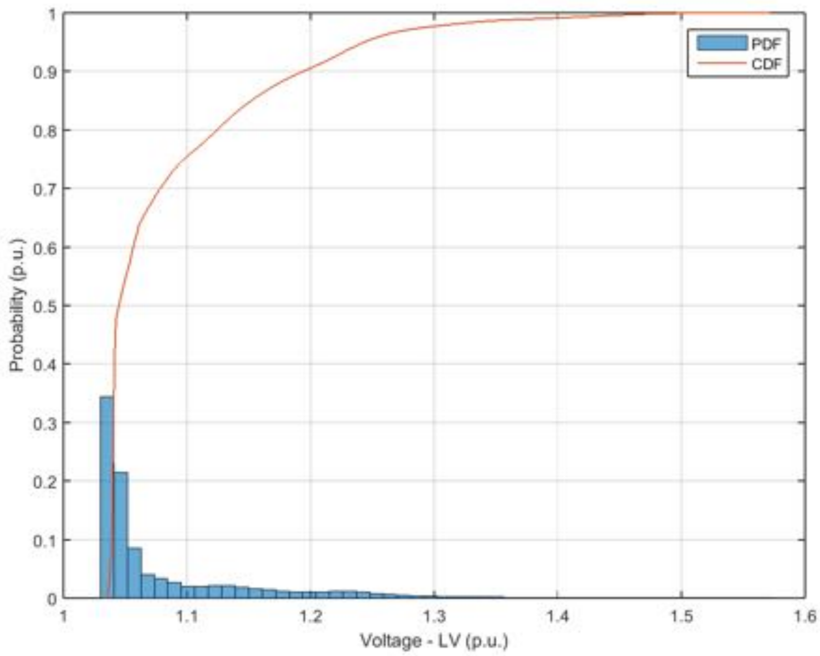


**Figure 227.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity power factor.

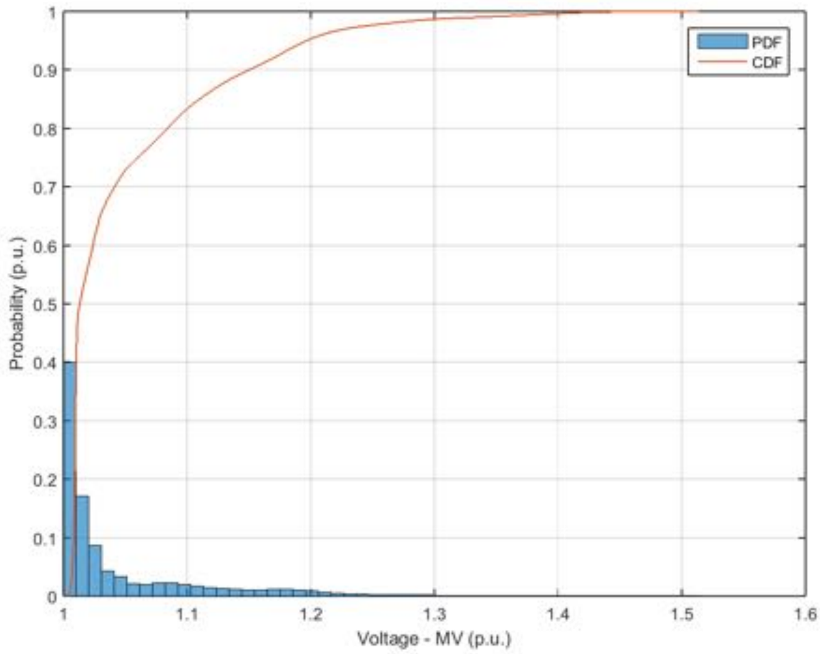


**Figure 228.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Unity power factor.

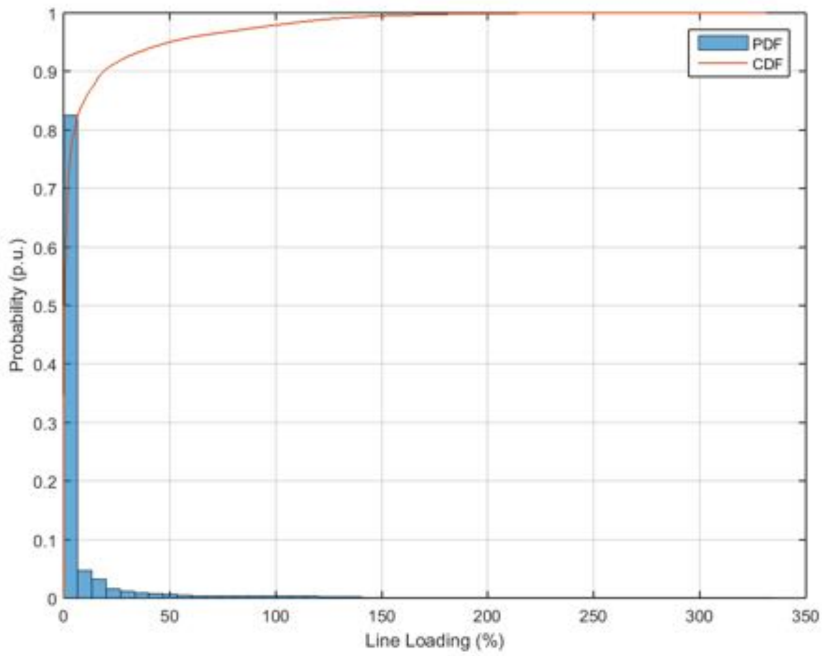


**Figure 229.** Probability distribution and cumulative probability distribution – Line Loading – Unity power factor.

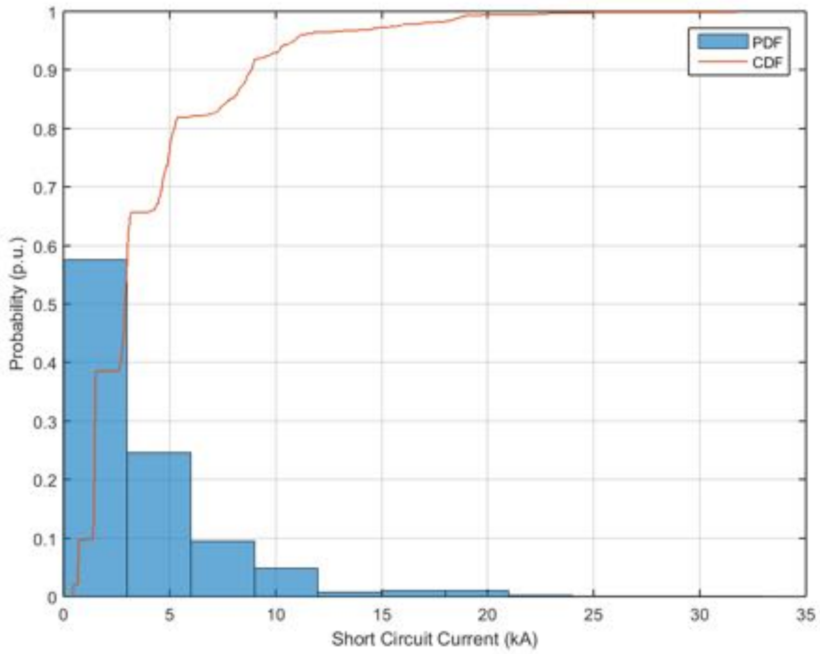


**Figure 230.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity power factor.

### E1.1.2 Power Factor equal to 0.95

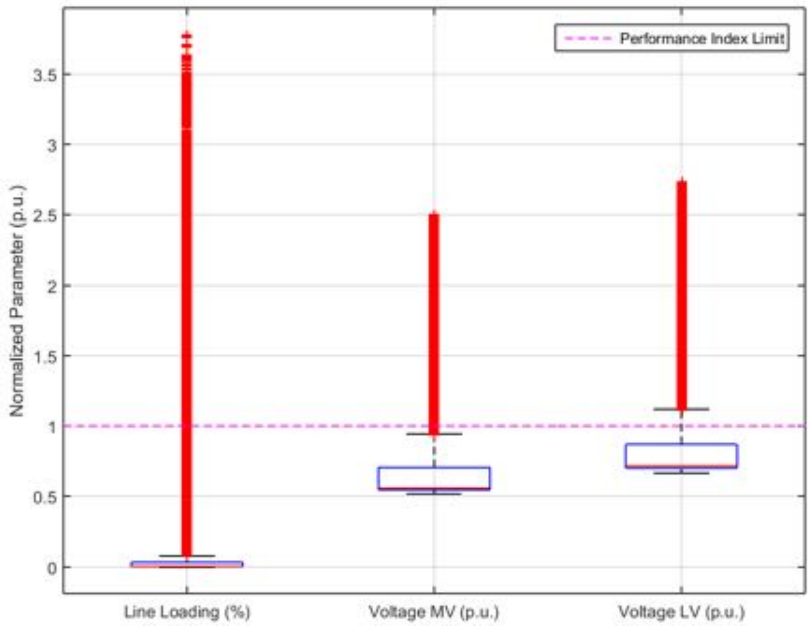


**Figure 231.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

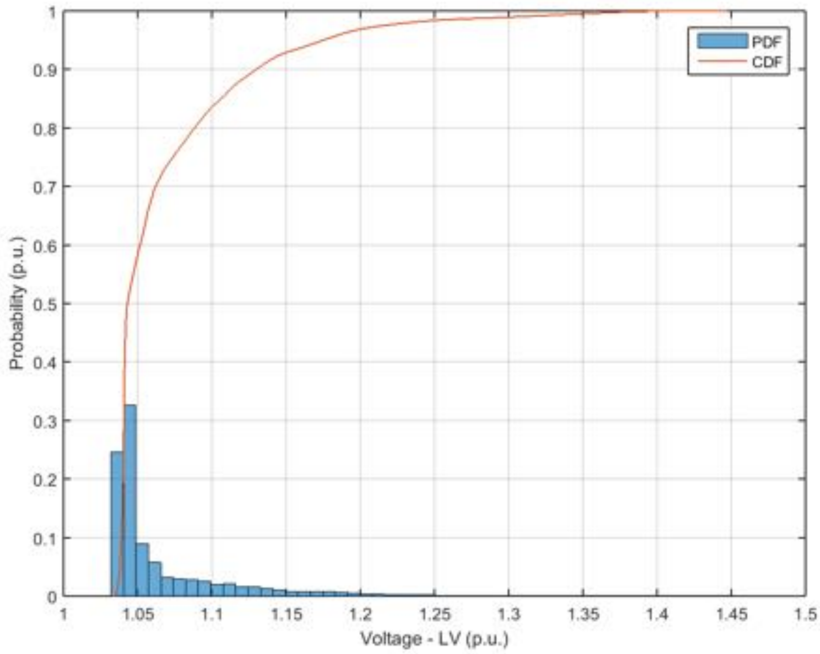


**Figure 232.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

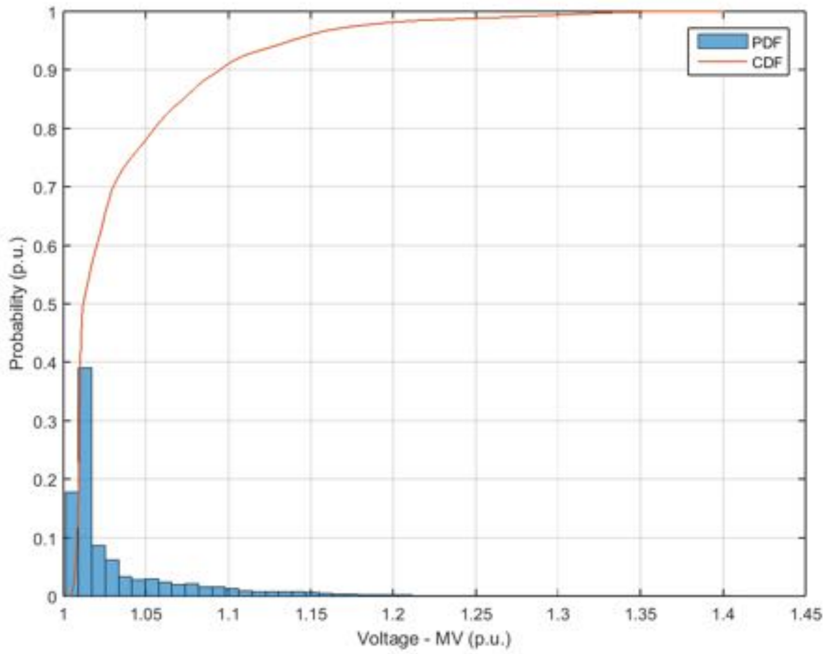


**Figure 233.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor equal to 0.95.

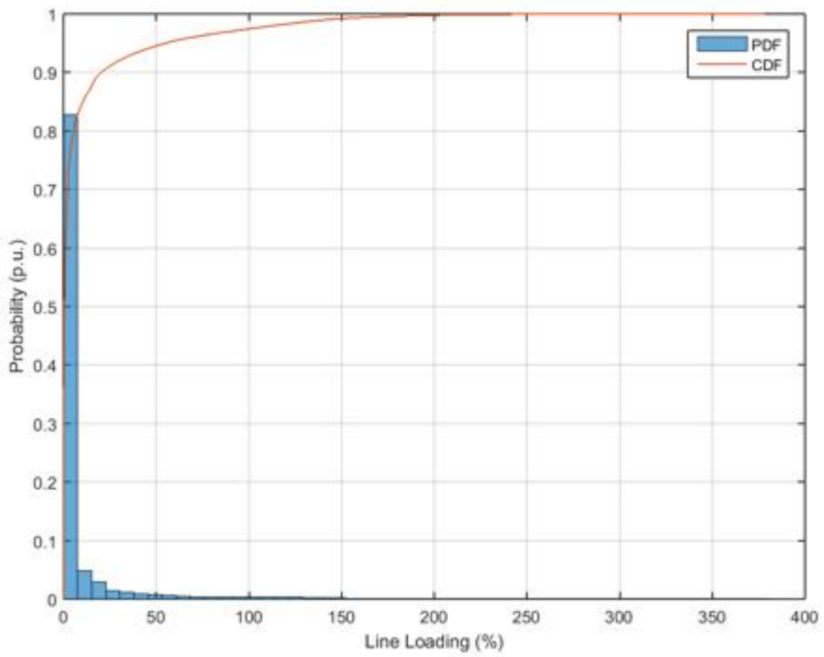


**Figure 234.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

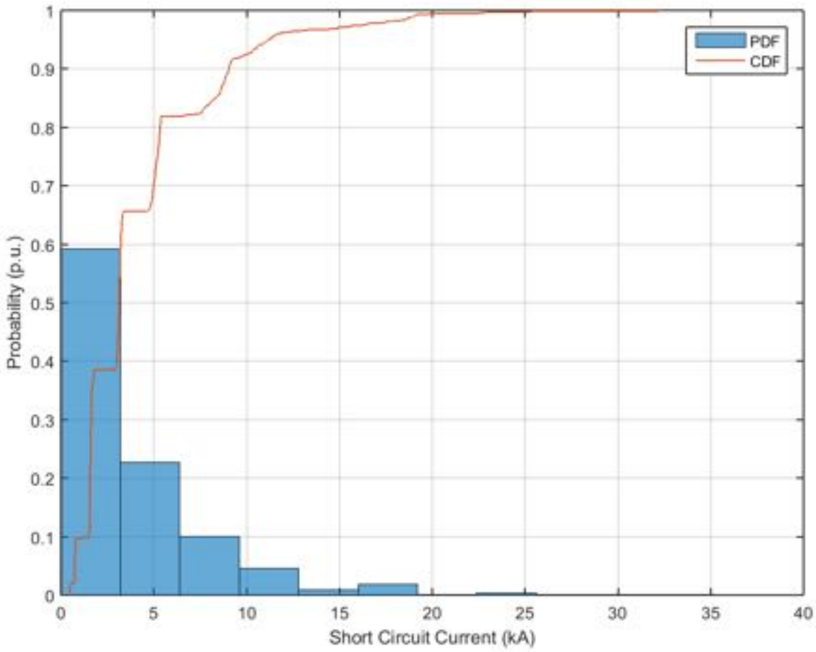


**Figure 235.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### E1.1.3 Power Factor cosφ(P)

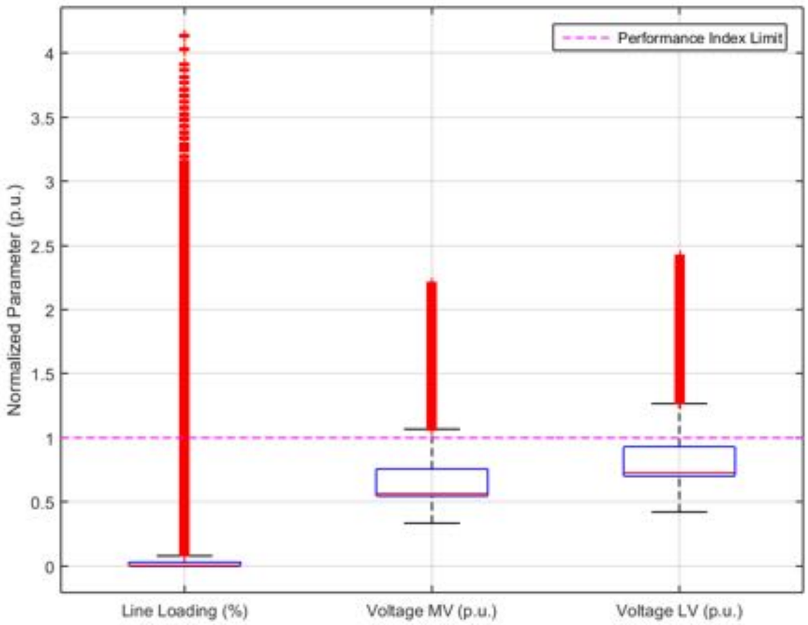


**Figure 236.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

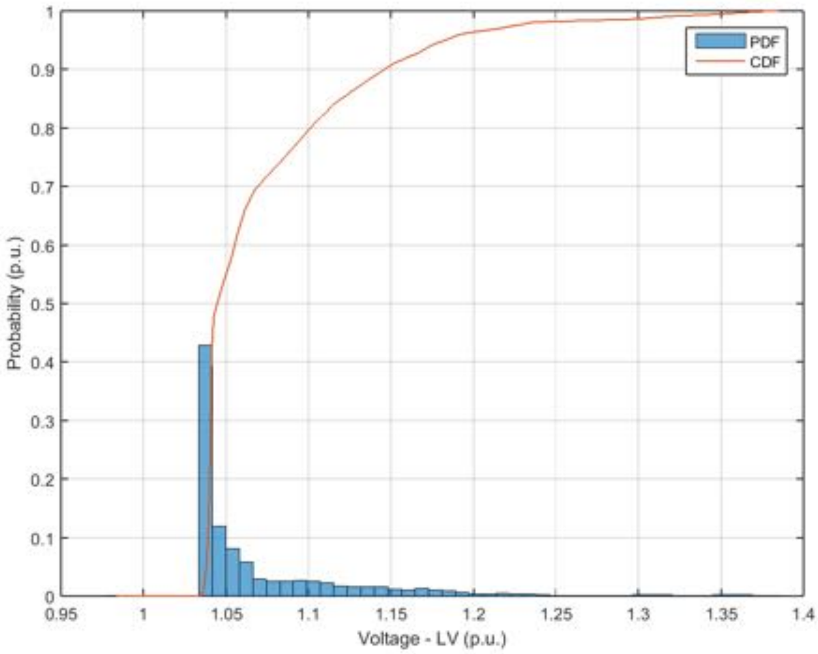


**Figure 237.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

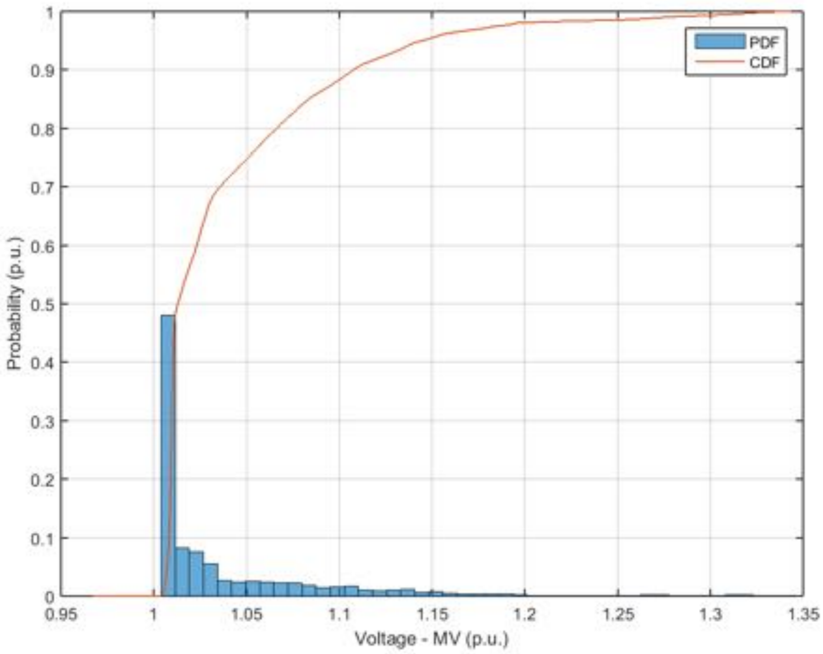


**Figure 238.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor cosφ(P).

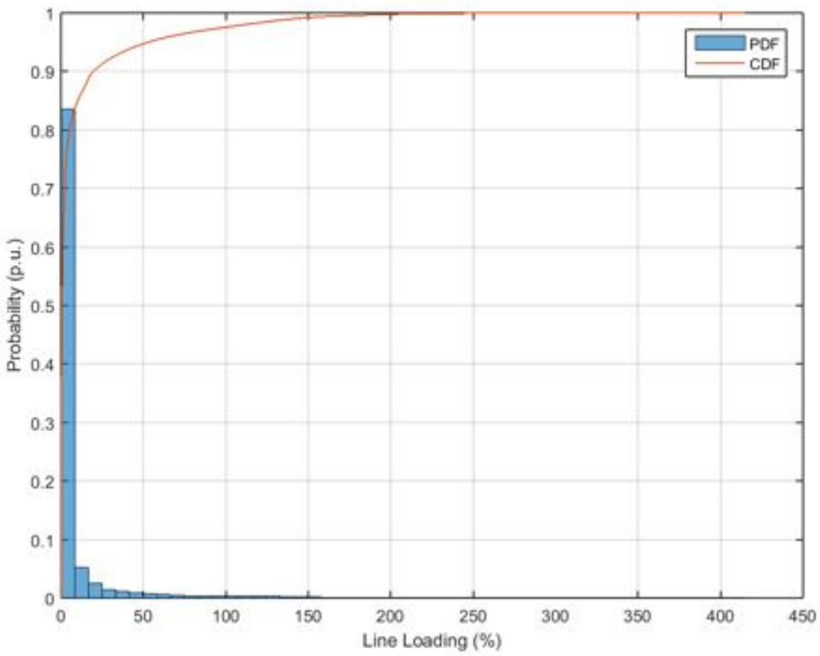


**Figure 239.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

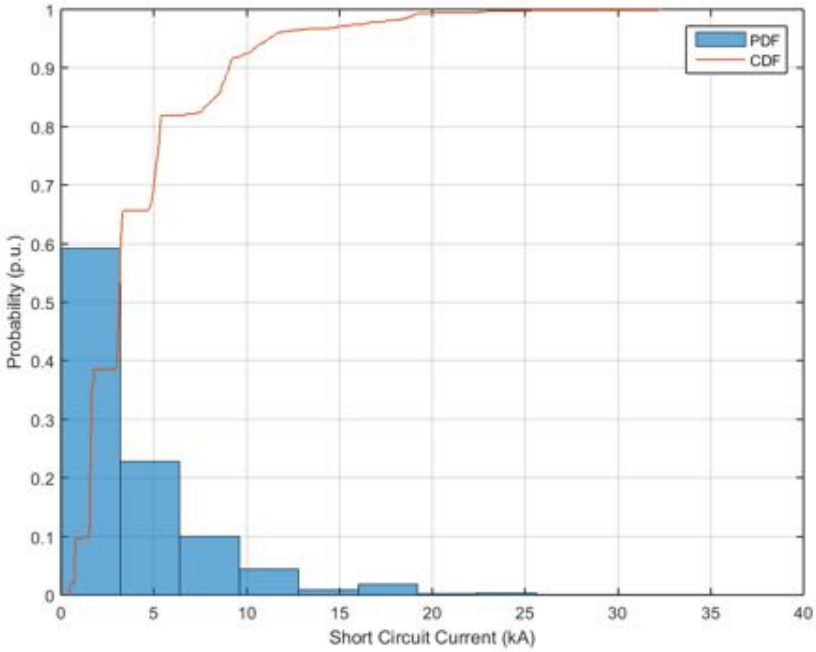


**Figure 240.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### E1.1.4 Summary and Discussion – Maximum Installed PV Capacity scenario

**Table 36.** Statistical analysis of PI parameters - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.668 | 0.668 | 0.419 |
| | 25th quantile | 0.702 | 0.702 | 0.702 |
| | Median | 0.725 | 0.715 | 0.723 |
| | Average | 0.919 | 0.840 | 0.862 |
| | Standard Deviation | 0.140 | 0.066 | 0.076 |
| | 75th quantile | 0.989 | 0.869 | 0.928 |
| | 95th quantile | 1.717 | 1.375 | 1.415 |
| | 99th quantile | 2.417 | 2.029 | 2.079 |
| | Maximum | 3.359 | 2.736 | 2.426 |
| **Number of elements of which the limit is violated** | | 654 out of 736 | 497 out of 736 | 548 out of 736 |
| **Voltage – Medium Voltage Side** | Minimum | 0.516 | 0.516 | 0.335 |
| | 25th quantile | 0.548 | 0.548 | 0.548 |
| | Median | 0.566 | 0.560 | 0.565 |
| | Average | 0.745 | 0.680 | 0.698 |
| | Standard Deviation | 0.121 | 0.061 | 0.069 |
| | 75th quantile | 0.800 | 0.706 | 0.755 |
| | 95th quantile | 1.483 | 1.192 | 1.225 |
| | 99th quantile | 2.173 | 1.832 | 1.877 |
| | Maximum | 3.067 | 2.506 | 2.217 |
| **Number of elements of which the limit is violated** | | 583 out of 736 | 335 out of 736 | 367 out of 736 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.001 | 0.001 | 0.001 |
| | Median | 0.006 | 0.006 | 0.006 |
| | Average | 0.082 | 0.090 | 0.088 |
| | Standard Deviation | 0.056 | 0.070 | 0.069 |
| | 75th quantile | 0.030 | 0.032 | 0.031 |
| | 95th quantile | 0.501 | 0.550 | 0.530 |
| | 99th quantile | 1.263 | 1.412 | 1.413 |
| | Maximum | 3.312 | 3.780 | 4.149 |
| | CDF-100% loading | 97.92% | 97.43% | 97.55% |
| **Number of elements of which the limit is violated** | | 196 out of 1293 | 208 out of 1293 | 221 out of 1293 |

