A Design Alternative to Improve the Interconnection Capability of New Distributed-Generation Installations into Existing Griddle

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Abstract: Most distributed-generation facilities are performed on pre-built distribution grids. The design conditions of these existing grids may limit the ability of new users to get a connection due to technical and/or cost constraints. This work proposes a simple solution, adjusted to the relevant regulations and embodied in a radial distribution grid of Spanish low voltage, to improve the interconnection of distributed generation, usually grid connected photovoltaic systems. The proposed solution, based on increasing the section of the neutral line, achieves a capacity of increasing the length of the supply grid by more than 20%.

Keywords: distribution grids; distributed generation; low voltage feeders; grid-connected; installation efficiency; sustainable cities

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1. Introduction

According to previous studies [1,2], the production of renewable energy sources (RES) in Europe, and more specifically in Spain [3], will increase their portion of the total energy consumption from 10.5% in 2008 to 22.7% in 2020. Because of this, it has been emphasized that if Europe wants to achieve its target to keep the global mean temperature increment below 2 °C, it has to strive for a 100% renewable electricity system by 2050 [4].

It has been stated that the option of expanding solar as well as wind energy is viable in Spain [5–7], as the former could rise 30% and the latter 15% with