**Table 37.** Statistical analysis of Short Circuit Values - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 0.441 | 0.456 | 0.456 |
| | 25th quantile | 1.470 | 1.583 | 1.585 |
| | Median | 2.888 | 3.134 | 3.139 |
| | Average | 3.993 | 4.205 | 4.208 |
| | Standard Deviation | 3.821 | 3.891 | 3.893 |
| | 75th quantile | 4.948 | 5.192 | 5.193 |
| | 95th quantile | 10.908 | 11.180 | 11.195 |
| | 99th quantile | 18.667 | 18.967 | 18.969 |
| | Maximum | 31.745 | 32.196 | 32.344 |

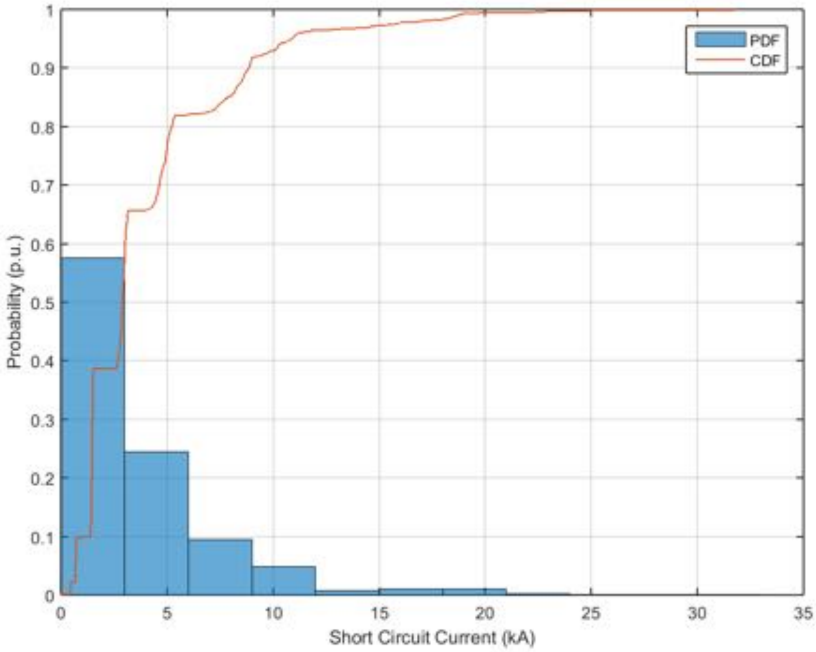


**Figure 241.** Probability distribution and cumulative probability distribution – Short Circuit Current – No PV.

## E1.2 Maximum PV Capacity per Distribution Substation

### E1.2.1 Unity Power Factor Scheme

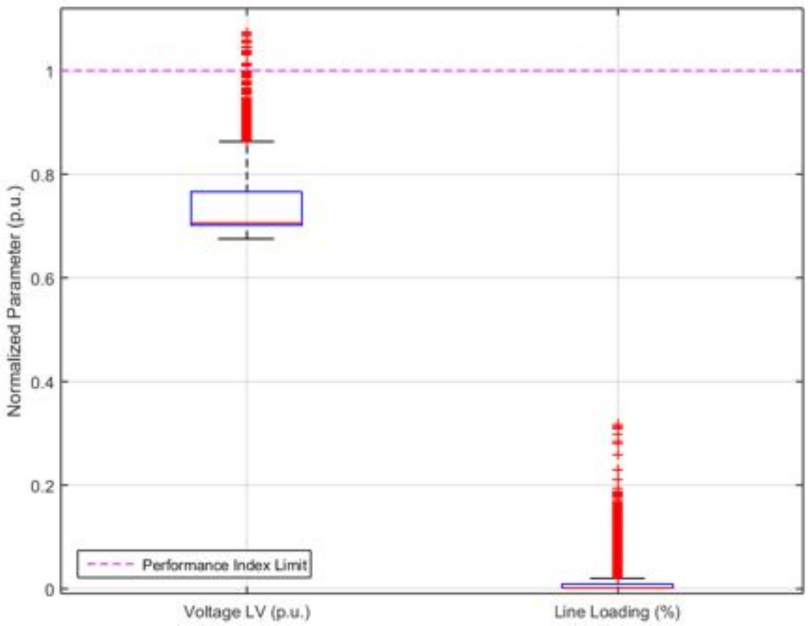


**Figure 242.** Performance Index parameters normalized to their limit – Unity Power Factor.

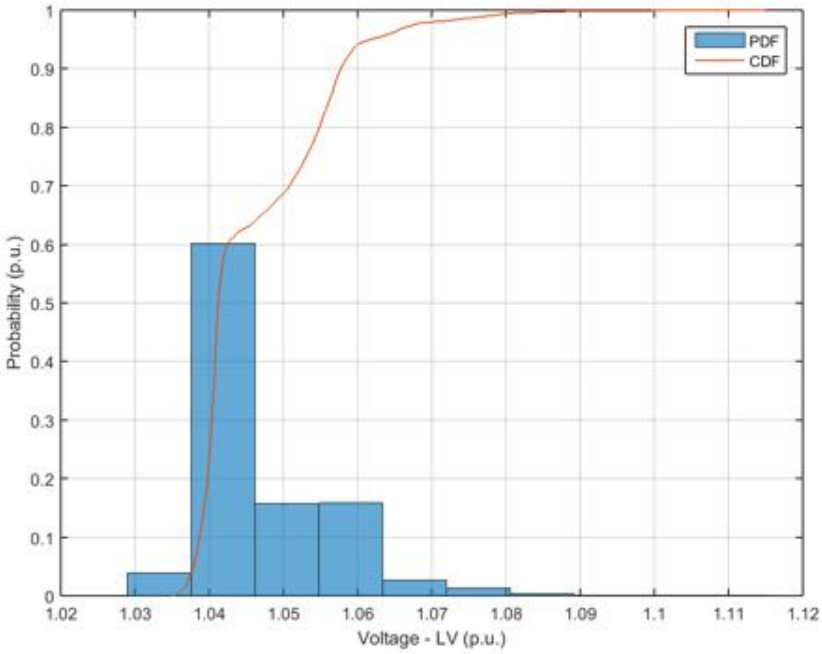


**Figure 243.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity Power Factor.

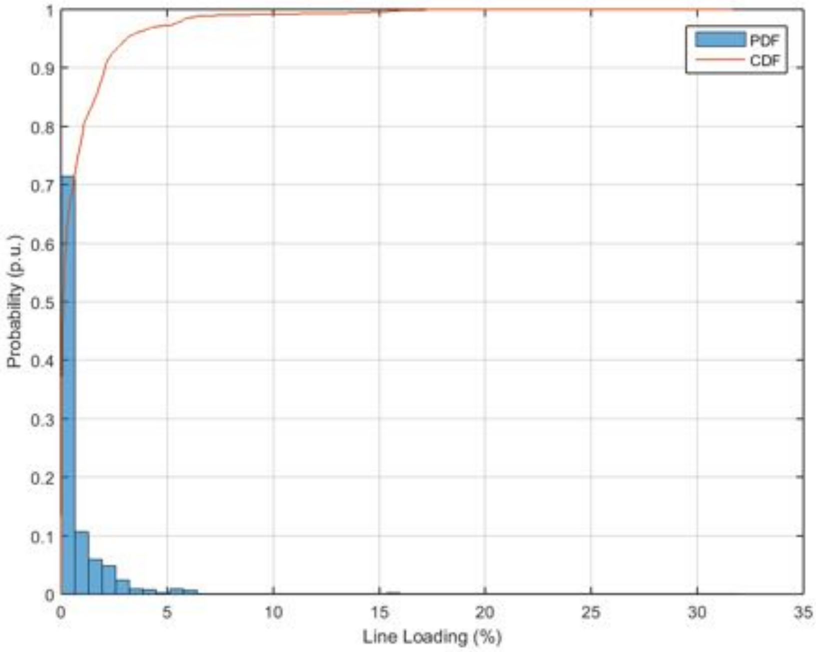


**Figure 244.** Probability distribution and cumulative probability distribution – Line Loading – Unity Power Factor.

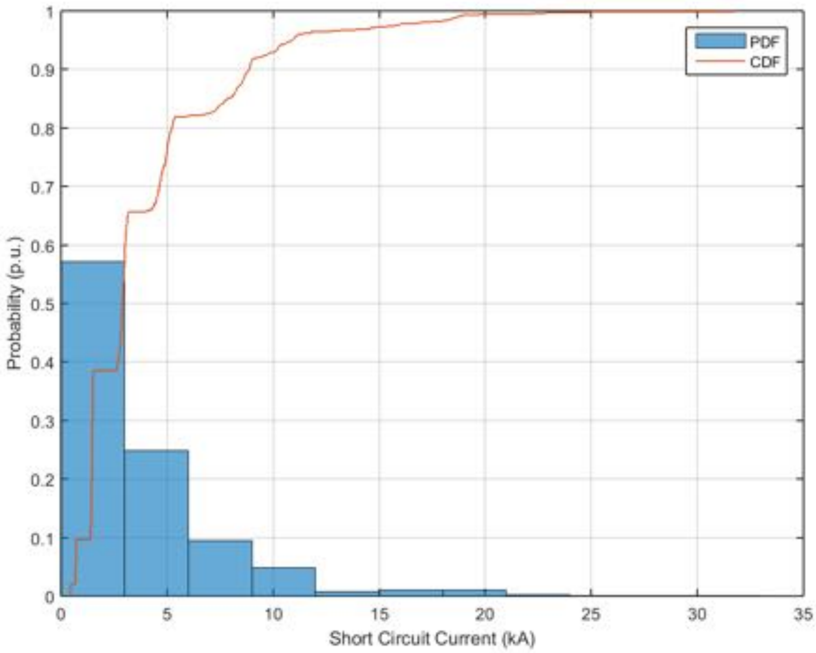


**Figure 245.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity Power Factor.

### E1.2.2 Power Factor equal to 0.95

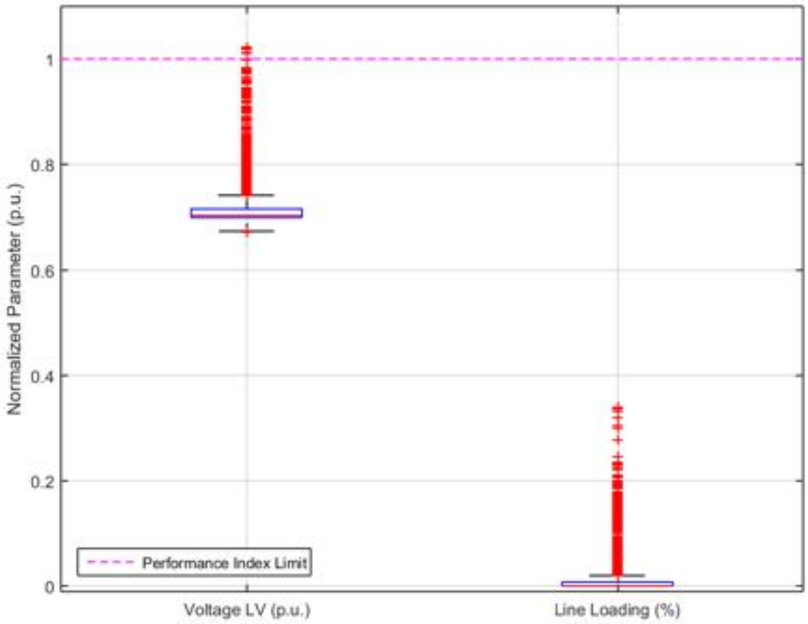


**Figure 246.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

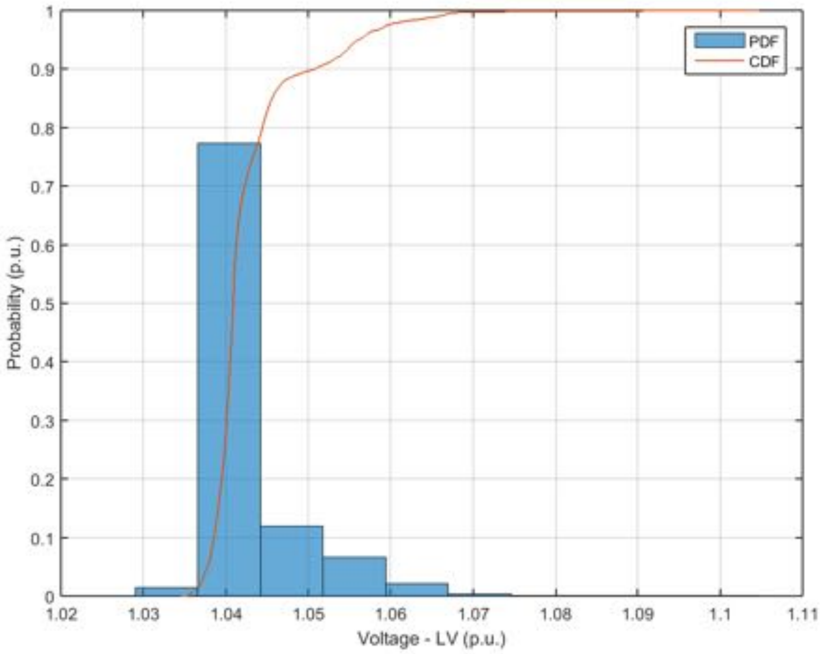


**Figure 247.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

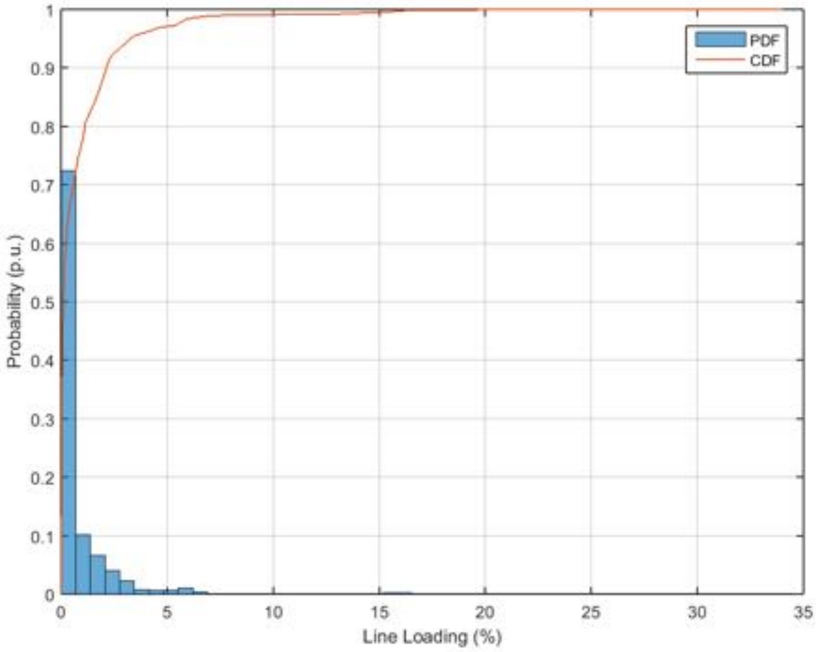


**Figure 248.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

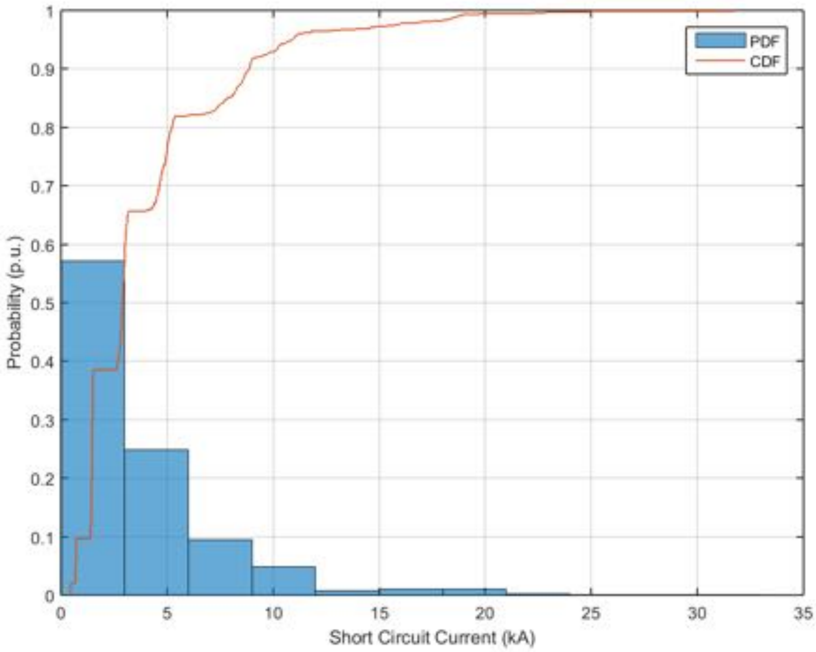


**Figure 249.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### E1.2.3 Power Factor cosφ(P)

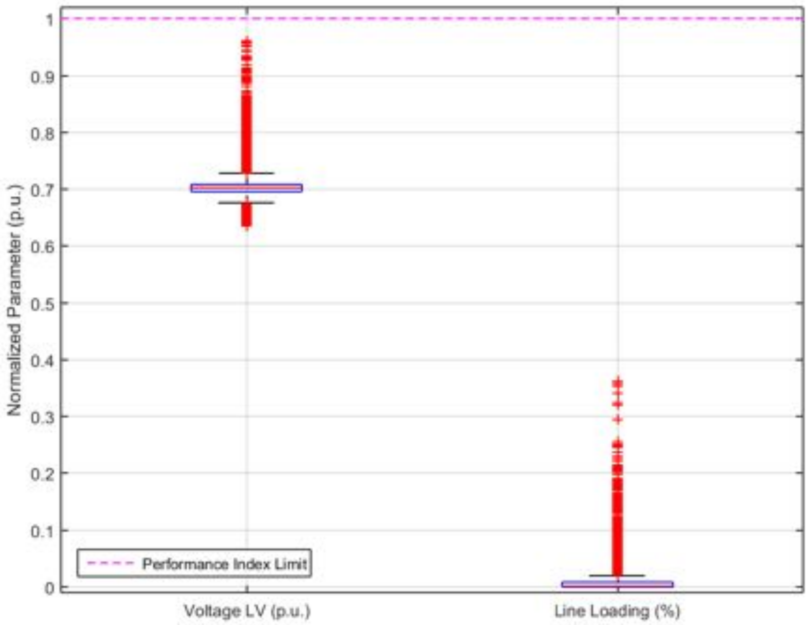


**Figure 250.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

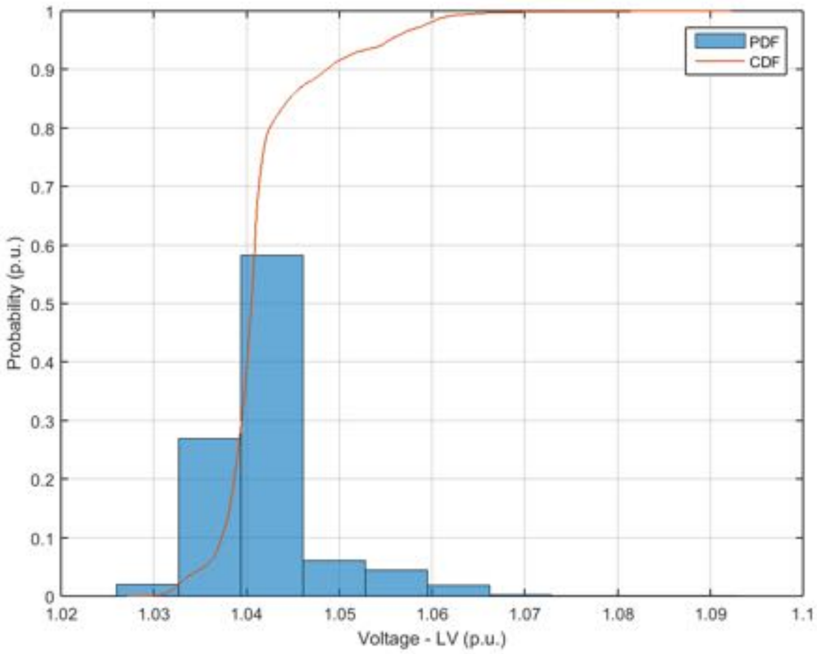


**Figure 251.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

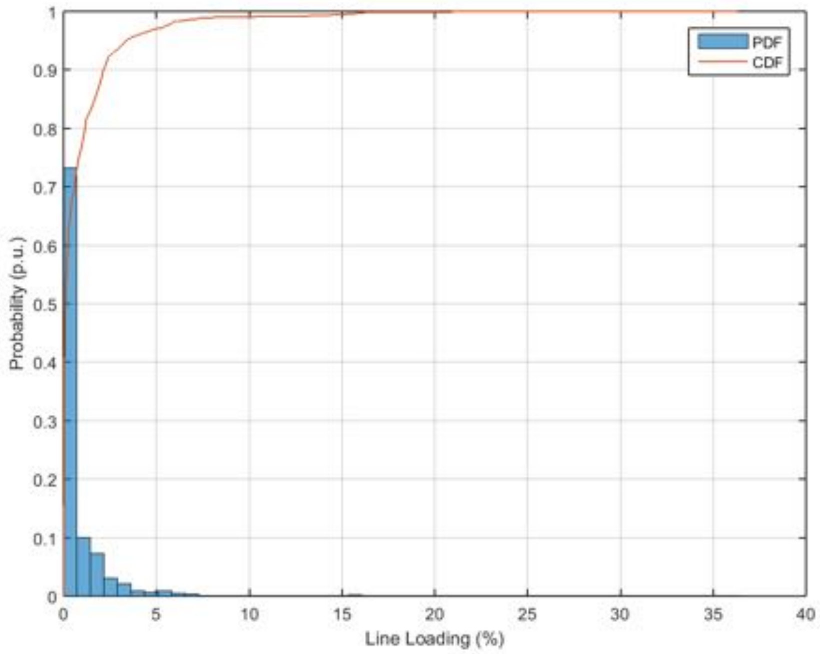


**Figure 252.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

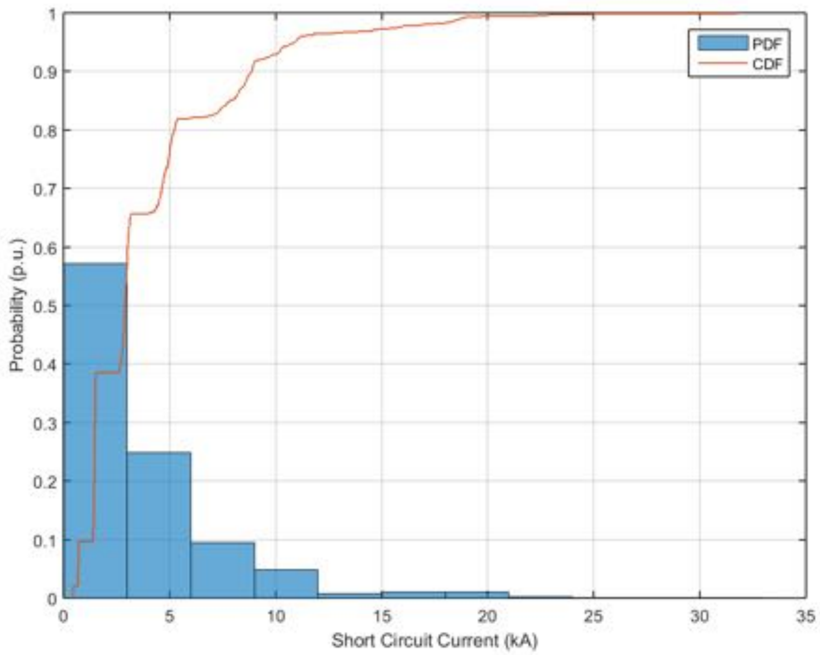


**Figure 253.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### E1.2.4 Summary and Discussion – Maximum PV Capacity per Distribution Substation

**Table 38.** Statistical analysis of PI parameters - Maximum PV Capacity per Distribution Substation.

| | | Scenario | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.676 | 0.673 | 0.636 |
| | 25th quantile | 0.701 | 0.699 | 0.696 |
| | Median | 0.706 | 0.704 | 0.703 |
| | Average | 0.731 | 0.714 | 0.708 |
| | Standard Deviation | 0.002 | 0.001 | 0.001 |
| | 75th quantile | 0.765 | 0.716 | 0.709 |
| | 95th quantile | 0.809 | 0.781 | 0.777 |
| | 99th quantile | 0.888 | 0.829 | 0.808 |
| | Maximum | 1.075 | 1.024 | 0.961 |
| **Number of elements of which the limit is violated** | | 5 out of 736 | 1 out of 736 | 0 out of 736 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.000 | 0.000 | 0.000 |
| | Median | 0.001 | 0.001 | 0.001 |
| | Average | 0.008 | 0.008 | 0.008 |
| | Standard Deviation | 0.000 | 0.000 | 0.000 |
| | 75th quantile | 0.008 | 0.008 | 0.008 |
| | 95th quantile | 0.031 | 0.033 | 0.034 |
| | 99th quantile | 0.077 | 0.082 | 0.088 |
| | Maximum | 0.317 | 0.340 | 0.363 |
| **Number of elements of which the limit is violated** | | 0 out of 1293 | 0 out of 1293 | 0 out of 1293 |

**Table 39.** Statistical analysis of Short Circuit Values - Maximum PV Capacity per Distribution Substation.

| | | Scenario | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 0.441 | 0.441 | 0.441 |
| | 25th quantile | 1.471 | 1.471 | 1.471 |
| | Median | 2.889 | 2.889 | 2.889 |
| | Average | 3.994 | 3.994 | 3.994 |
| | Standard Deviation | 3.823 | 3.823 | 3.823 |
| | 75th quantile | 4.949 | 4.949 | 4.949 |
| | 95th quantile | 10.901 | 10.901 | 10.901 |
| | 99th quantile | 18.697 | 18.697 | 18.697 |
| | Maximum | 31.736 | 31.736 | 31.736 |

# E1.3 Assessing PV Capacity using Monte Carlo method

## E1.3.1 Unity Power Factor Operation

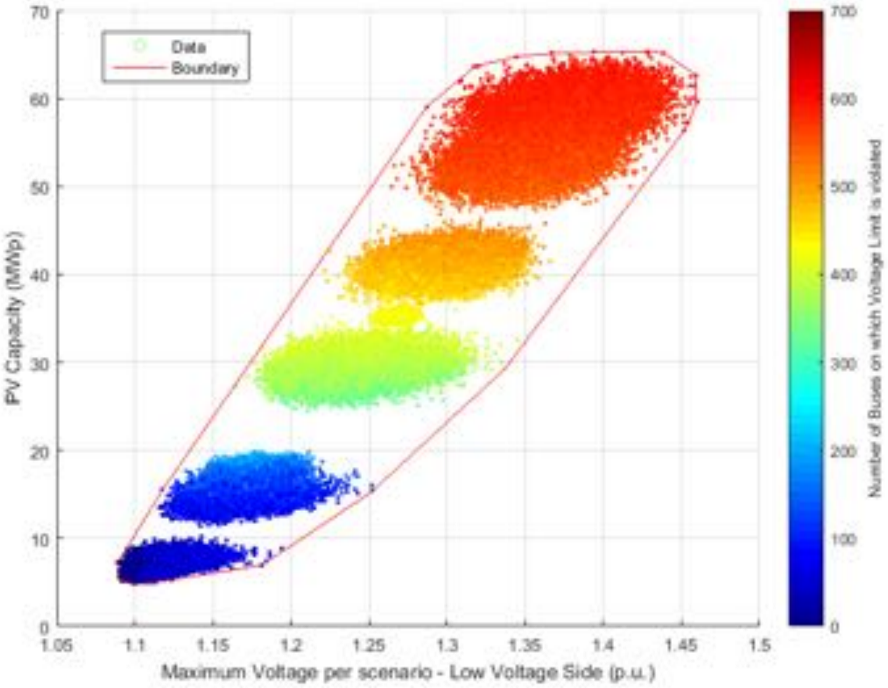


**Figure 254.** PV Capacity against Voltage – Low voltage side - Unity Power Factor.

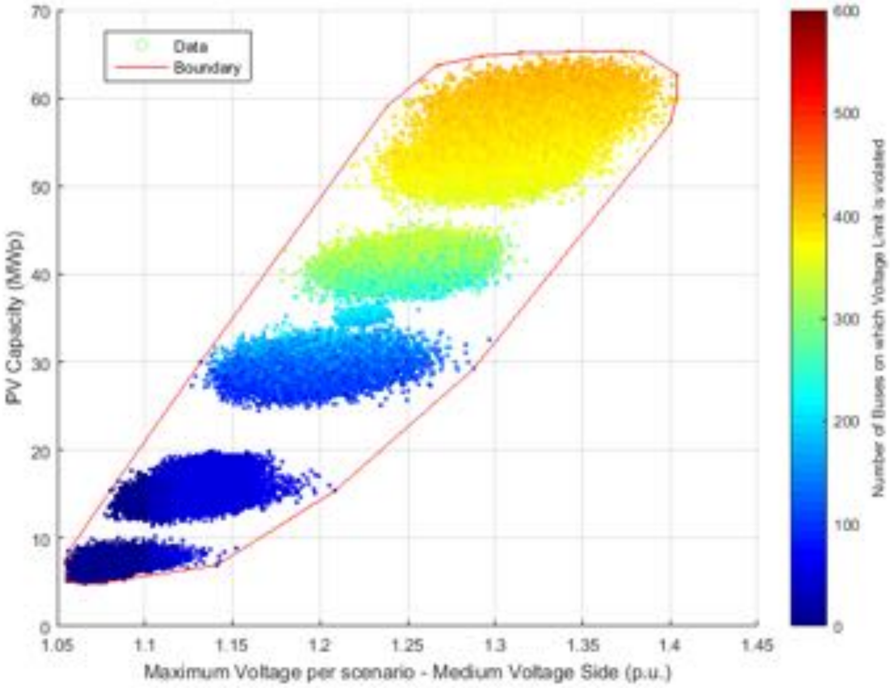


**Figure 255.** PV Capacity against Voltage – Medium voltage side - Unity Power Factor.

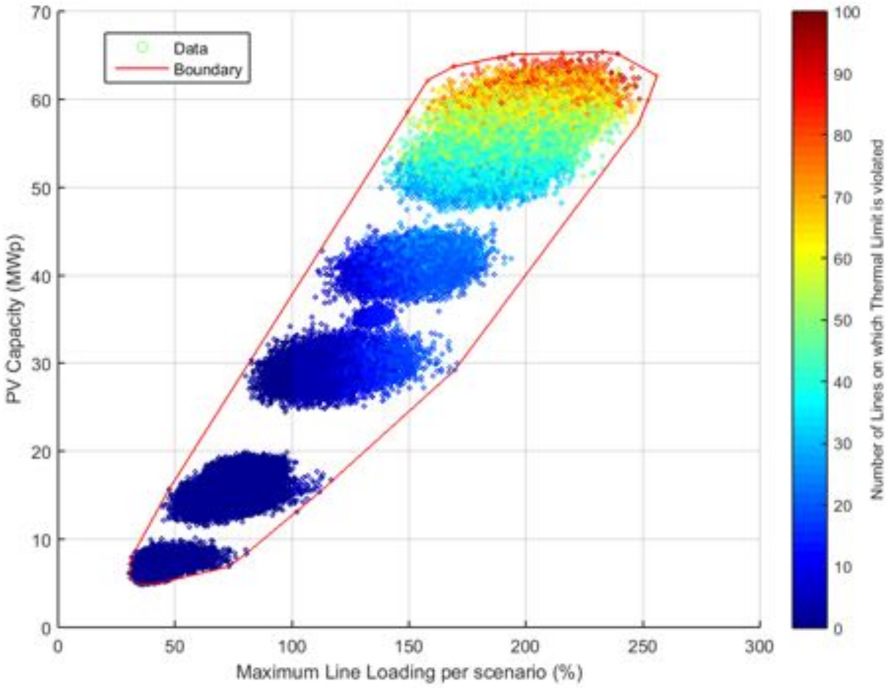


**Figure 256.** PV Capacity against Line Loading - Unity Power Factor.

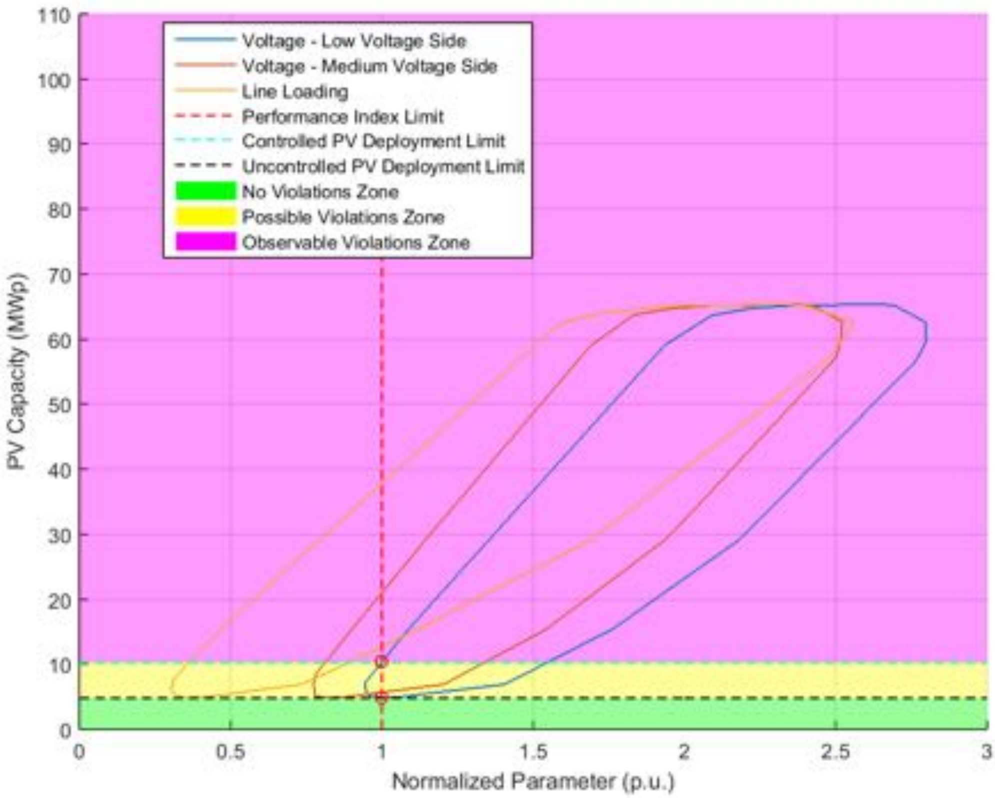


**Figure 257.** Normalized performance index parameters - Unity Power Factor.

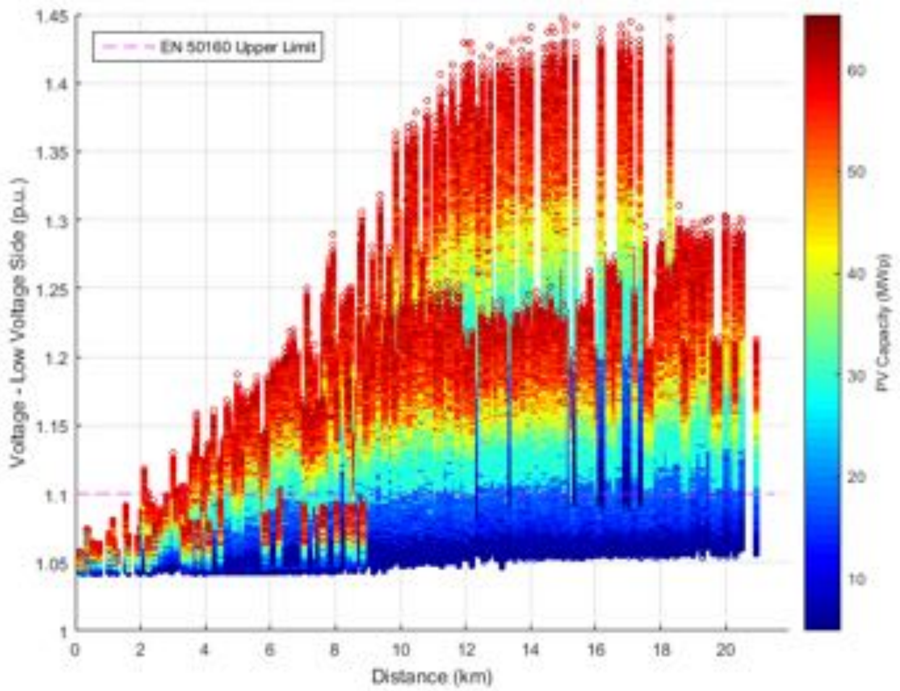


**Figure 258.** Voltage at low voltage side against distance from transmission substation - Unity Power Factor.

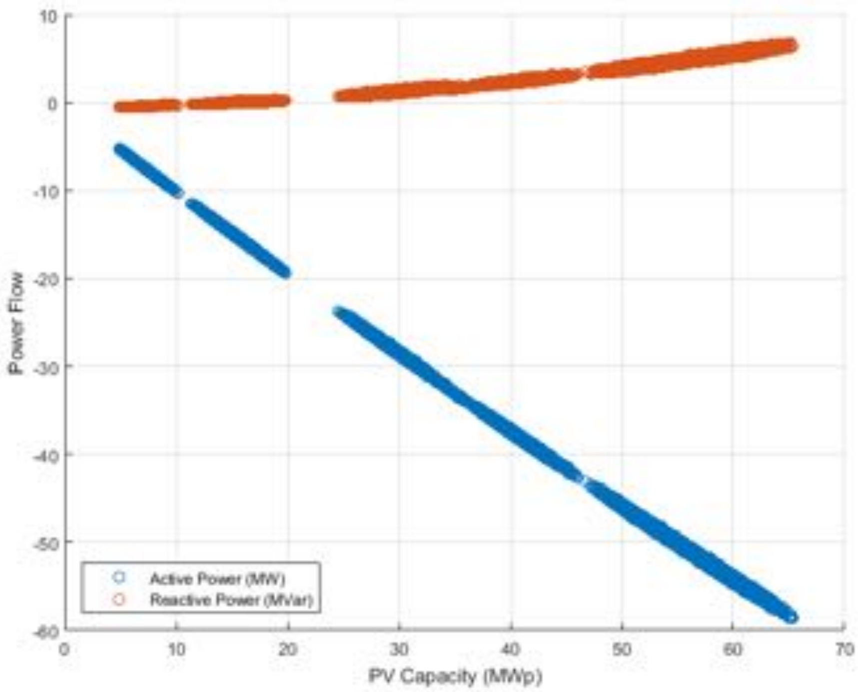


**Figure 259.** Power flow at PCC (connection of the reference substation with HV network) against PV capacity - Unity Power Factor (negative sign denotes reverse power flow).

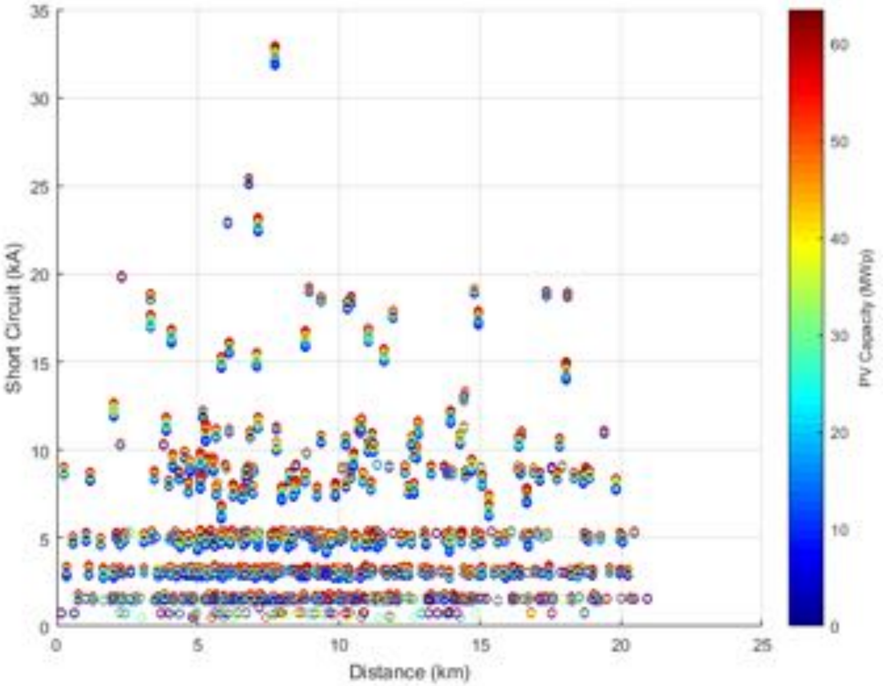


**Figure 260.** Short circuit current against distance - Unity Power Factor.

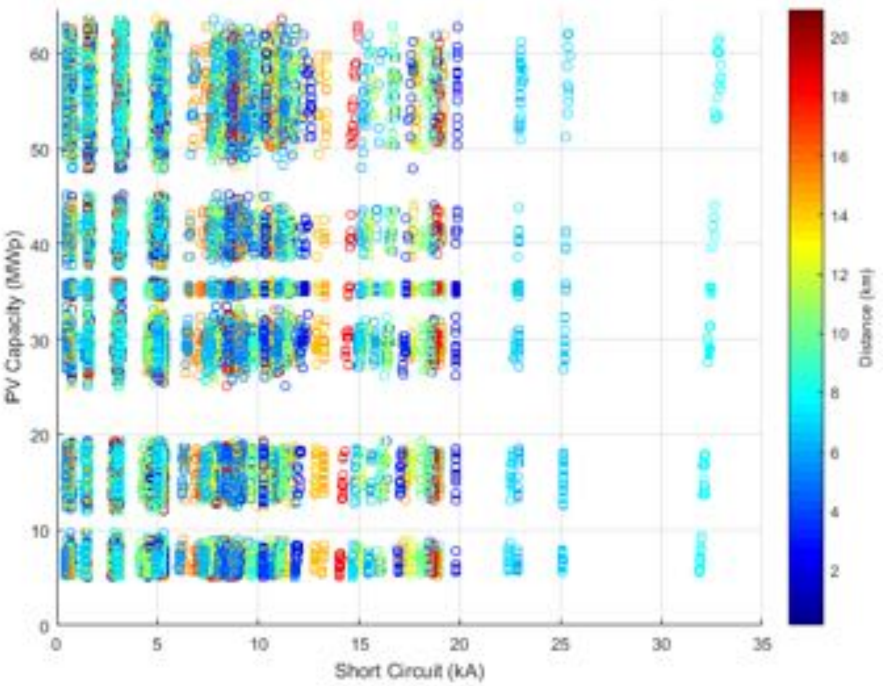


**Figure 261.** PV Capacity against Short circuit current - Unity Power Factor

### E1.3.2 Power Factor equal to 0.95

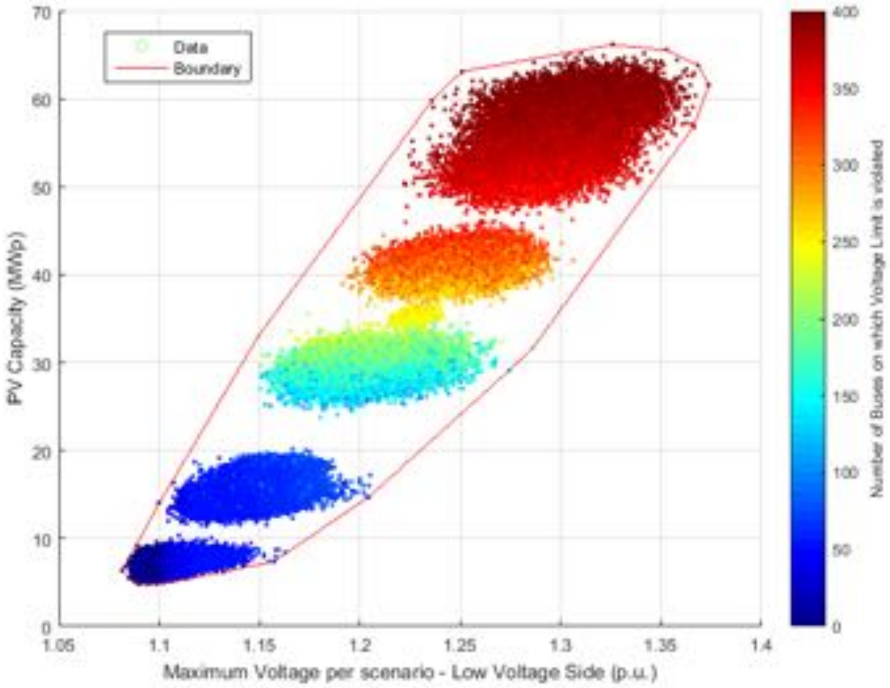


**Figure 262.** PV Capacity against Voltage – Low voltage side - Power Factor equal to 0.95.

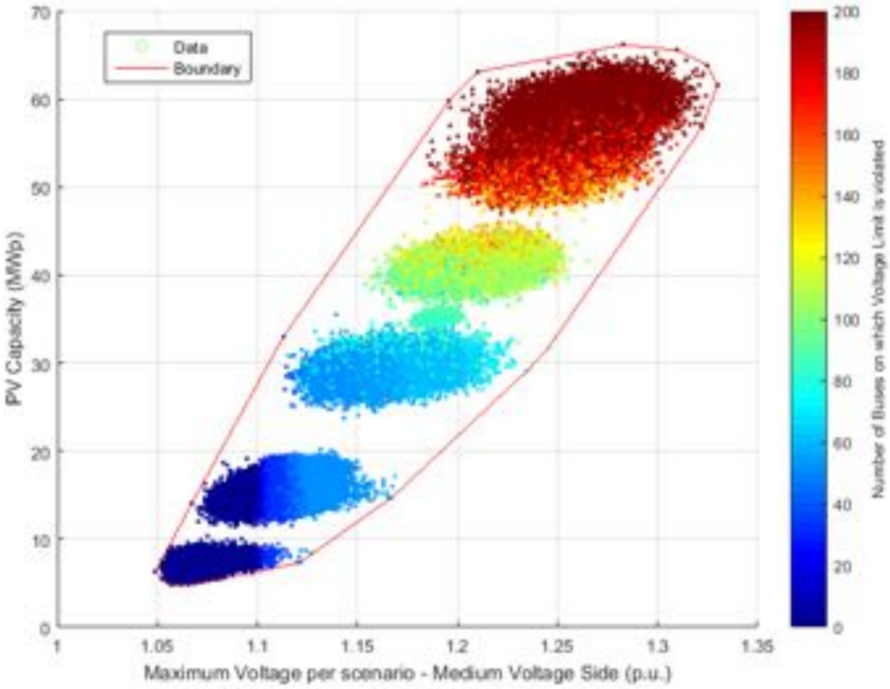


**Figure 263.** PV Capacity against Voltage – Medium voltage side - Power Factor equal to 0.95.

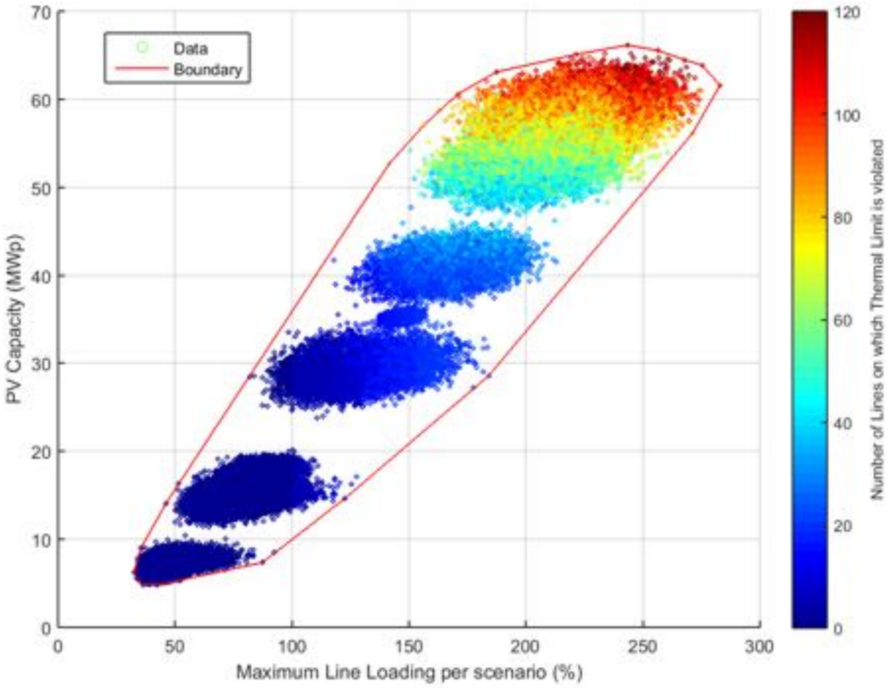


**Figure 264.** PV Capacity against Line Loading - Power Factor equal to 0.95.

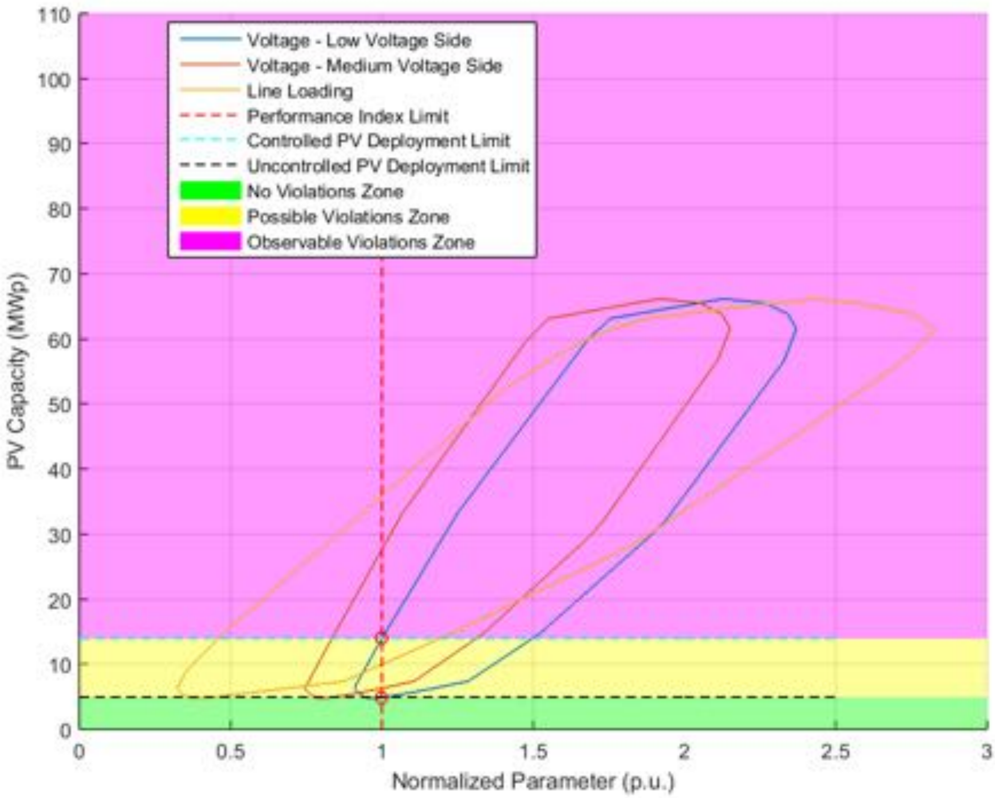


**Figure 265.** Normalized performance index parameters - Power Factor equal to 0.95.

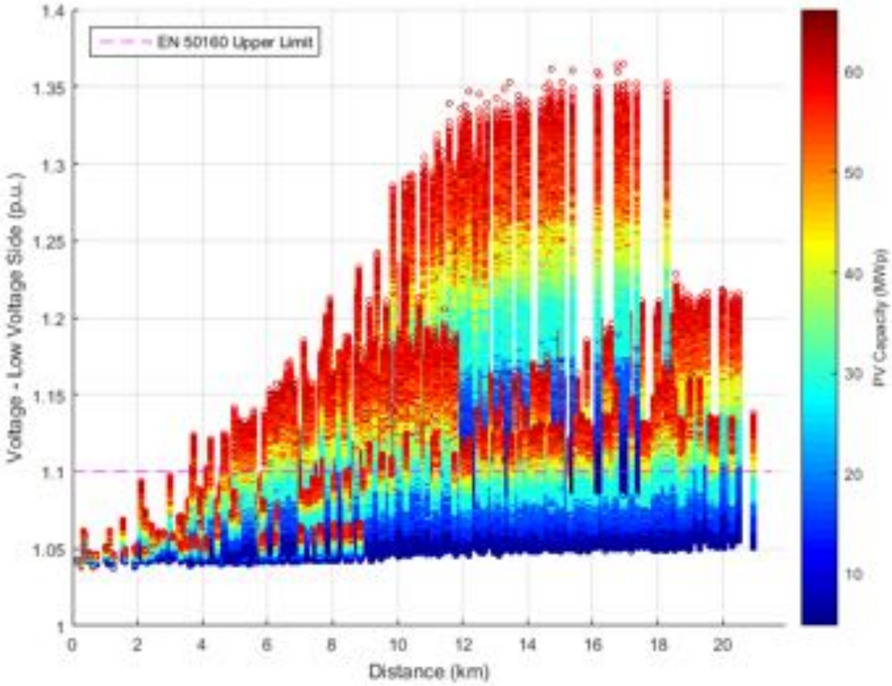


**Figure 266.** Voltage at low voltage side against Distance from transmission substation - Power Factor equal to 0.95.

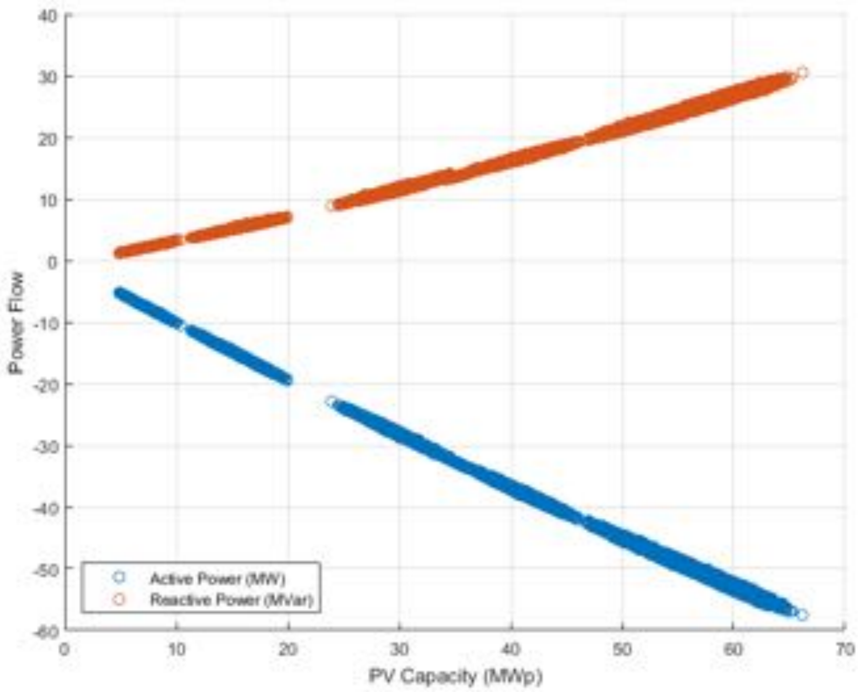


**Figure 267.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor equal to 0.95.

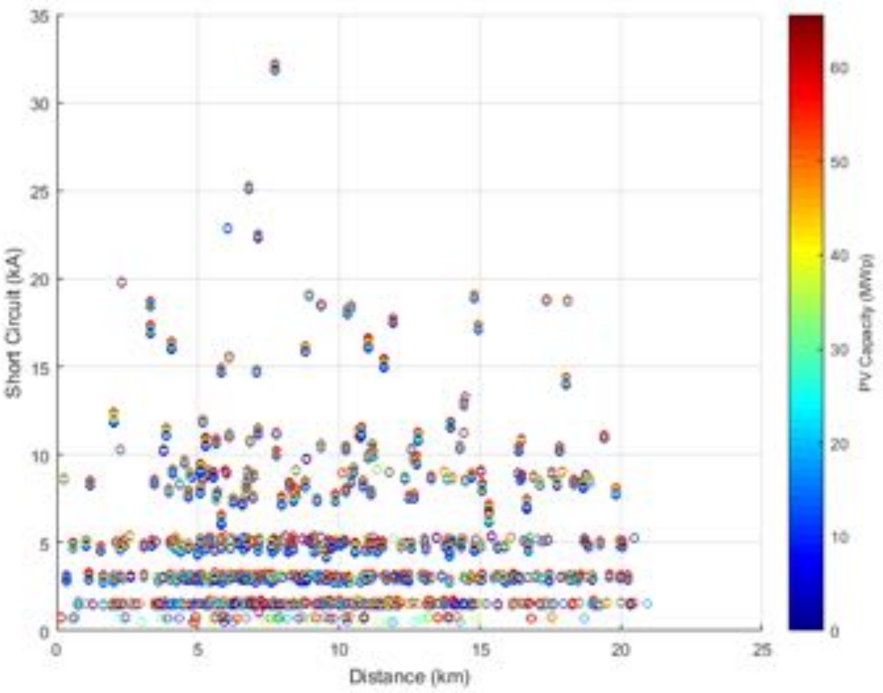


**Figure 268.** Short circuit current against Distance - Power Factor equal to 0.95.

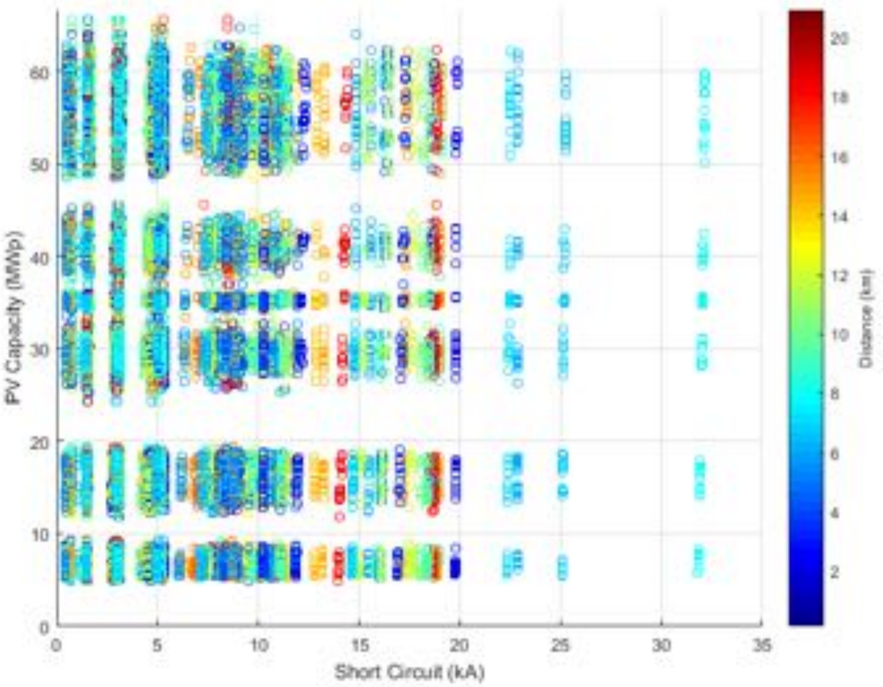


**Figure 269.** PV Capacity against Short Circuit current - Power Factor equal to 0.95.

### E1.3.3 Power Factor cosφ(P)

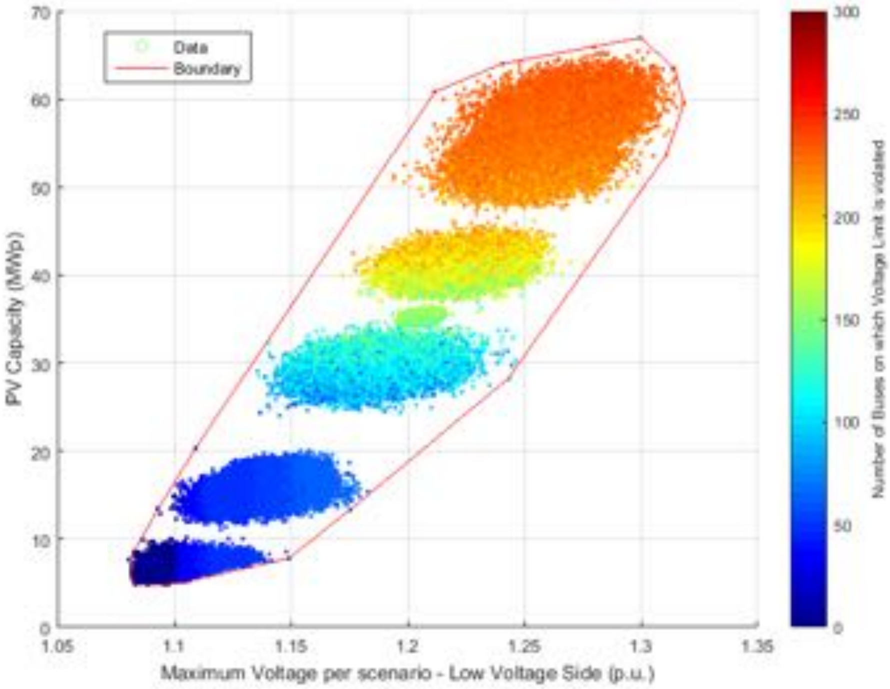


**Figure 270.** PV Capacity against Voltage – Low voltage side - Power Factor cosφ(P).

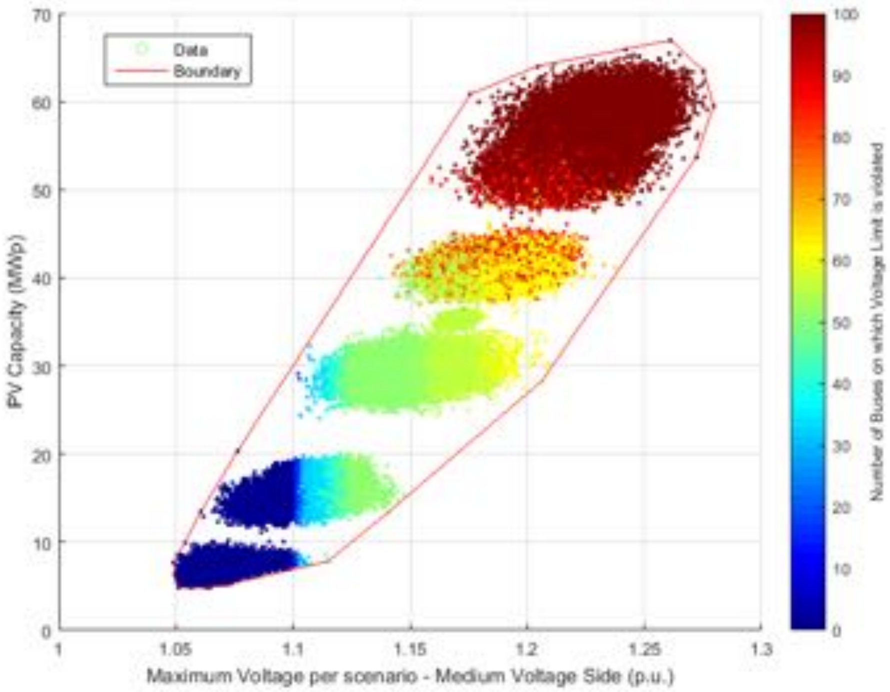


**Figure 271.** PV Capacity against Voltage – Medium voltage side - Power Factor cosφ(P).

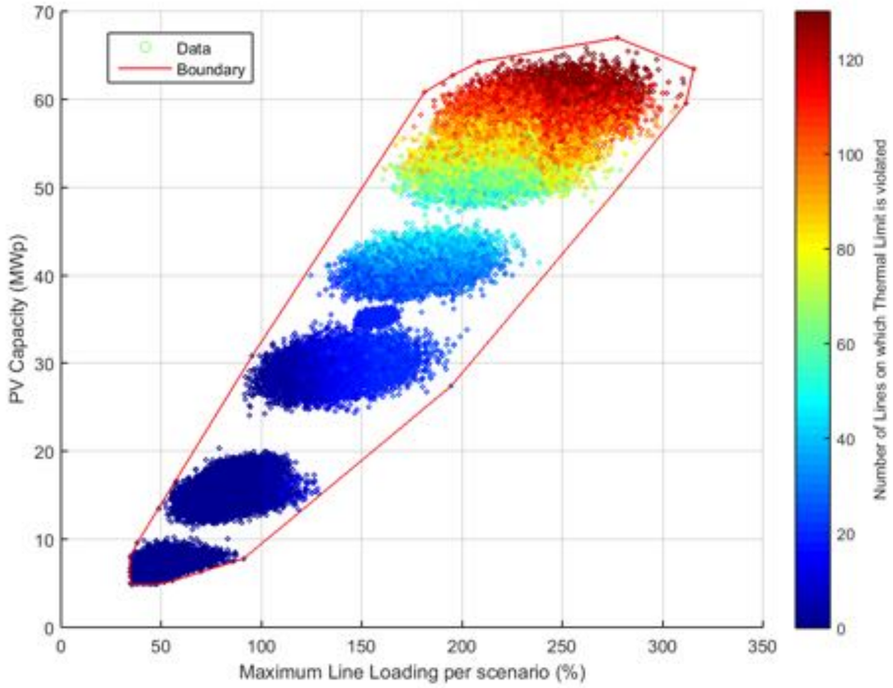


**Figure 272.** PV Capacity against Line Loading - Power Factor cosφ(P).

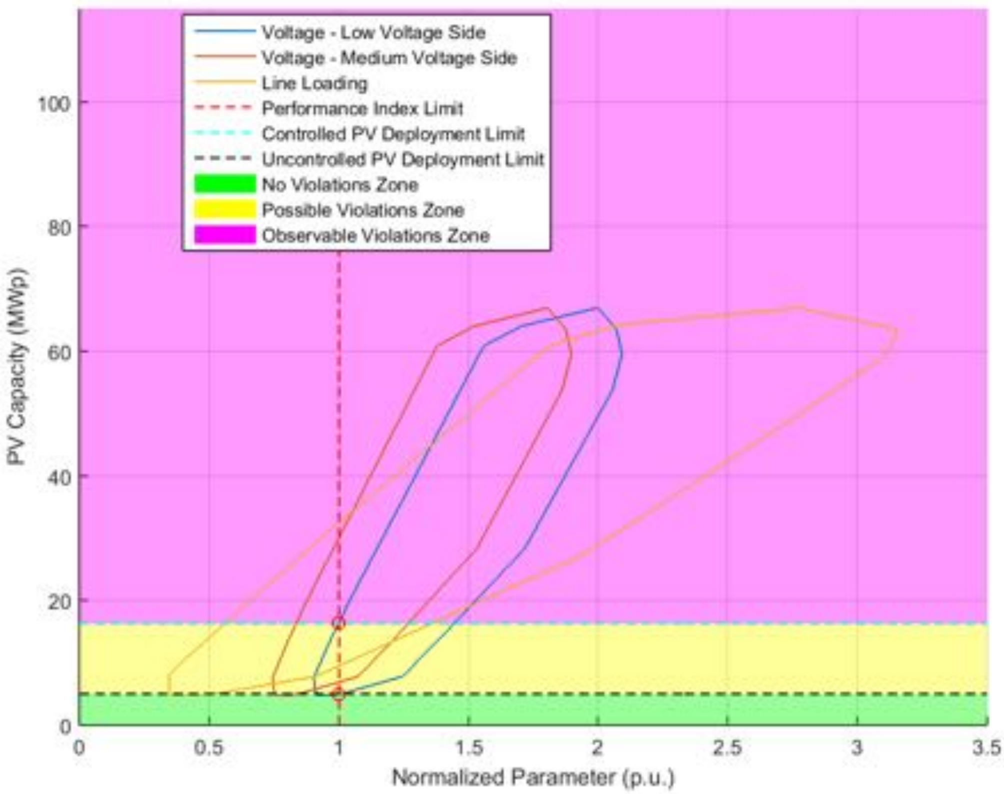


**Figure 273.** Normalized performance index parameters - Power Factor cosφ(P).

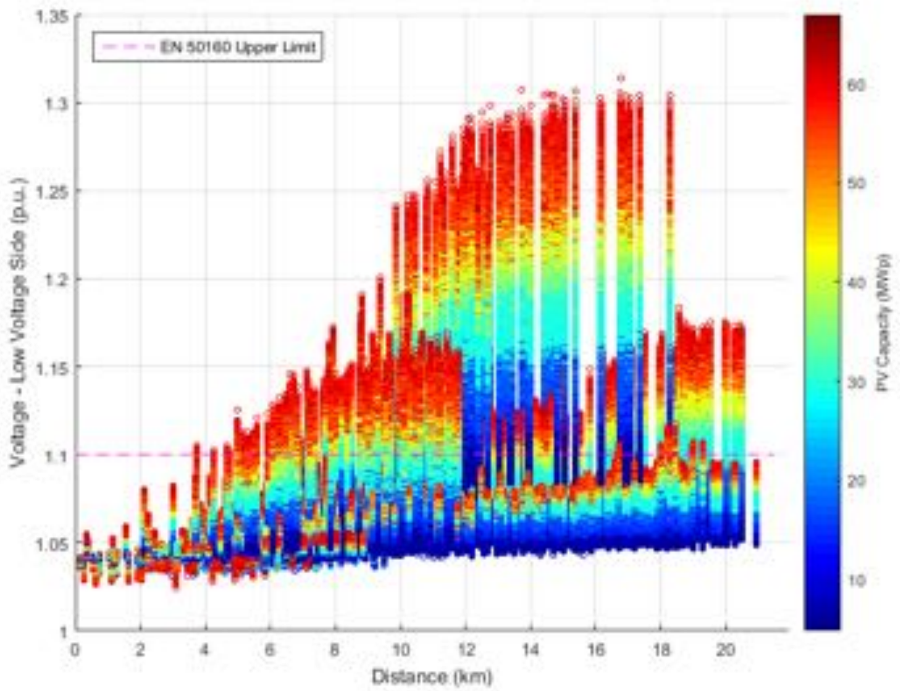


**Figure 274.** Voltage at low voltage side against distance from transmission substation - Power Factor cosφ(P).

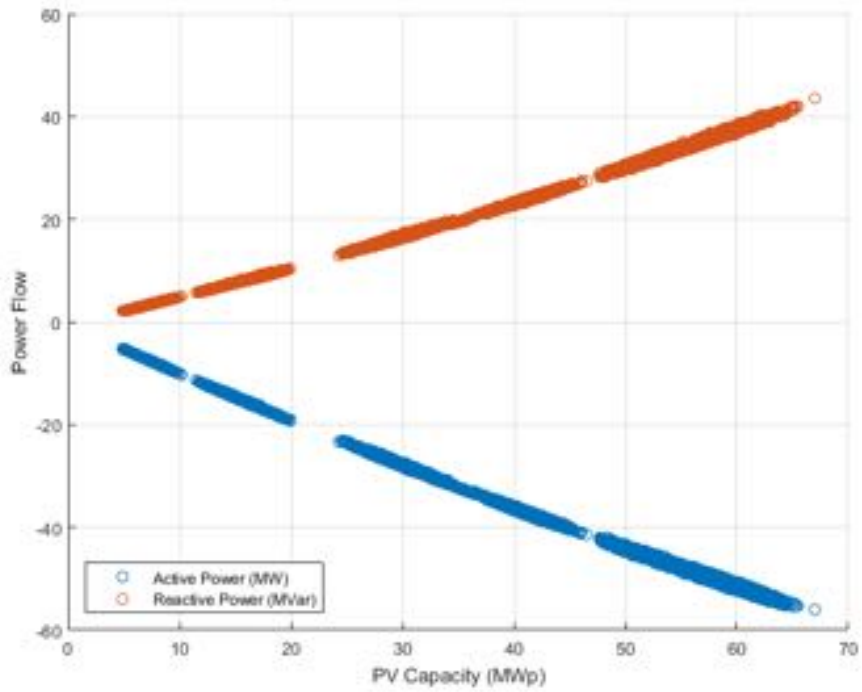


**Figure 275.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor cosφ(P).

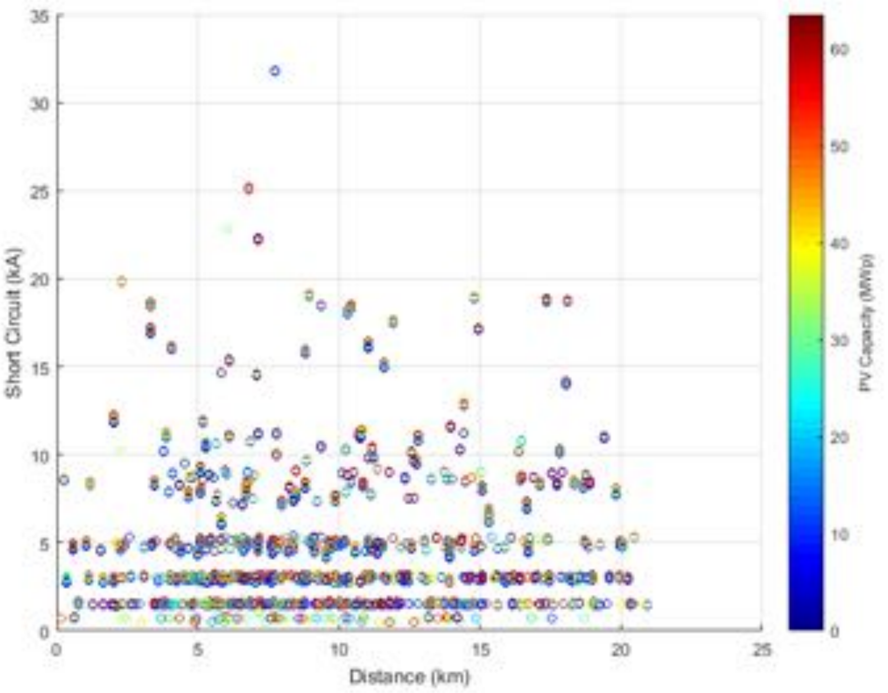


**Figure 276.** Short circuit current against distance - Power Factor cosφ(P).

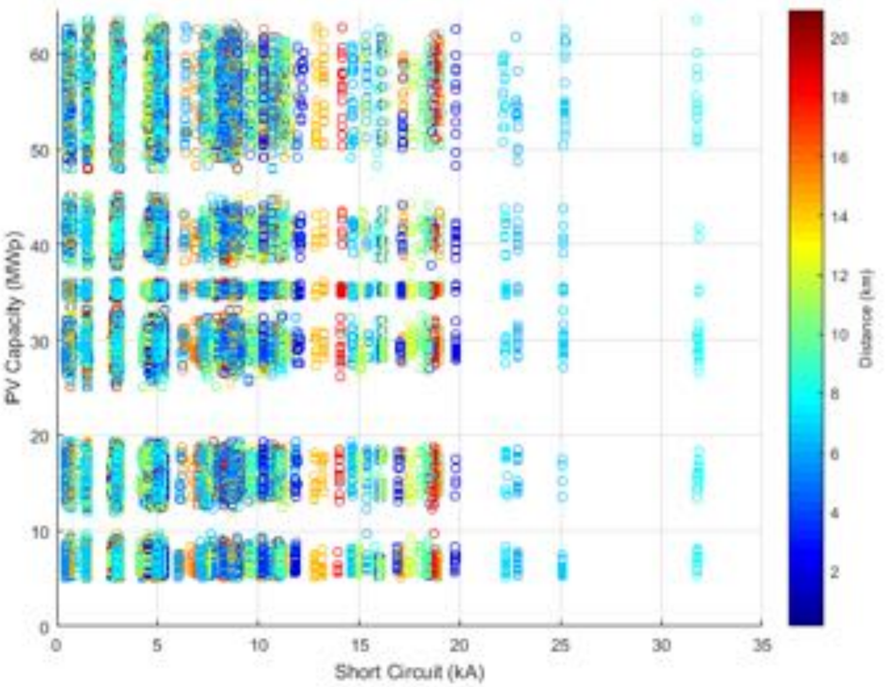


**Figure 277.** PV Capacity against short circuit current - Power Factor cosφ(P).

### E1.3.4 Summary – Monte Carlo Simulation

**Table 40.** Categorization of violations into zones.

| Scenario | No Violations Zone (MWp) | Possible Violations Zone (MWp) | Observable Violations Zone (MWp) |
|---|---|---|---|
| **Unity Power Factor** | below 4.84 | 4.84 - 10.36 | above 10.36 |
| **Power Factor equal to 0.95** | below 4.90 | 4.90 - 13.96 | above 13.96 |
| **Power Factor cosφ(P)** | below 5.00 | 5.00 - 16.37 | above 16.37 |

**Table 41.** Uncontrolled/Controlled PV Deployment Limit.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| **Unity Power Factor** | 4.84 | 10.36 | 5.68 | 21.00 | 12.72 | 37.79 |
| **Power Factor equal to 0.95** | 4.90 | 13.96 | 6.30 | 27.63 | 9.98 | 35.88 |
| **Power Factor cosφ(P)** | 5.00 | 16.37 | 6.89 | 29.99 | 9.50 | 32.46 |

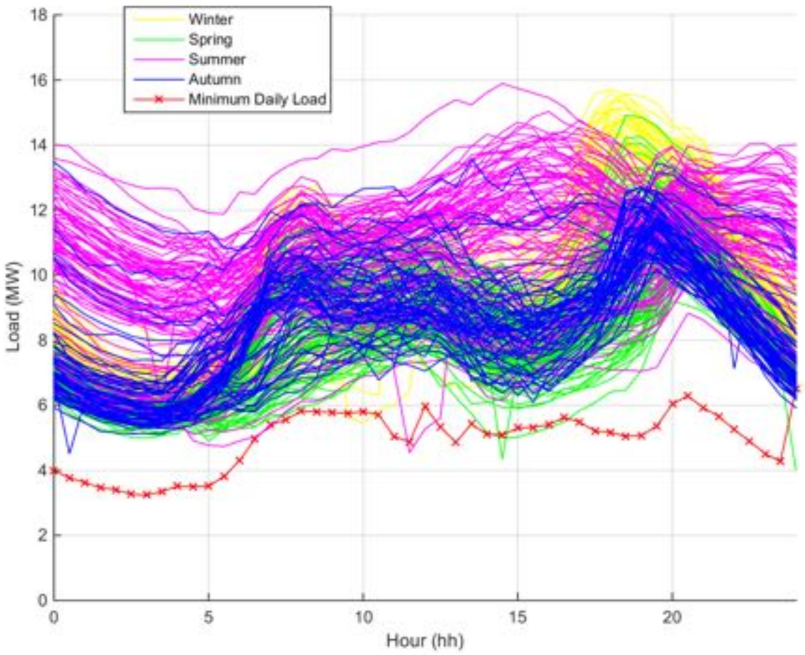


**Figure 278.** Alambra S/S - Minimum daily load.

# Appendix F

# F. Sotera s/s - Executive Summary

The results of the PV hosting capacity for Sotera substation with two 31.5 MVA transmission transformers (with a total distribution transformer capacity of 88.126 MVA), 11 feeders, 369 distribution substations/transformers/busbars and 688 distribution lines either underground or overhead located in Larnaca district area, are presented and analysed in this Appendix. For this PV hosting capacity assessment, it was assumed that the inverter of PV systems is oversized by 10% (as imposed by newly formulated regulations).

## F.1 Results

### F1.1 Maximum Installed PV Capacity scenario

#### F1.1.1 Unity Power Factor Operation

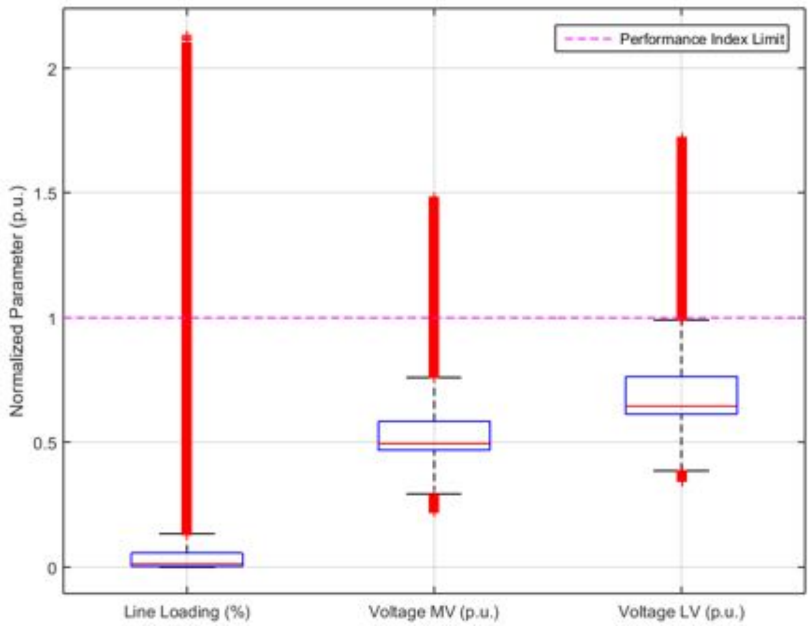


**Figure 279.** Performance Index parameters normalized to their limit – Unity Power Factor.

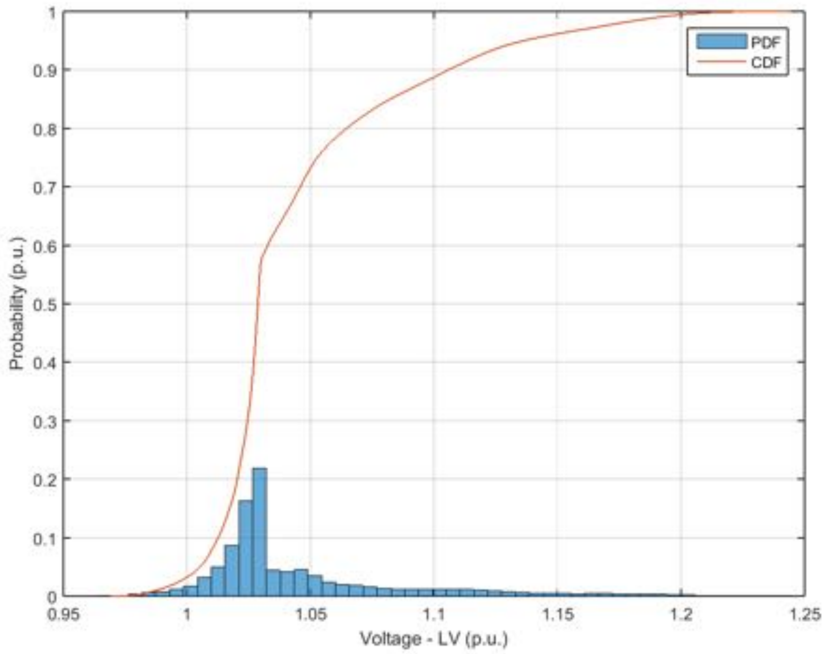


**Figure 280.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity power factor.

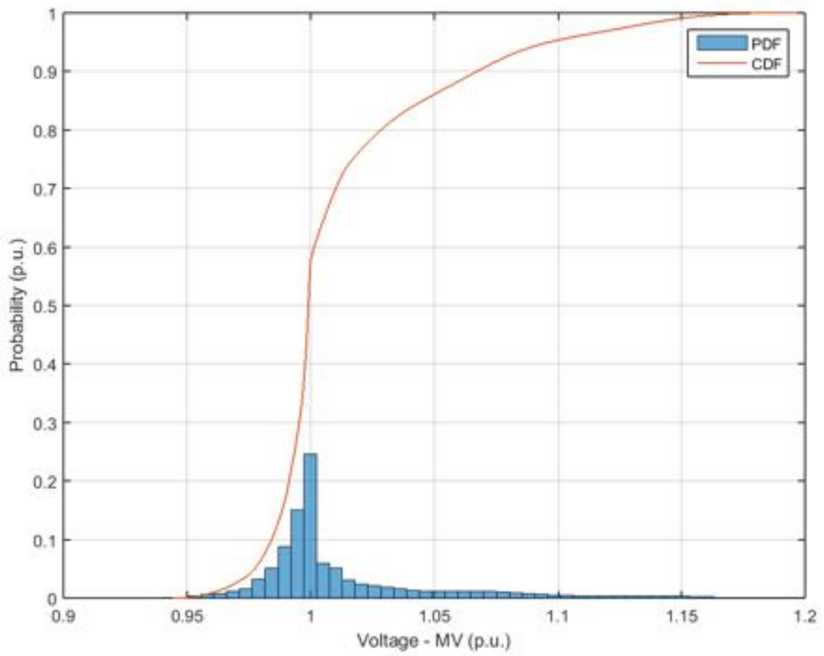


**Figure 281.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Unity power factor.

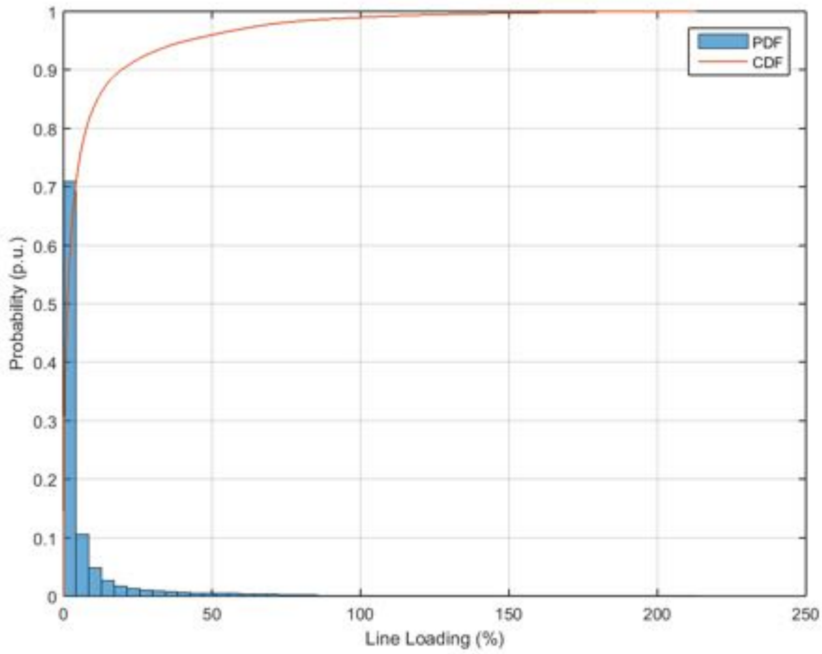


**Figure 282.** Probability distribution and cumulative probability distribution – Line Loading – Unity power factor.

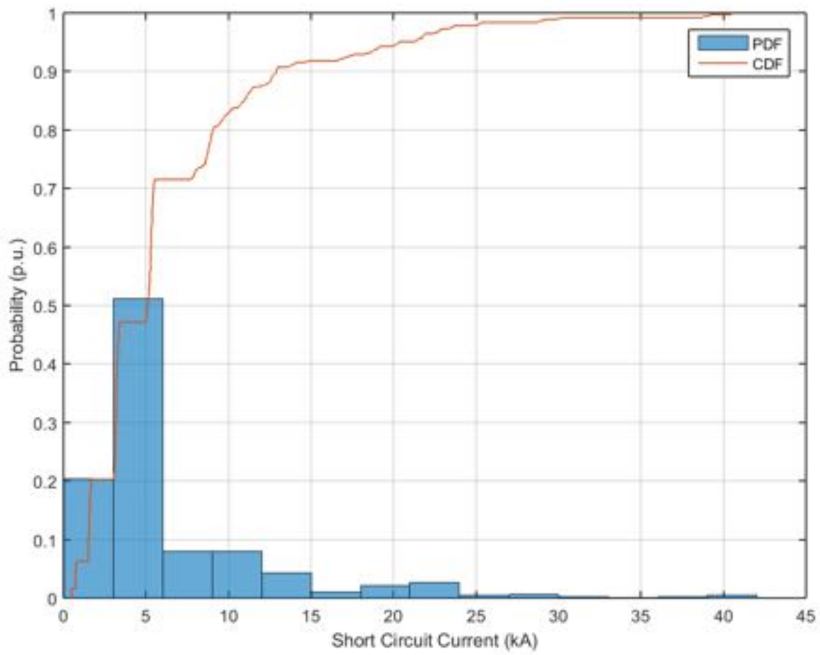


**Figure 283.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity power factor.

### F1.1.2 Power Factor equal to 0.95

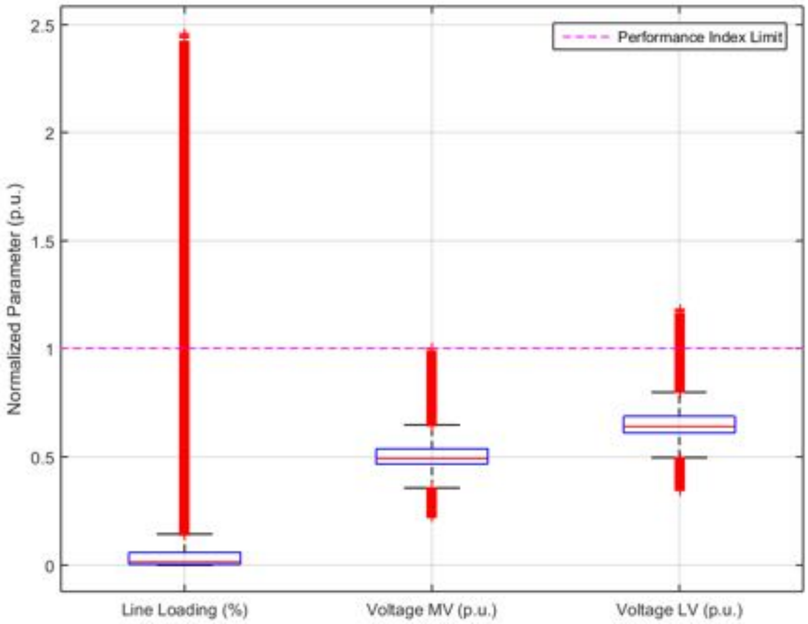


**Figure 284.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

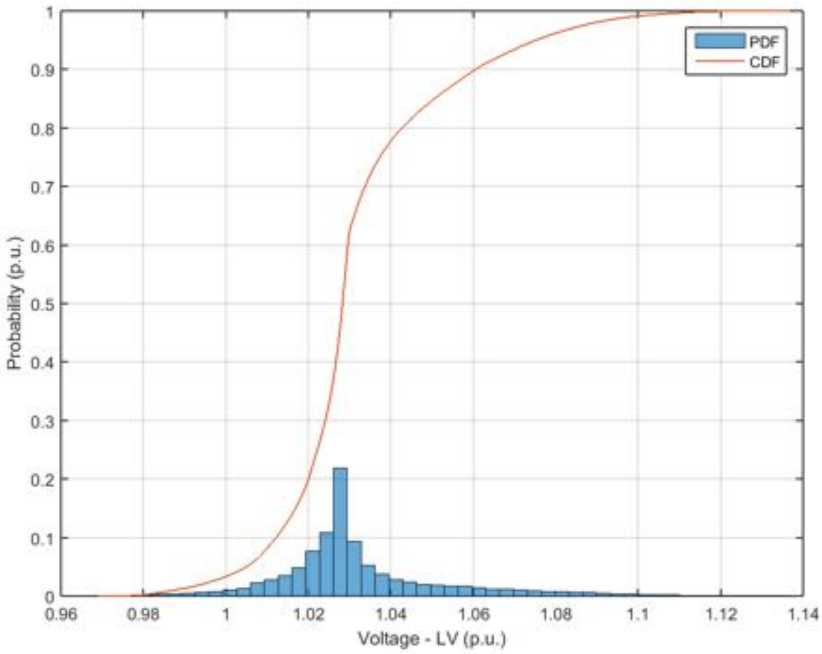


**Figure 285.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

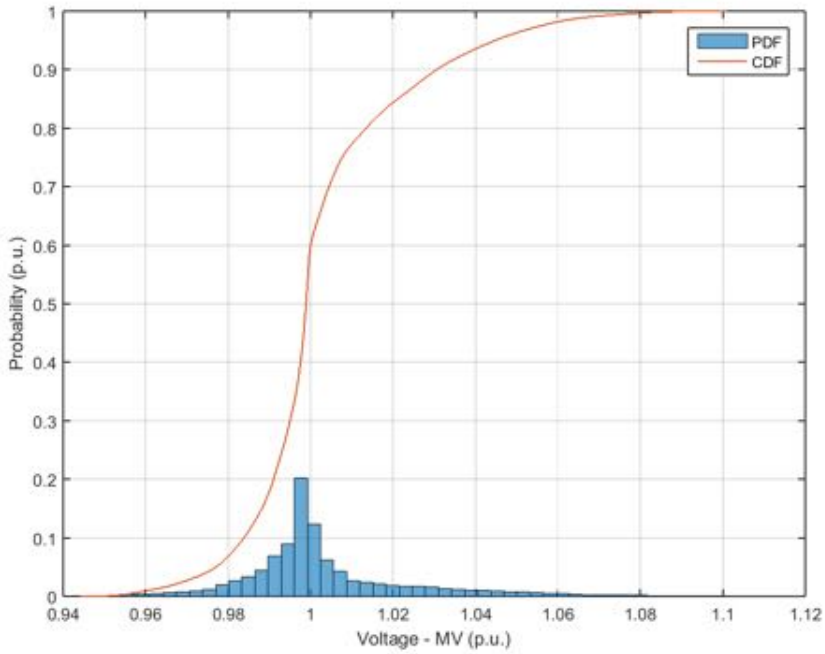


**Figure 286.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor equal to 0.95.

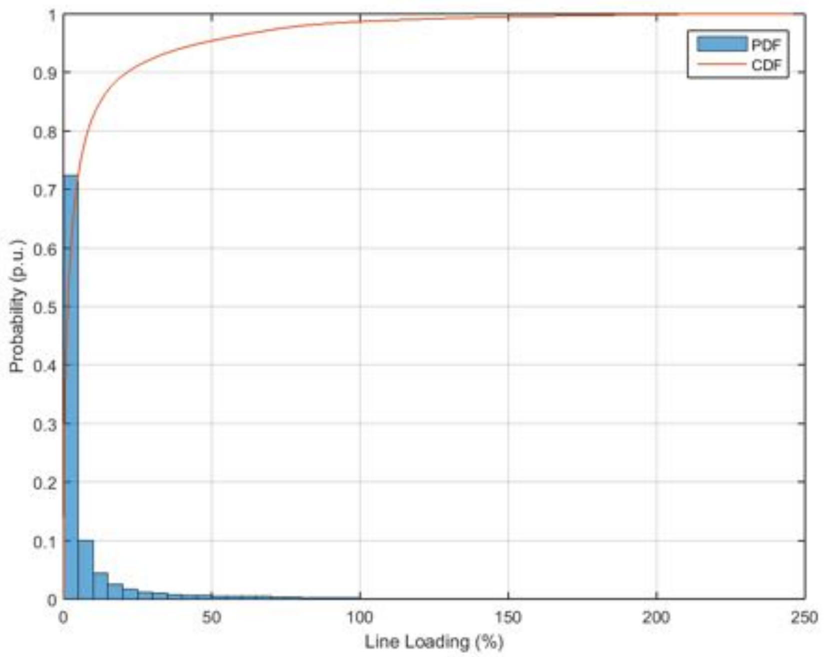


**Figure 287.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

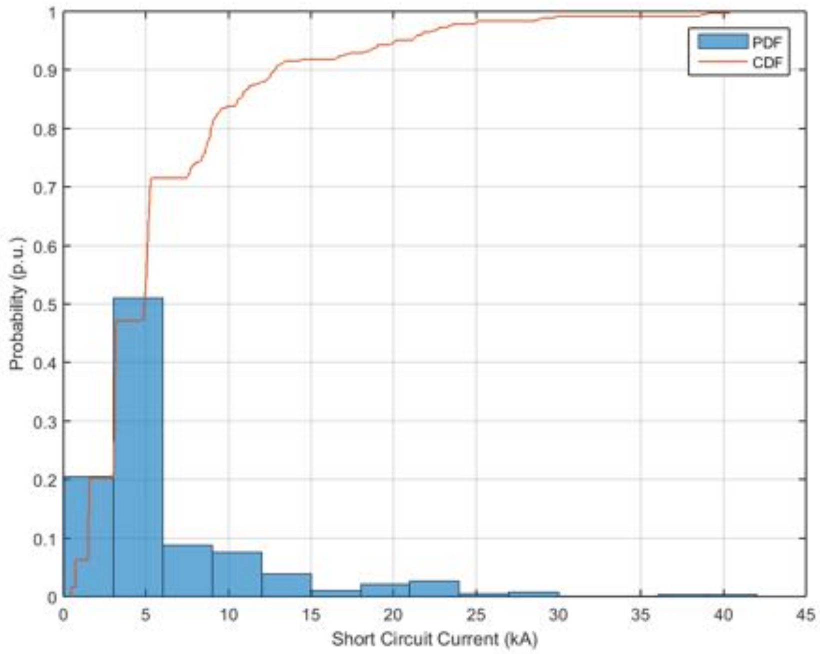


**Figure 288.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### F1.1.3 Power Factor cosφ(P)

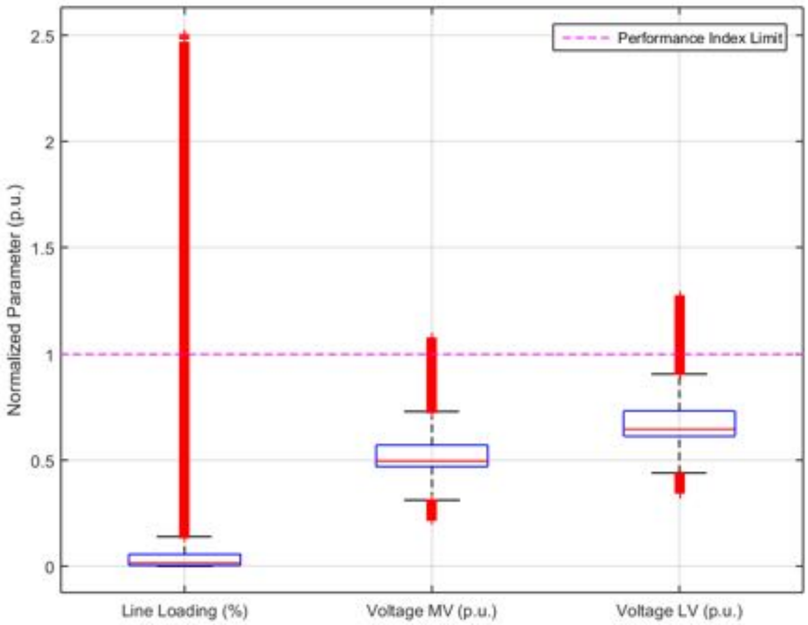


**Figure 289.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

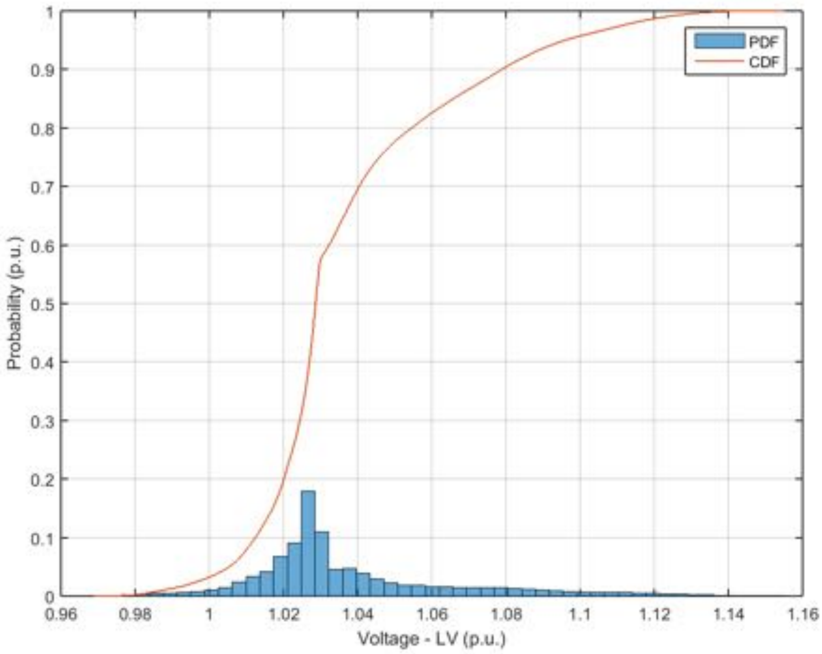


**Figure 290.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

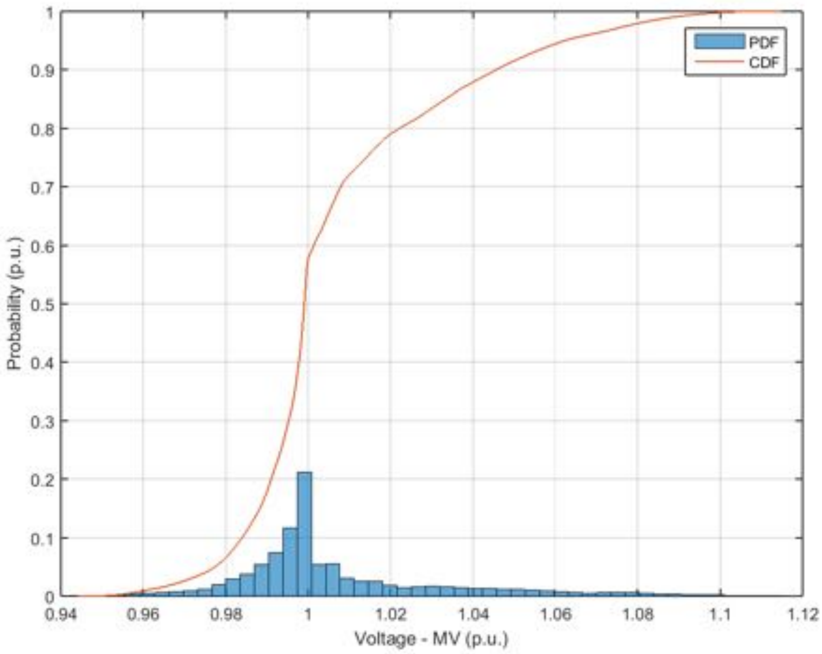


**Figure 291.** Probability distribution and cumulative probability distribution – Voltage at medium voltage side – Power Factor cosφ(P).

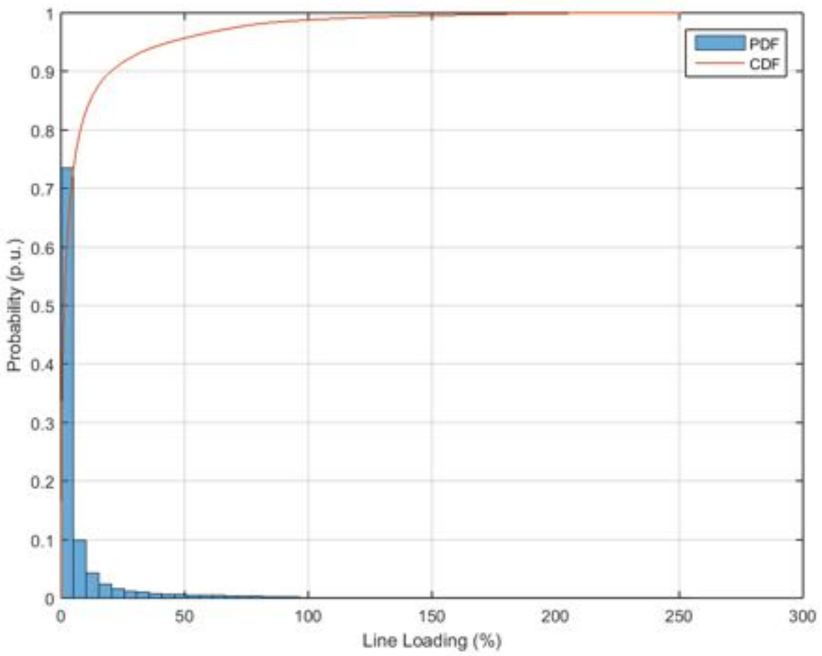


**Figure 292.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

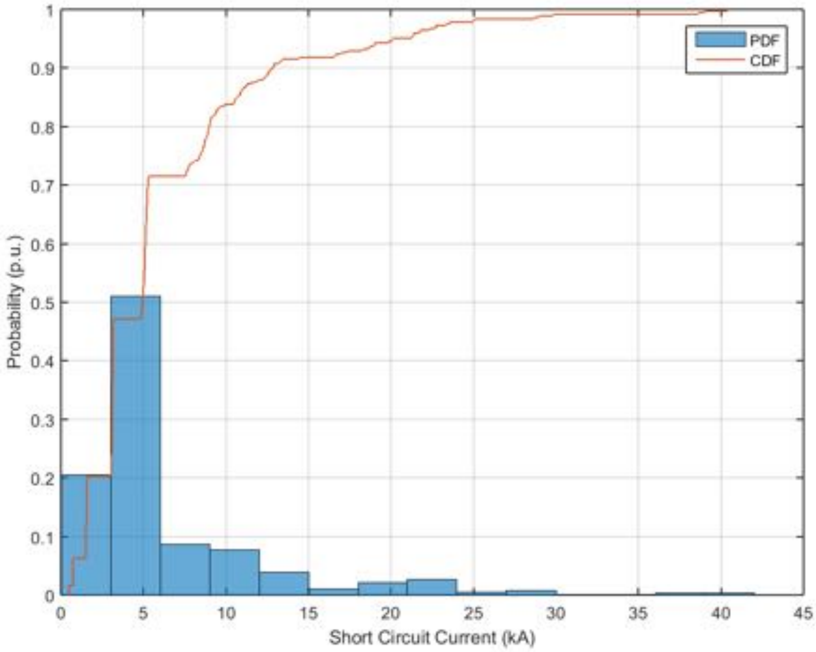


**Figure 293.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### F1.1.4 Summary and Discussion – Maximum Installed PV Capacity scenario

**Table 42.** Statistical analysis of PI parameters - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.345 | 0.345 | 0.345 |
| | 25th quantile | 0.613 | 0.611 | 0.612 |
| | Median | 0.644 | 0.642 | 0.643 |
| | Average | 0.723 | 0.660 | 0.687 |
| | Standard Deviation | 0.042 | 0.010 | 0.018 |
| | 75th quantile | 0.764 | 0.687 | 0.730 |
| | 95th quantile | 1.182 | 0.876 | 0.980 |
| | 99th quantile | 1.453 | 0.991 | 1.116 |
| | Maximum | 1.721 | 1.184 | 1.275 |
| **Number of elements of which the limit is violated** | | 201 out of 369 | 64 out of 369 | 108 out of 369 |
| **Voltage – Medium Voltage Side** | Minimum | 0.220 | 0.220 | 0.220 |
| | 25th quantile | 0.468 | 0.466 | 0.467 |
| | Median | 0.495 | 0.495 | 0.495 |
| | Average | 0.563 | 0.514 | 0.535 |
| | Standard Deviation | 0.034 | 0.010 | 0.016 |
| | 75th quantile | 0.585 | 0.538 | 0.571 |
| | 95th quantile | 0.983 | 0.724 | 0.812 |
| | 99th quantile | 1.242 | 0.837 | 0.942 |
| | Maximum | 1.484 | 1.004 | 1.074 |
| **Number of elements of which the limit is violated** | | 115 out of 369 | 6 out of 369 | 38 out of 369 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.003 | 0.003 | 0.003 |
| | Median | 0.013 | 0.014 | 0.013 |
| | Average | 0.077 | 0.086 | 0.082 |
| | Standard Deviation | 0.036 | 0.046 | 0.043 |
| | 75th quantile | 0.055 | 0.059 | 0.056 |
| | 95th quantile | 0.417 | 0.465 | 0.439 |
| | 99th quantile | 1.010 | 1.146 | 1.095 |
| | Maximum | 2.133 | 2.461 | 2.507 |
| | CDF-100% loading | 98.98% | 98.68% | 98.81% |
| **Number of elements of which the limit is violated** | | 48 out of 688 | 62 out of 688 | 62 out of 688 |

**Table 43.** Statistical analysis of Short Circuit Values - Maximum Installed PV Capacity scenario.

| | | Scenario | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 0.460 | 0.455 | 0.456 |
| | 25th quantile | 3.137 | 3.062 | 3.078 |
| | Median | 5.102 | 4.903 | 4.932 |
| | Average | 6.390 | 6.235 | 6.250 |
| | Standard Deviation | 6.238 | 6.197 | 6.200 |
| | 75th quantile | 8.636 | 8.402 | 8.412 |
| | 95th quantile | 20.332 | 20.125 | 20.122 |
| | 99th quantile | 30.038 | 29.782 | 29.818 |
| | Maximum | 40.523 | 40.435 | 40.440 |

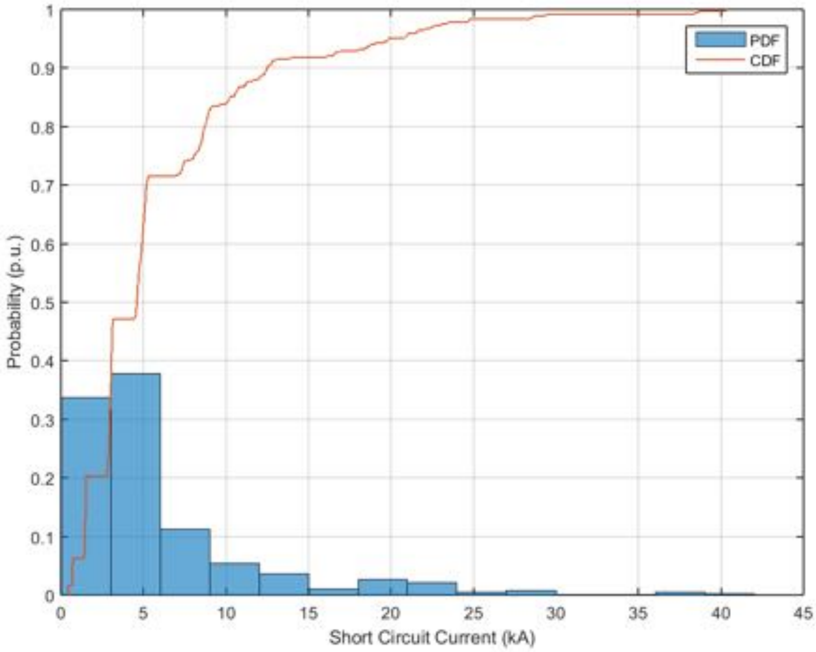


**Figure 294.** Probability distribution and cumulative probability distribution – Short Circuit Current – No PV.

## F1.2 Maximum PV Capacity per Distribution Substation

### F1.2.1 Unity Power Factor Scheme

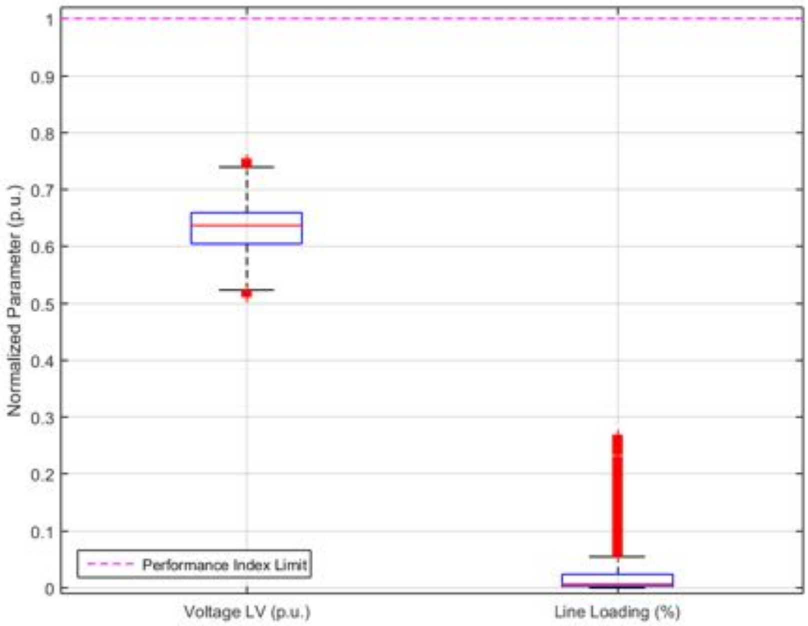


**Figure 295.** Performance Index parameters normalized to their limit – Unity Power Factor.

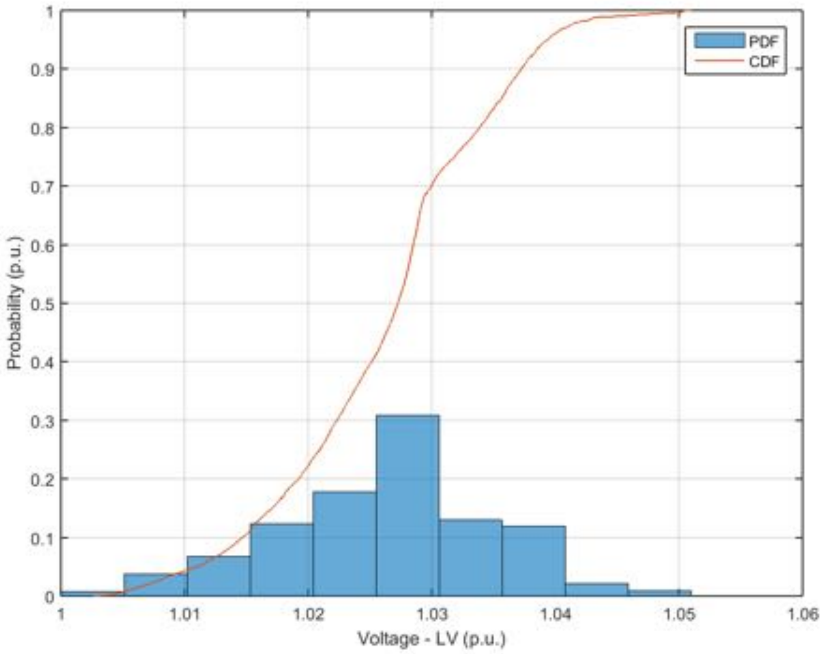


**Figure 296.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Unity Power Factor.

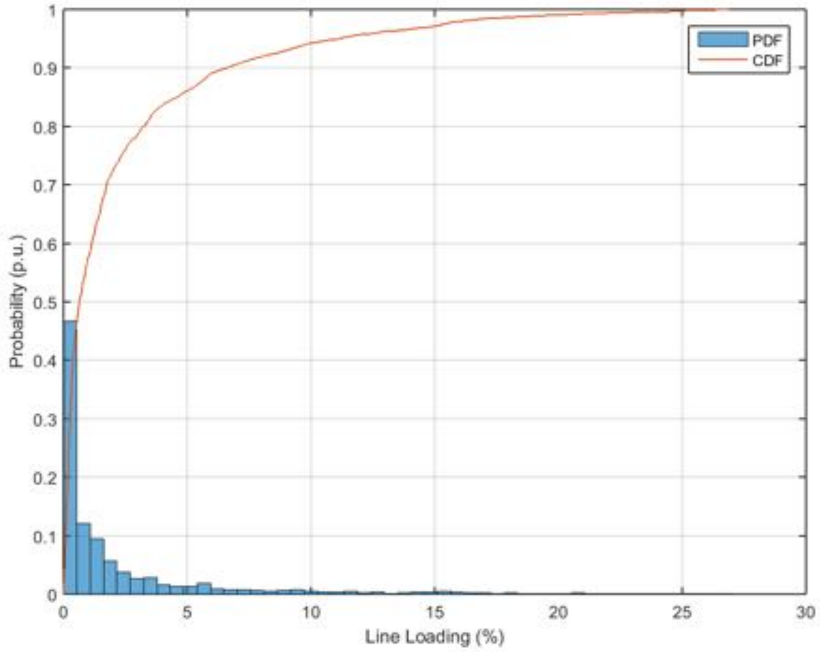


**Figure 297.** Probability distribution and cumulative probability distribution – Line Loading – Unity Power Factor.

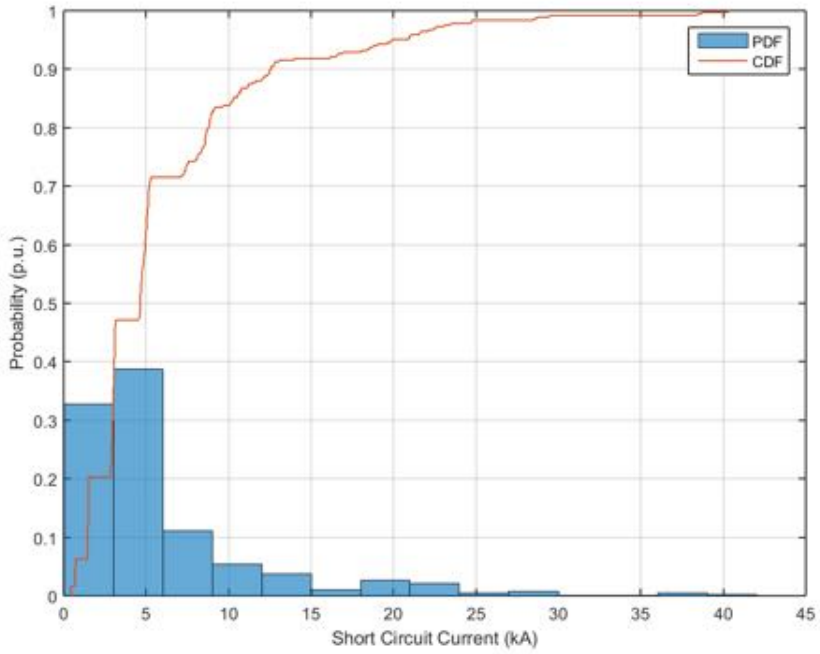


**Figure 298.** Probability distribution and cumulative probability distribution – Short Circuit Current – Unity Power Factor.

### F1.2.2 Power Factor equal to 0.95

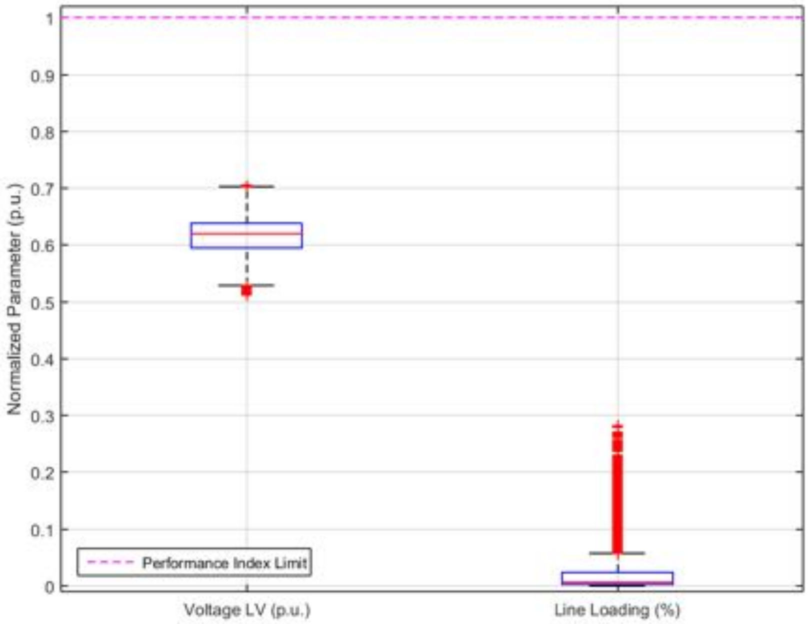


**Figure 299.** Performance Index parameters normalized to their limit – Power Factor equal to 0.95.

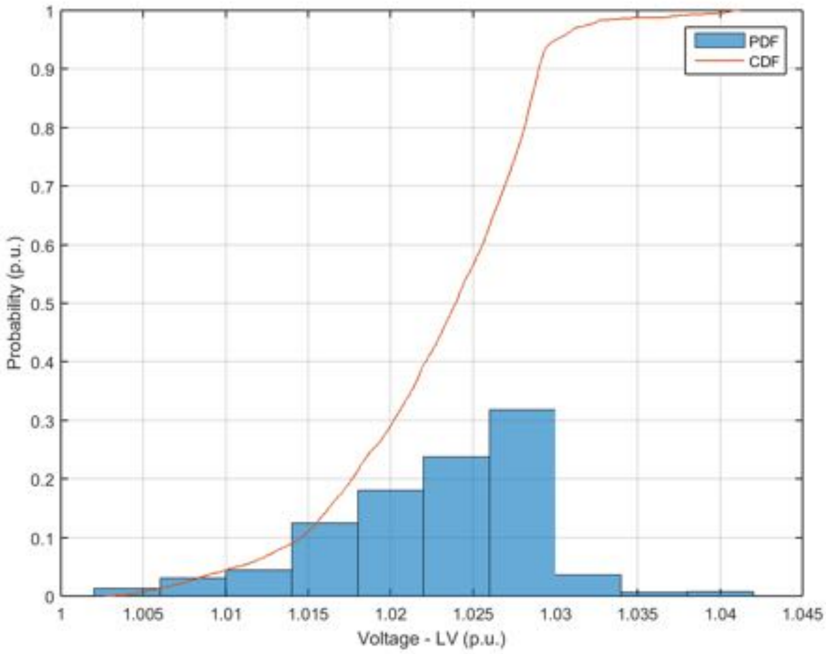


**Figure 300.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor equal to 0.95.

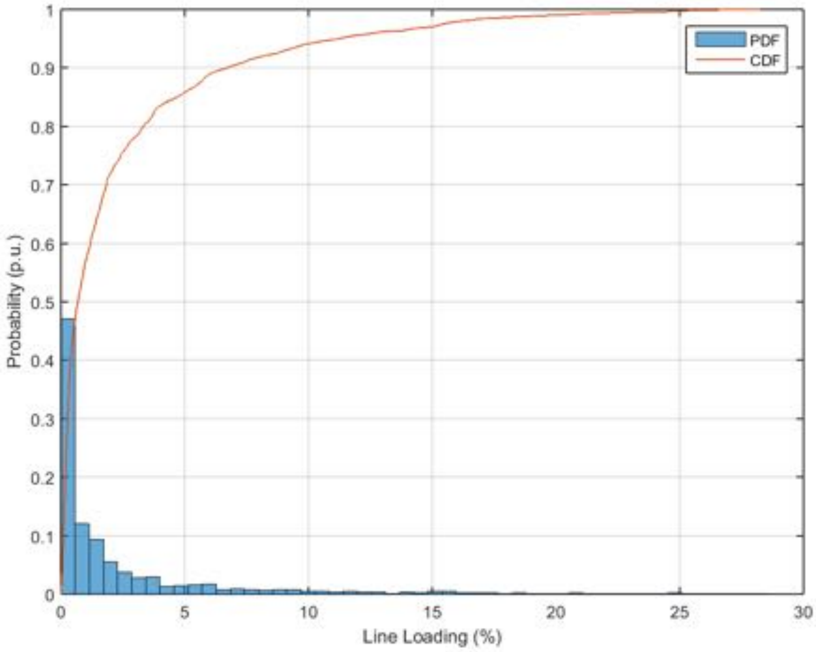


**Figure 301.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor equal to 0.95.

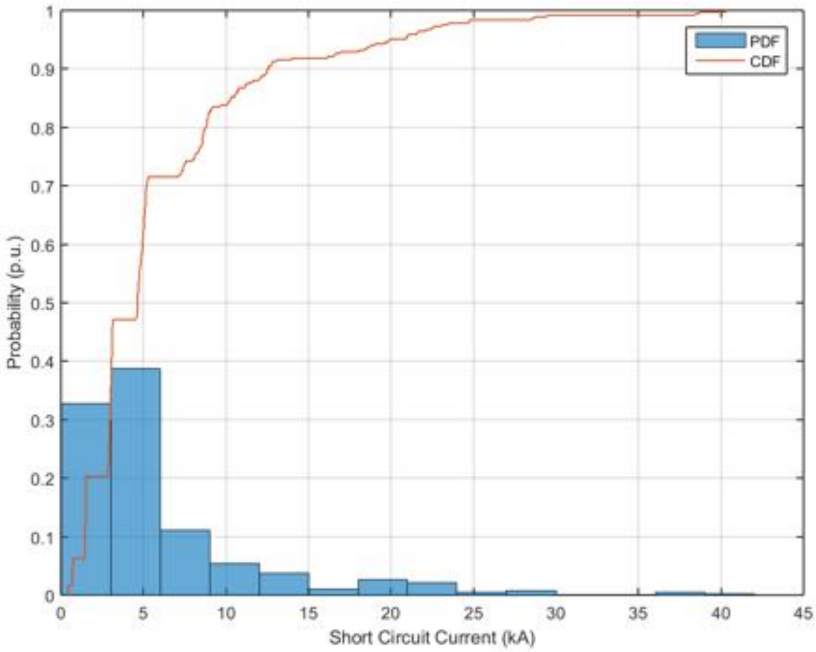


**Figure 302.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor equal to 0.95.

### 1.2.3 Power Factor cosφ(P)

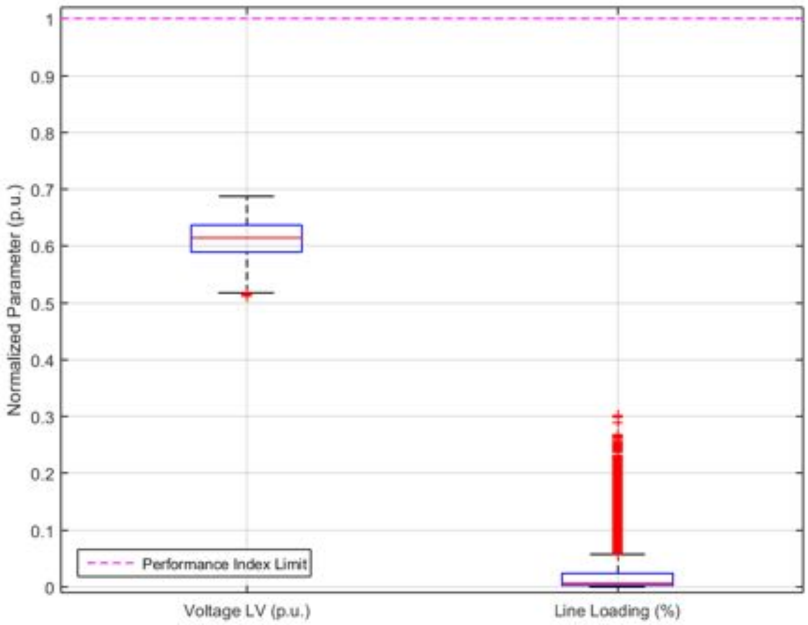


**Figure 303.** Performance Index parameters normalized to their limit – Power Factor cosφ(P).

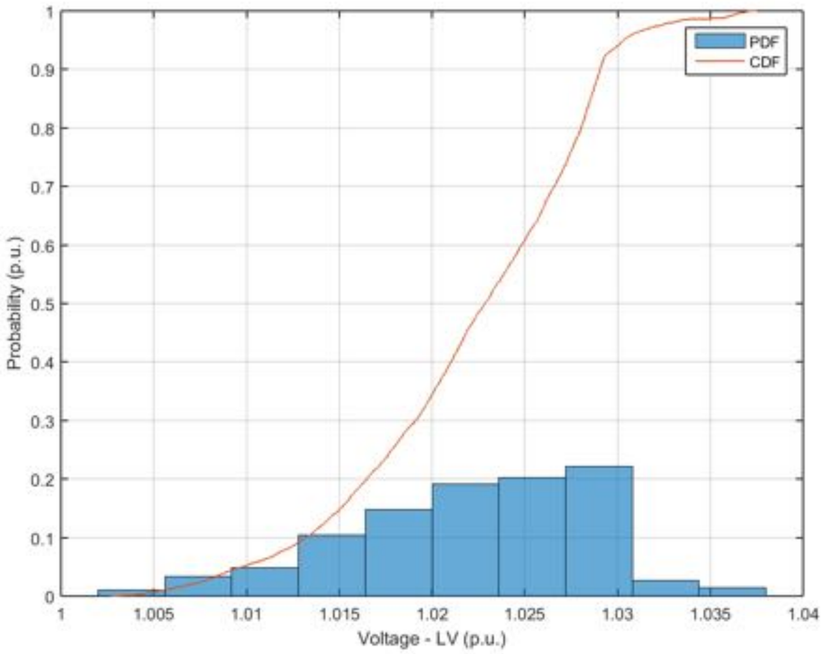


**Figure 304.** Probability distribution and cumulative probability distribution – Voltage at low voltage side – Power Factor cosφ(P).

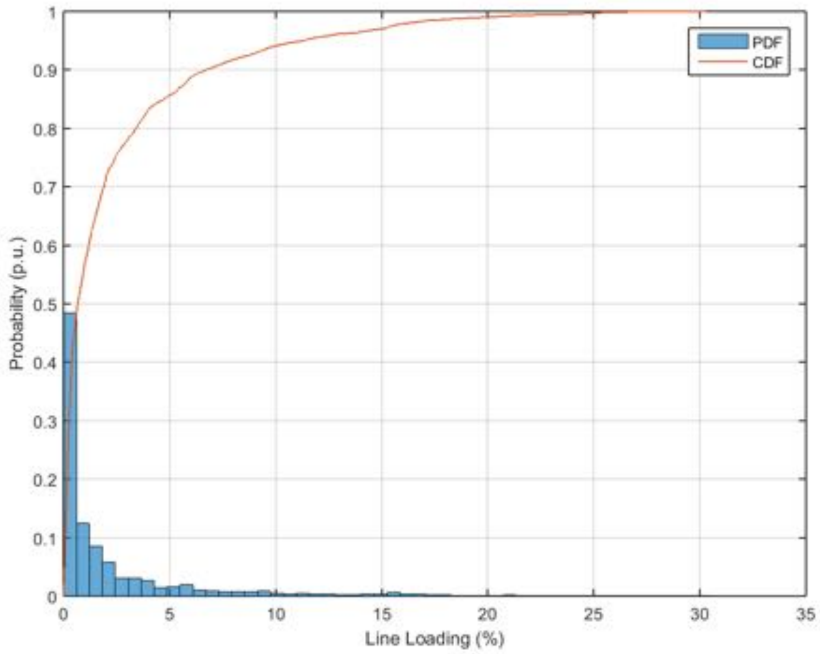


**Figure 305.** Probability distribution and cumulative probability distribution – Line Loading – Power Factor cosφ(P).

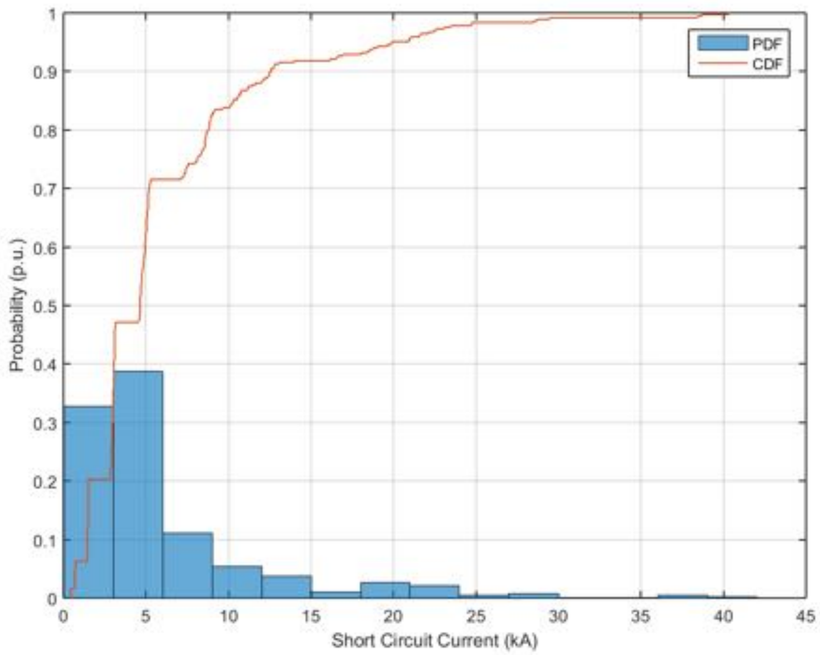


**Figure 306.** Probability distribution and cumulative probability distribution – Short Circuit Current – Power Factor cosφ(P).

### F1.2.4 Summary and Discussion – Maximum PV Capacity per Distribution Substation

**Table 44.** Statistical analysis of PI parameters - Maximum PV Capacity per Distribution Substation.

| | | Scenario | | |
|---|---|---|---|---|
| **Normalized Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Voltage – Low Voltage Side** | Minimum | 0.513 | 0.513 | 0.513 |
| | 25th quantile | 0.605 | 0.594 | 0.589 |
| | Median | 0.636 | 0.620 | 0.614 |
| | Average | 0.631 | 0.614 | 0.611 |
| | Standard Deviation | 0.002 | 0.001 | 0.001 |
| | 75th quantile | 0.659 | 0.638 | 0.637 |
| | 95th quantile | 0.697 | 0.650 | 0.652 |
| | 99th quantile | 0.725 | 0.686 | 0.680 |
| | Maximum | 0.755 | 0.706 | 0.688 |
| **Number of elements of which the limit is violated** | | 0 out of 369 | 0 out of 369 | 0 out of 369 |
| **Line Loading** | Minimum | 0.000 | 0.000 | 0.000 |
| | 25th quantile | 0.002 | 0.002 | 0.002 |
| | Median | 0.006 | 0.007 | 0.007 |
| | Average | 0.023 | 0.023 | 0.024 |
| | Standard Deviation | 0.002 | 0.002 | 0.002 |
| | 75th quantile | 0.023 | 0.024 | 0.024 |
| | 95th quantile | 0.111 | 0.112 | 0.113 |
| | 99th quantile | 0.197 | 0.198 | 0.199 |
| | Maximum | 0.269 | 0.283 | 0.303 |
| **Number of elements of which the limit is violated** | | 0 out of 688 | 0 out of 688 | 0 out of 688 |

**Table 45.** Statistical analysis of Short Circuit Values - Maximum PV Capacity per Distribution Substation.

| | | Scenario | | |
|---|---|---|---|---|
| **Parameter** | Statistical Analysis | Unity Power Factor | Power Factor equal to 0.95 | Power Factor cosφ(P) |
| **Short Circuit (kA)** | Minimum | 0.445 | 0.445 | 0.445 |
| | 25th quantile | 2.904 | 2.904 | 2.904 |
| | Median | 4.655 | 4.655 | 4.655 |
| | Average | 6.087 | 6.087 | 6.087 |
| | Standard Deviation | 6.149 | 6.149 | 6.149 |
| | 75th quantile | 8.104 | 8.104 | 8.104 |
| | 95th quantile | 19.928 | 19.928 | 19.928 |
| | 99th quantile | 29.306 | 29.307 | 29.307 |
| | Maximum | 40.319 | 40.319 | 40.319 |

## F1.3 Assessing PV Capacity using Monte Carlo method

### F1.3.1 Unity Power Factor Operation

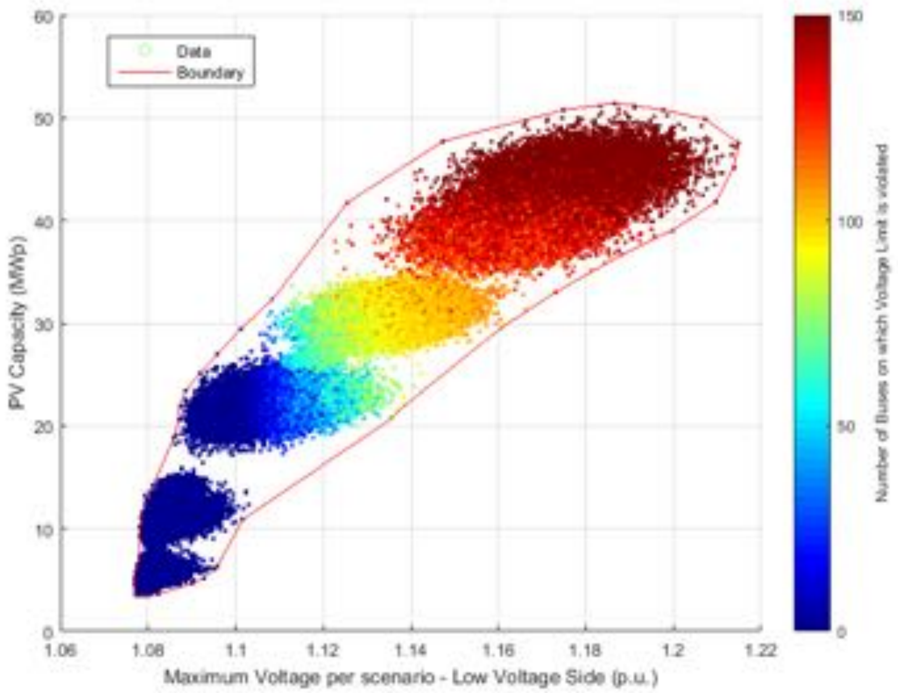


**Figure 307.** PV Capacity against Voltage – Low voltage side - Unity Power Factor.

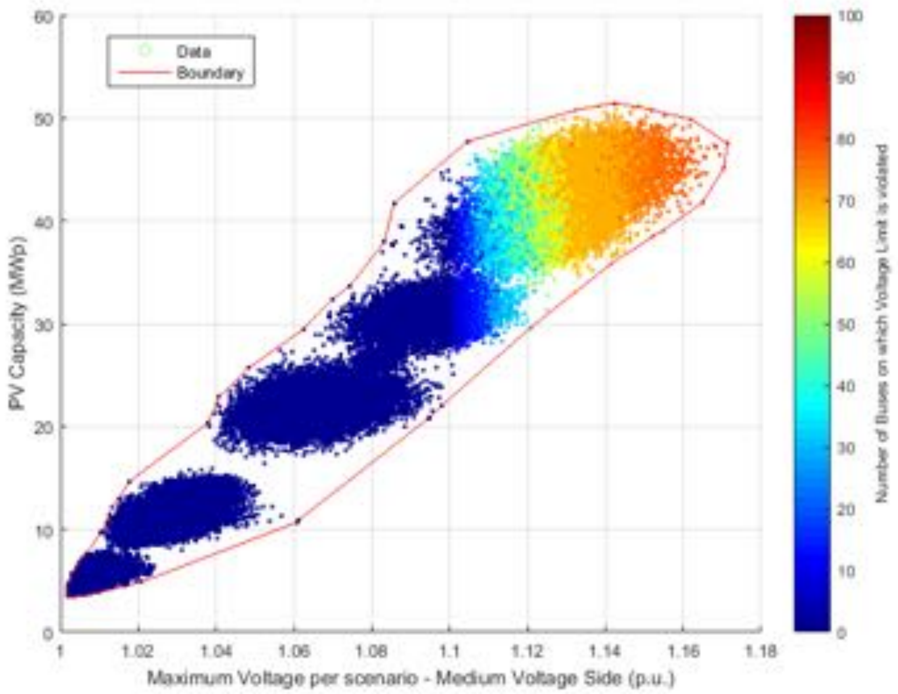


**Figure 308.** PV Capacity against Voltage – Medium voltage side - Unity Power Factor.

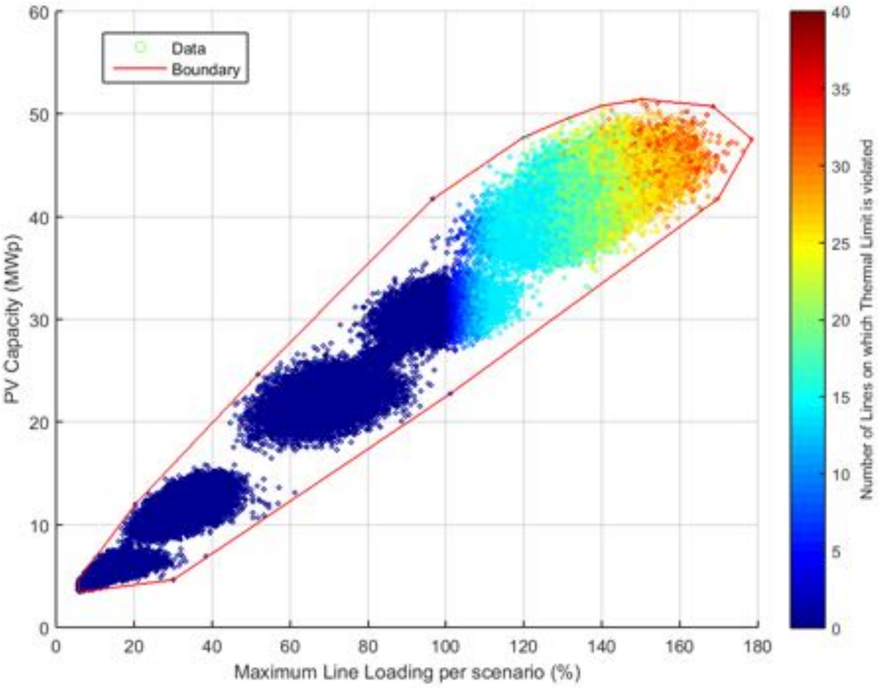


**Figure 309.** PV Capacity against Line Loading - Unity Power Factor.

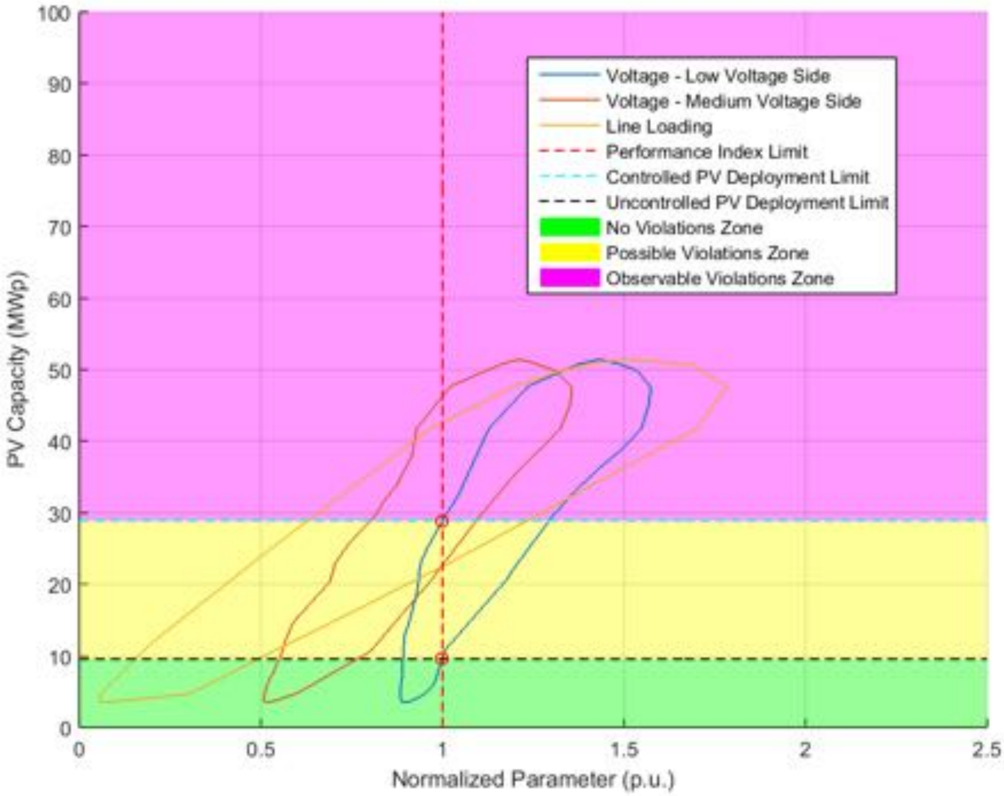


**Figure 310.** Normalized performance index parameters - Unity Power Factor.

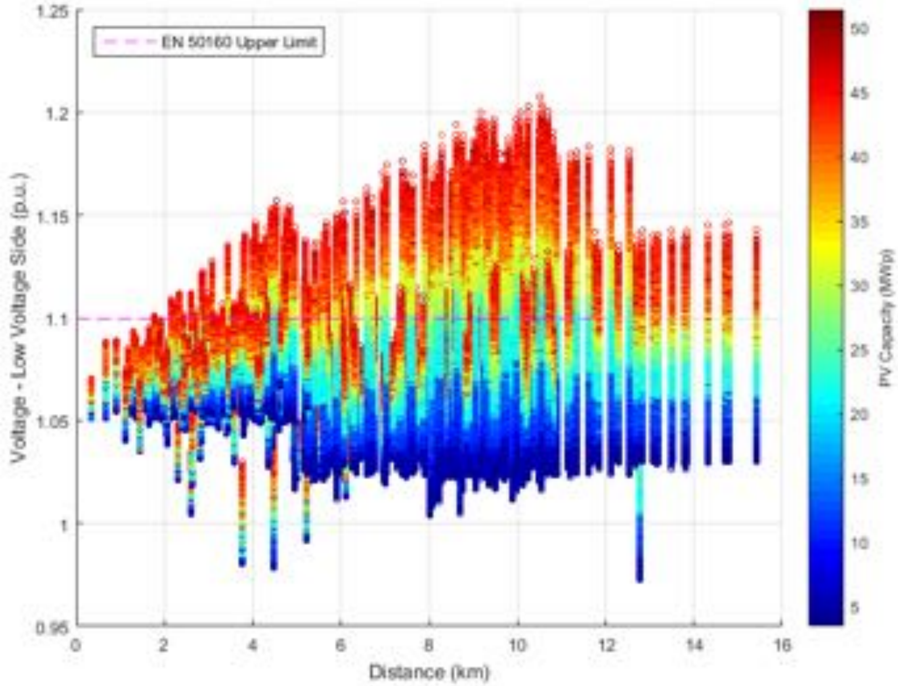


**Figure 311.** Voltage at low voltage side against distance from transmission substation - Unity Power Factor.

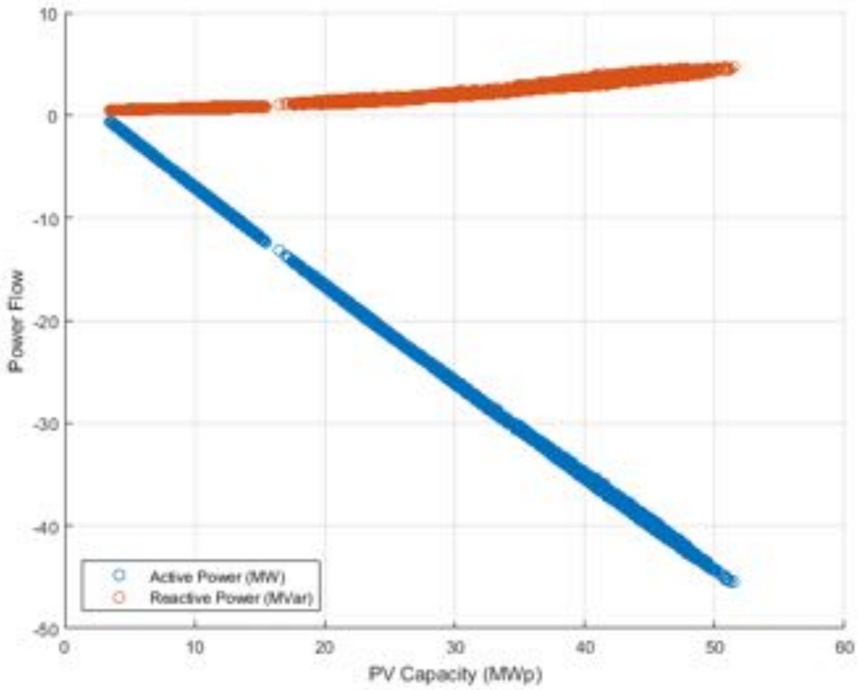


**Figure 312.** Power flow at PCC (connection of the reference substation with HV network) against PV capacity - Unity Power Factor (negative sign denotes reverse power flow).

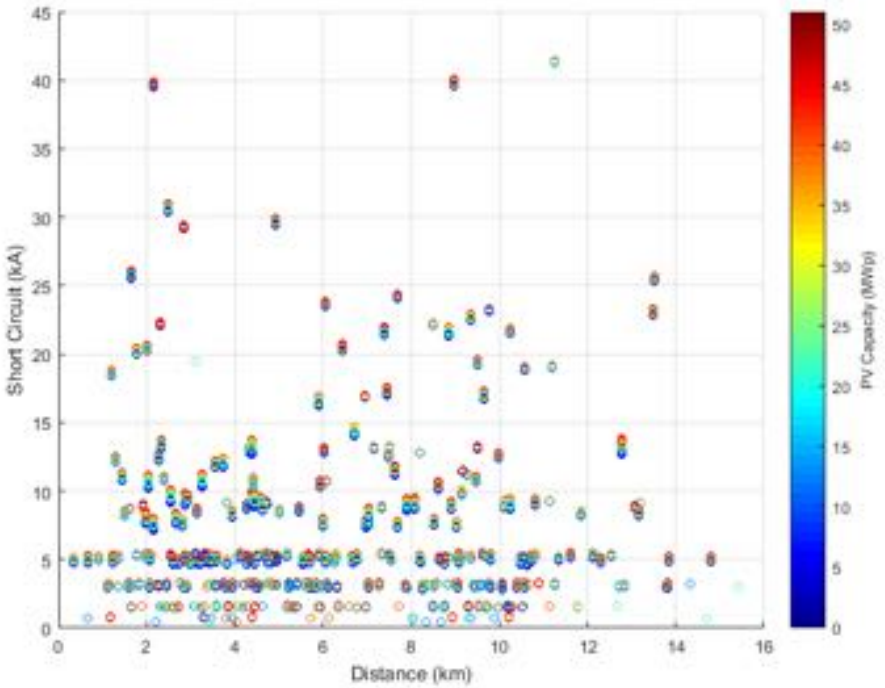


**Figure 313.** Short circuit current against distance - Unity Power Factor.

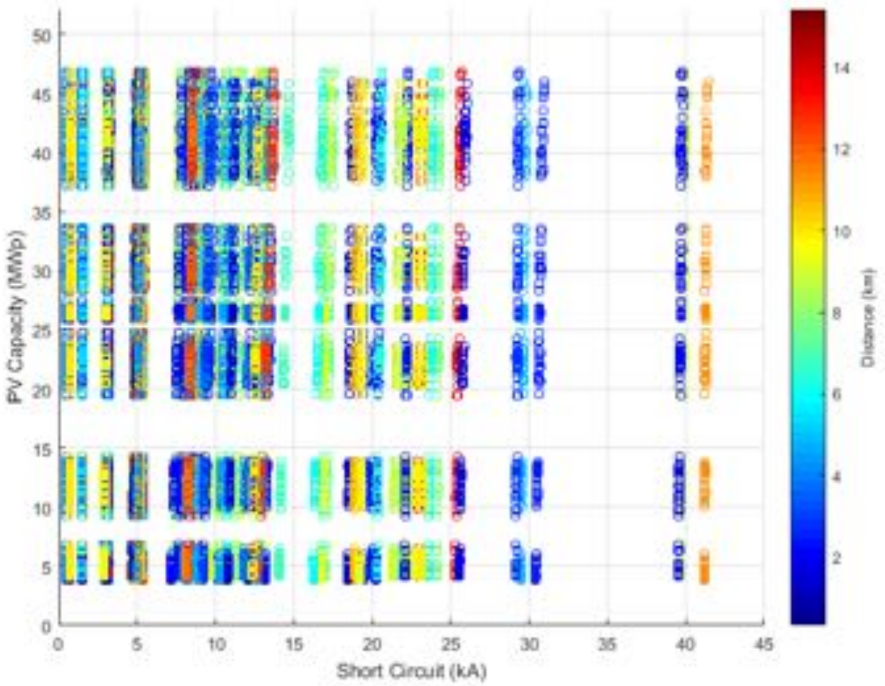


**Figure 314.** PV Capacity against Short circuit current - Unity Power Factor

### F1.3.2 Power Factor equal to 0.95

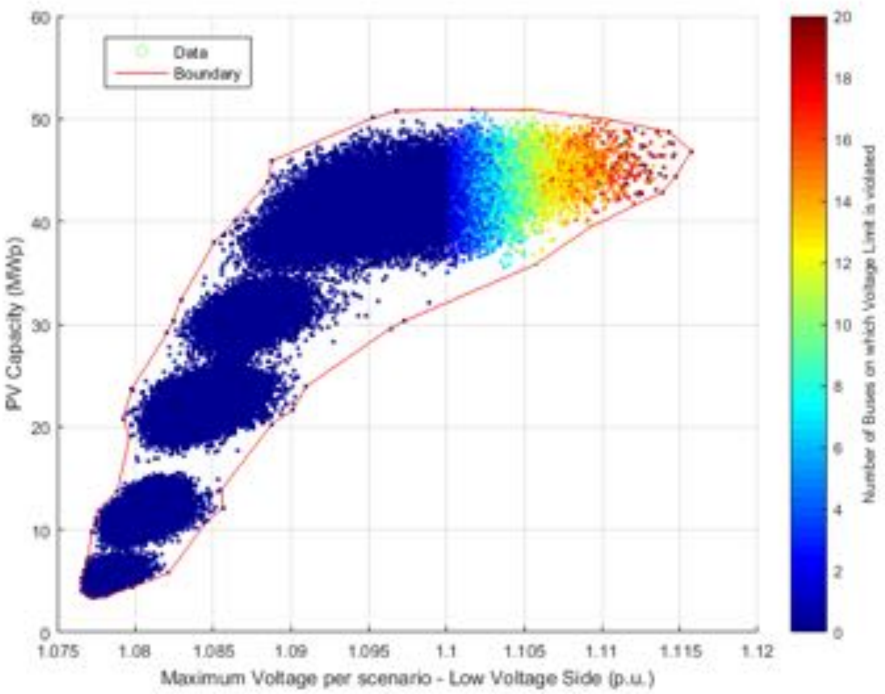


**Figure 315.** PV Capacity against Voltage – Low voltage side - Power Factor equal to 0.95.

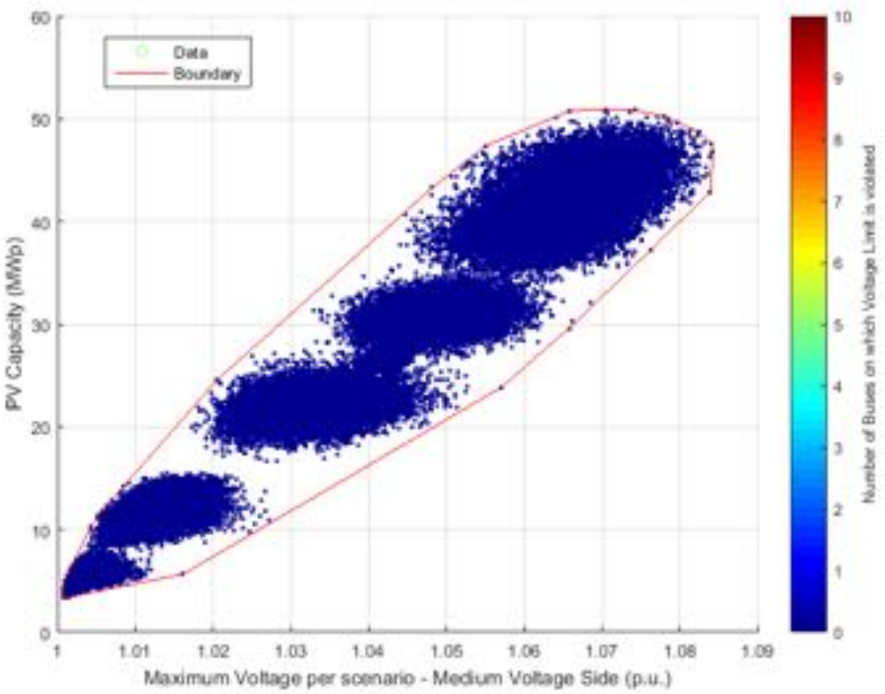


**Figure 316.** PV Capacity against Voltage – Medium voltage side - Power Factor equal to 0.95.

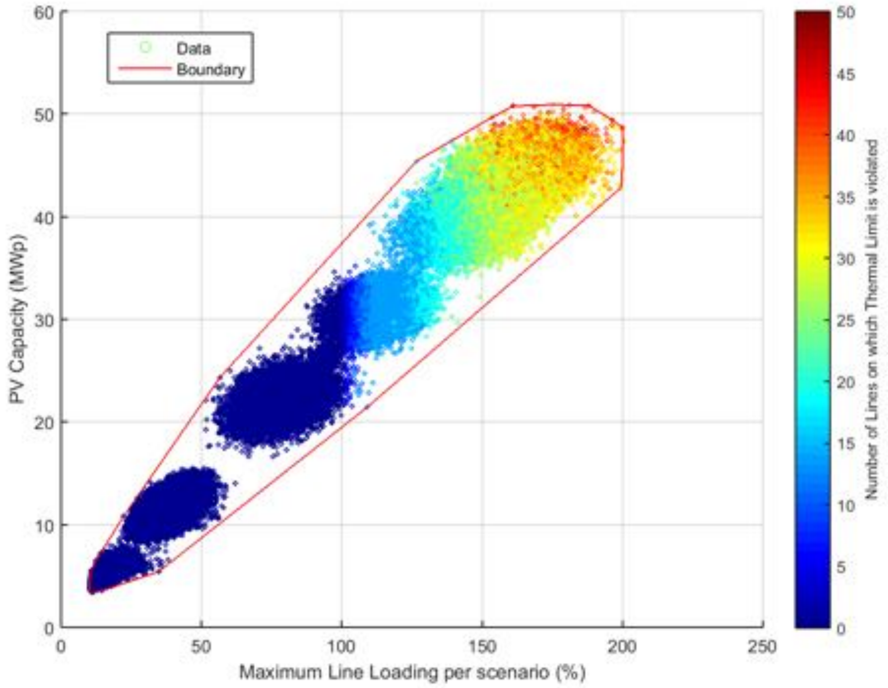


**Figure 317.** PV Capacity against Line Loading - Power Factor equal to 0.95.

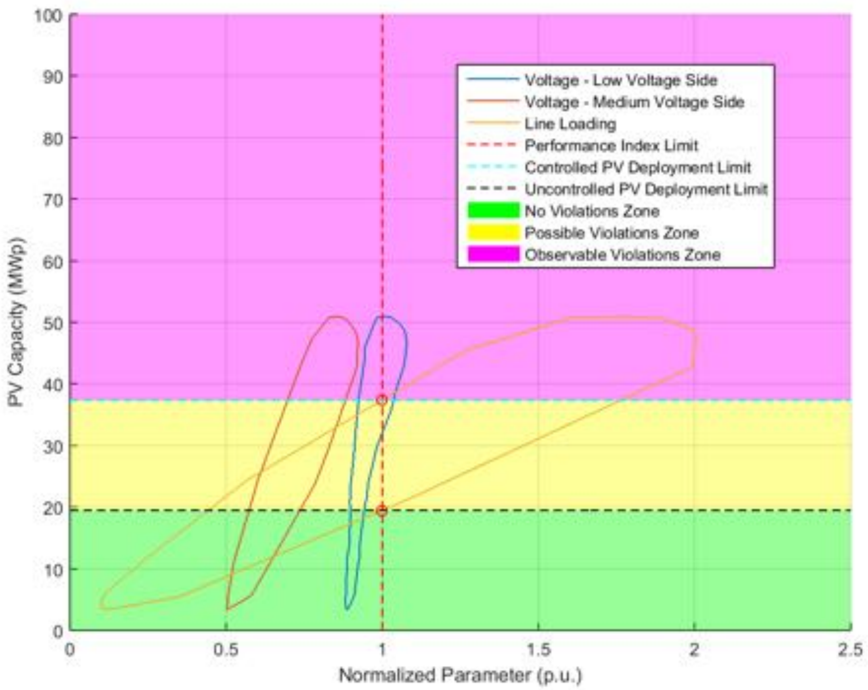


**Figure 318.** Normalized performance index parameters - Power Factor equal to 0.95.

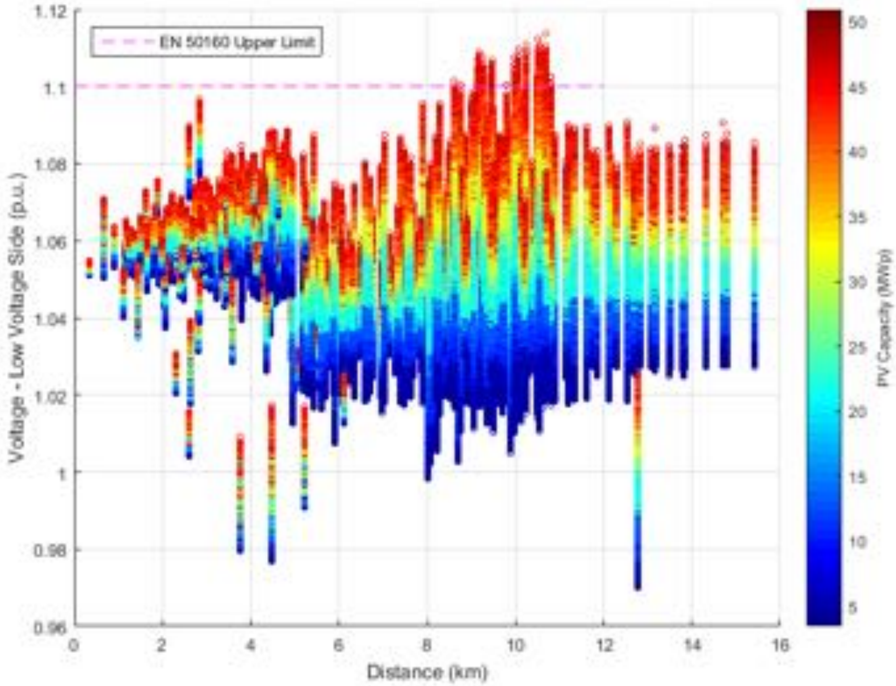


**Figure 319.** Voltage at low voltage side against Distance from transmission substation - Power Factor equal to 0.95.

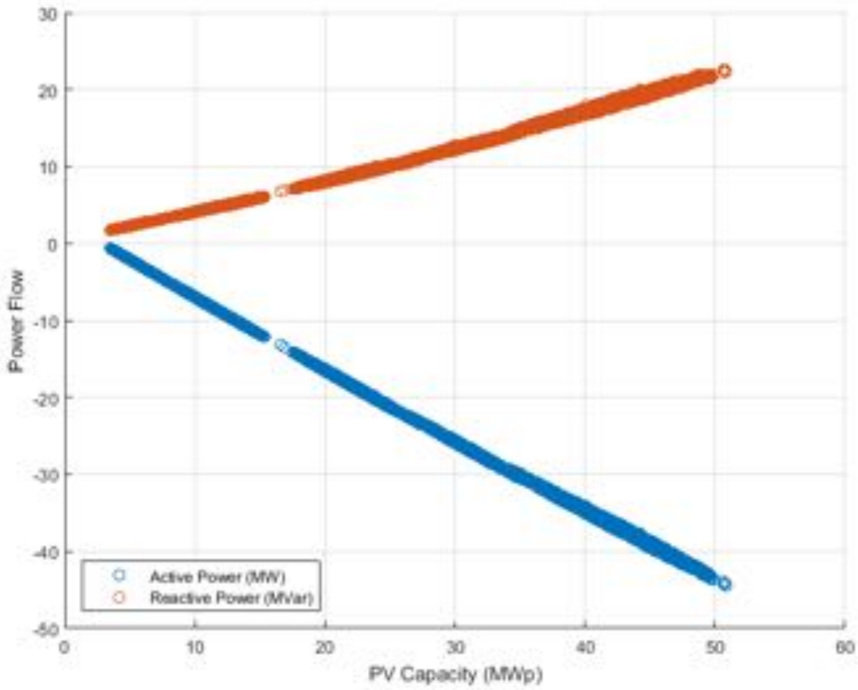


**Figure 320.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor equal to 0.95.

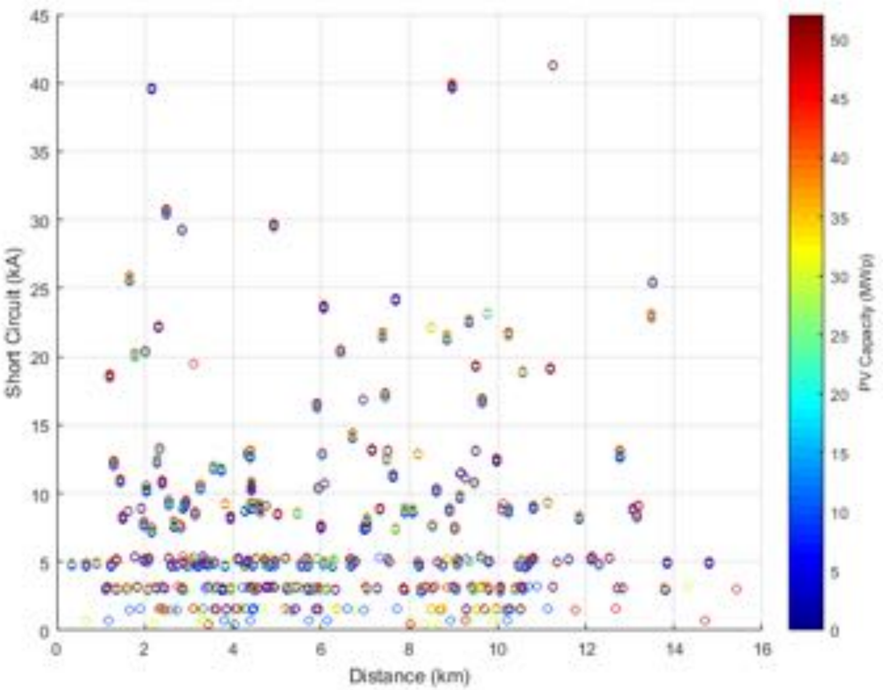


**Figure 321.** Short circuit current against Distance - Power Factor equal to 0.95.

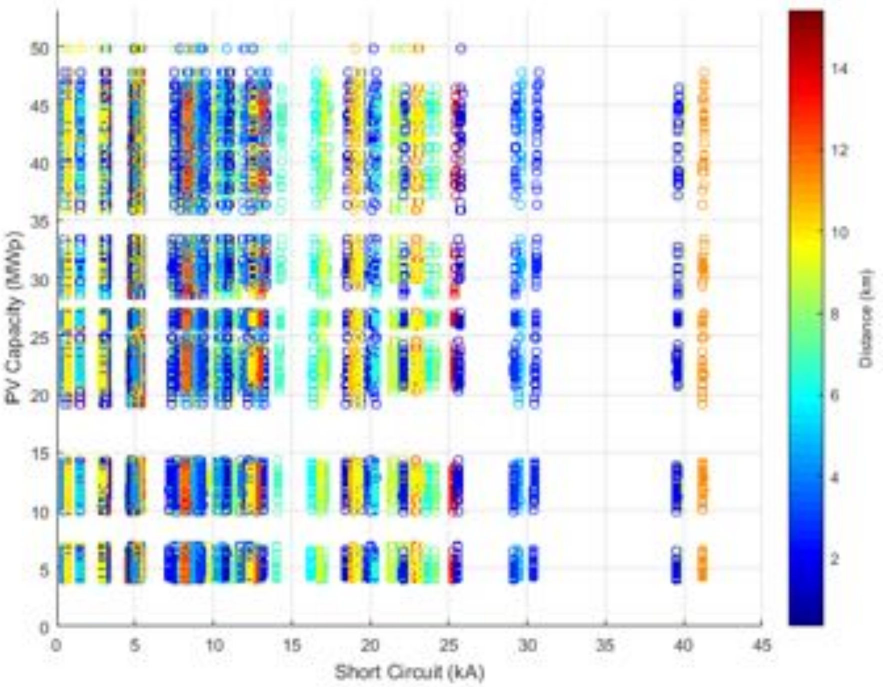


**Figure 322.** PV Capacity against Short Circuit current - Power Factor equal to 0.95.

### F1.3.3 Power Factor cosφ(P)

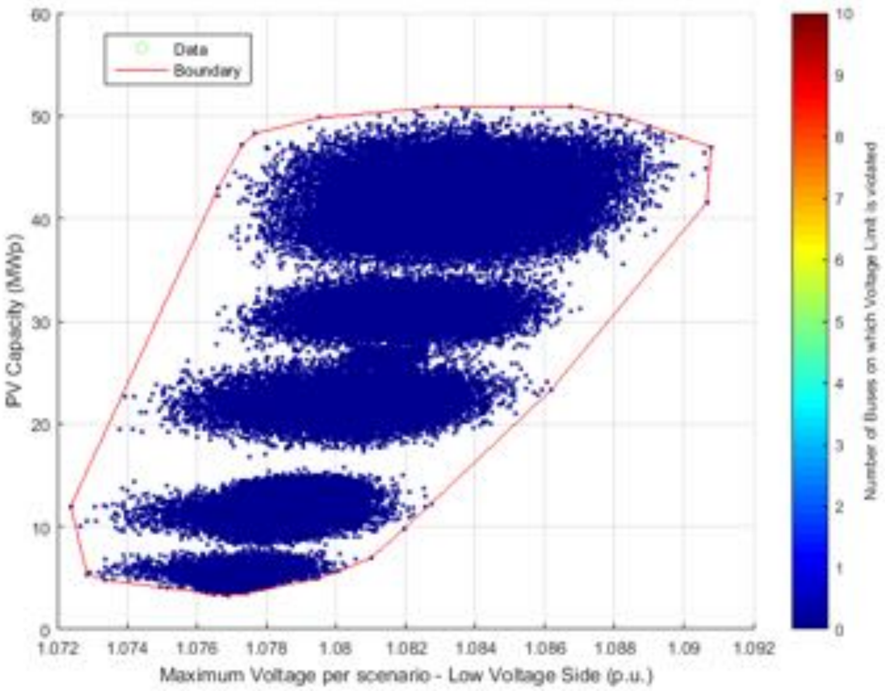


**Figure 323.** PV Capacity against Voltage – Low voltage side - Power Factor cosφ(P).

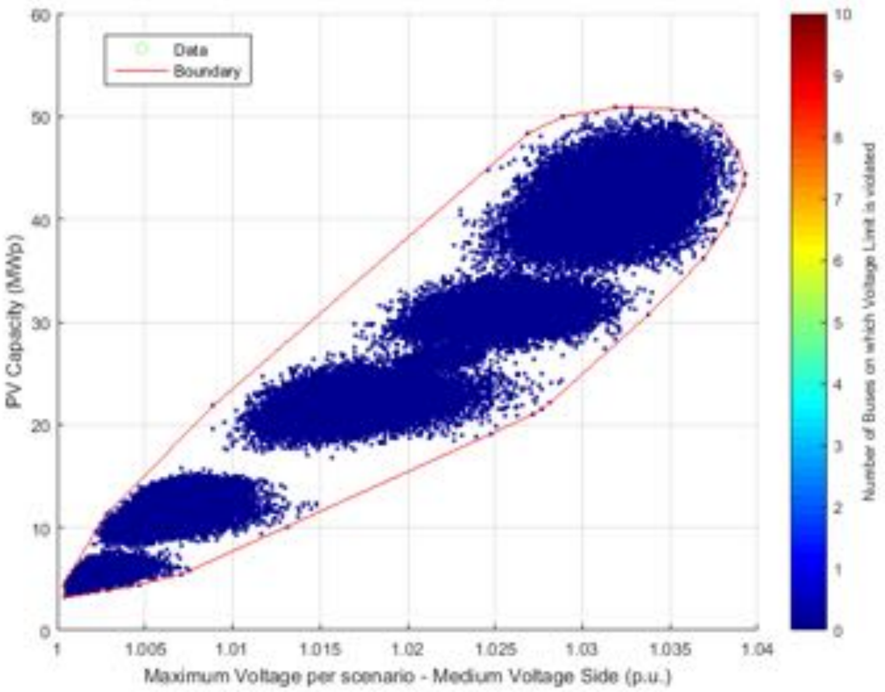


**Figure 324.** PV Capacity against Voltage – Medium voltage side - Power Factor cosφ(P).

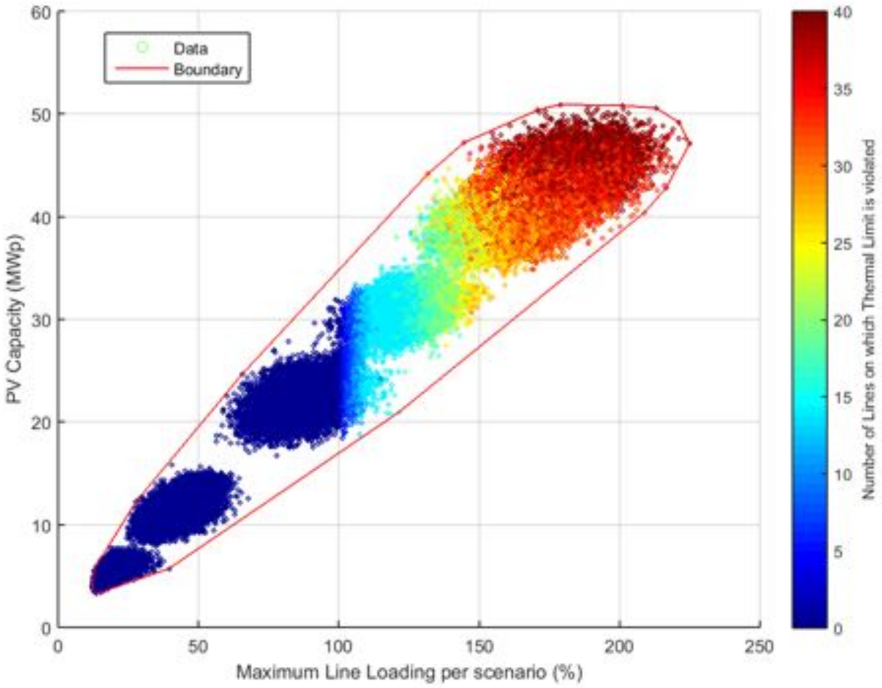


**Figure 325.** PV Capacity against Line Loading - Power Factor cosφ(P).

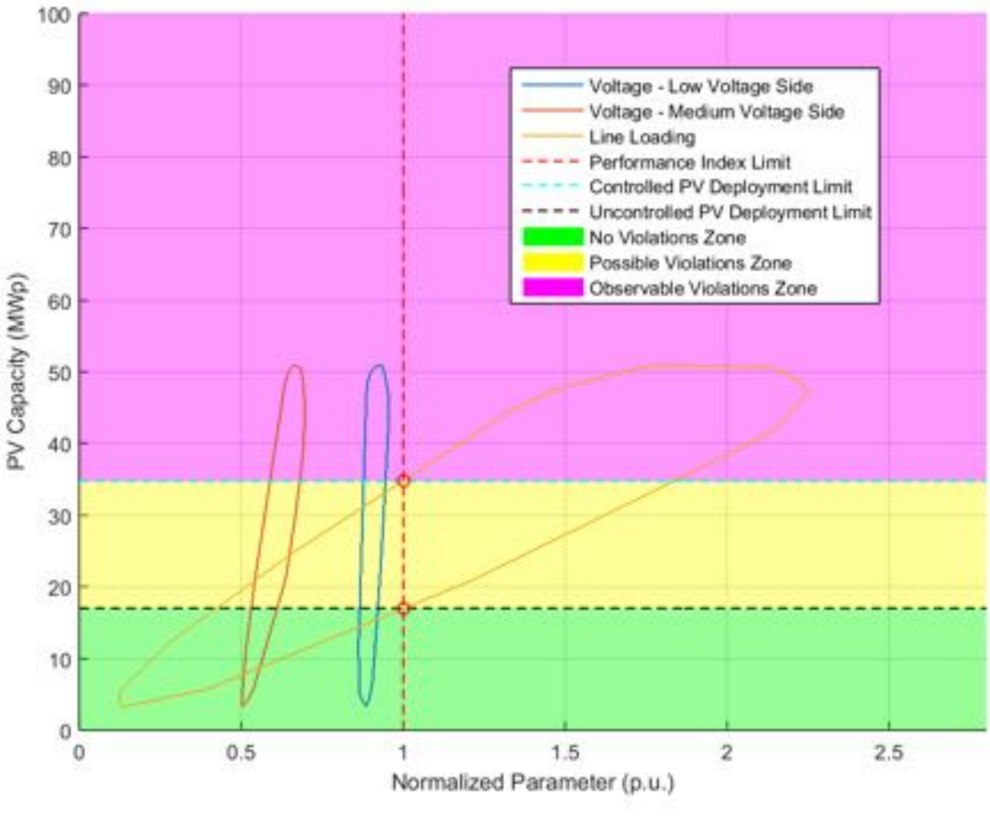


**Figure 326.** Normalized performance index parameters - Power Factor cosφ(P).

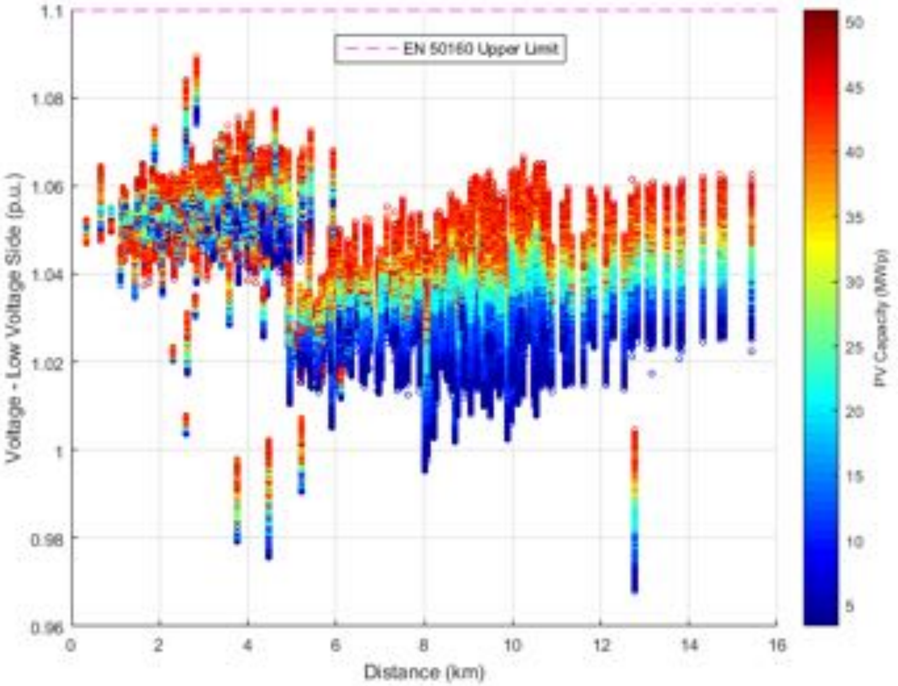


**Figure 327.** Voltage at low voltage side against distance from transmission substation - Power Factor cosφ(P).

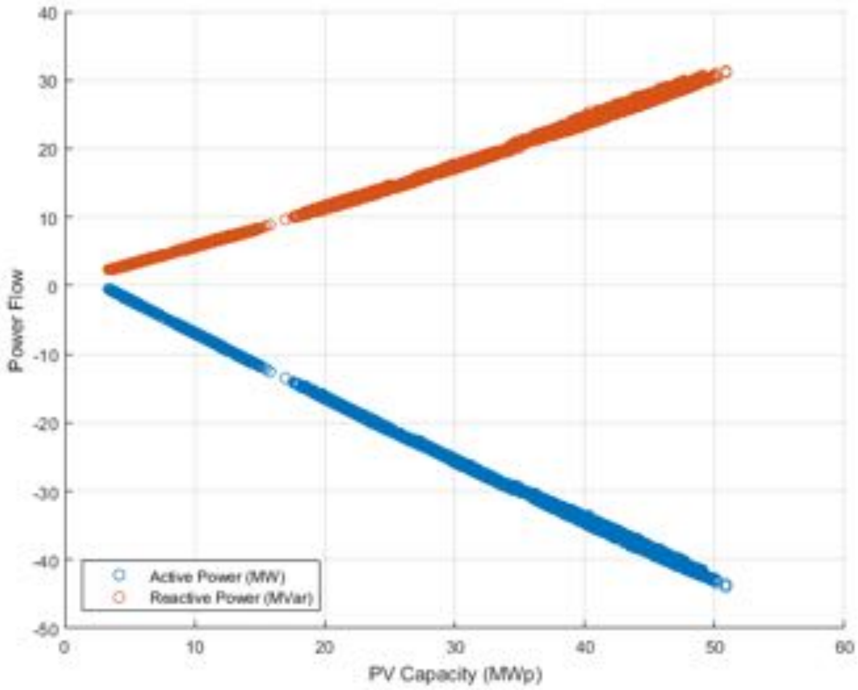


**Figure 328.** Power flow at PCC (connection of the reference substation with HV network) vs PV Capacity - Power Factor cosφ(P).

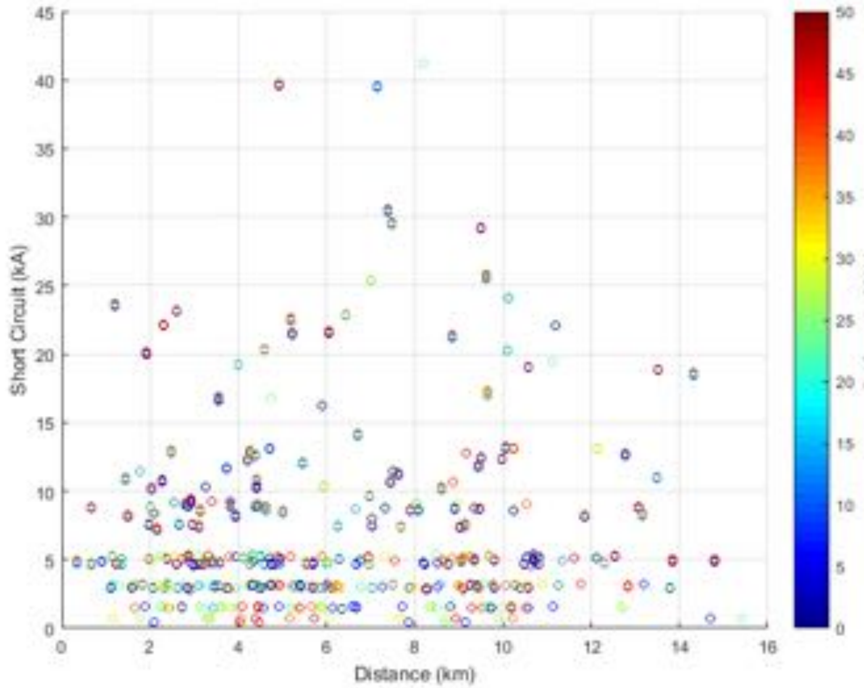


**Figure 329.** Short circuit current against distance - Power Factor cosφ(P).

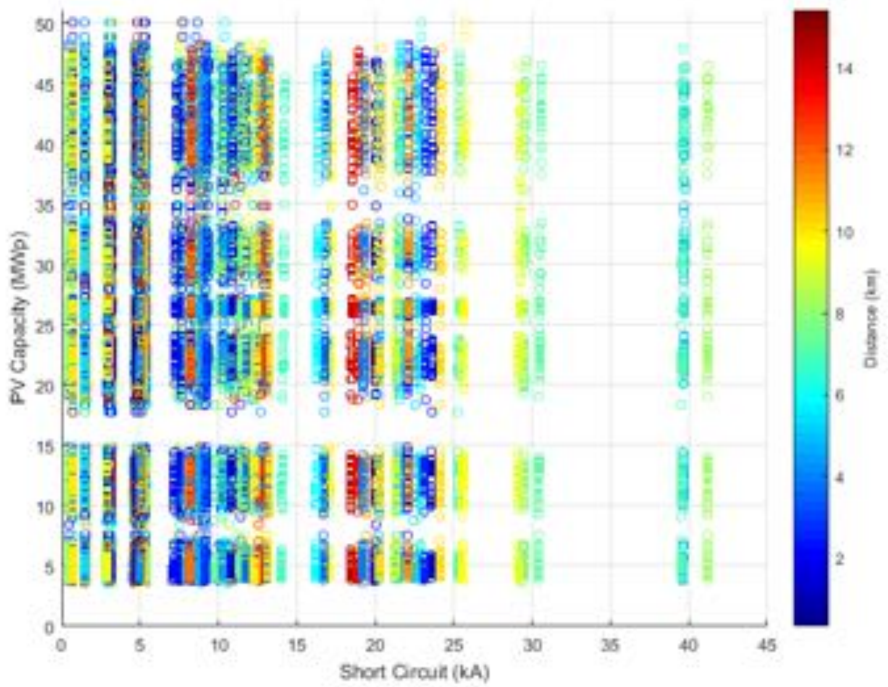


**Figure 330.** PV Capacity against short circuit current - Power Factor cosφ(P).

## F1.3.4 Summary – Monte Carlo Simulation

**Table 46.** Categorization of violations into zones.

| Scenario | No Violations Zone (MWp) | Possible Violations Zone (MWp) | Observable Violations Zone (MWp) |
|---|---|---|---|
| **Unity Power Factor** | below 9.59 | 9.59 – 28.87 | above 28.87 |
| **Power Factor equal to 0.95** | below 19.48 | 19.48 – 37.40 | above 37.40 |
| **Power Factor cosφ(P)** | below 16.97 | 16.97 – 34.80 | above 34.80 |

**Table 47.** Uncontrolled/Controlled PV Deployment Limit.

| Scenario | Low Voltage | | Medium Voltage | | Line Loading | |
|---|---|---|---|---|---|---|
| | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) | Uncontrolled Deployment Limit (MWp) | Controlled Deployment Limit (MWp) |
| **Unity Power Factor** | 9.59 | 28.87 | 22.70 | 46.22 | 22.47 | 42.60 |
| **Power Factor equal to 0.95** | 32.07 | 50.86 | above 50.91 | above 50.91 | 19.48 | 37.40 |
| **Power Factor cosφ(P)** | above 50.92 | above 50.92 | above 50.92 | above 50.92 | 16.97 | 34.80 |

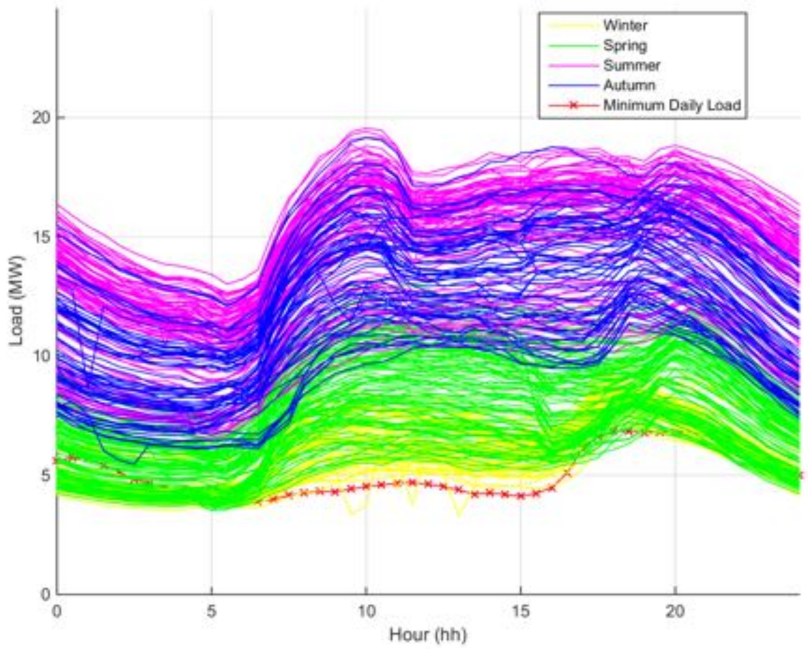


**Figure 331.** Sotera S/S - Minimum daily load.

# Appendix G

Appendix Ga: Consumption_per_postal_code_2014.xlsx
Appendix Gb: Substation_Share_Per_Postcode.xlsx.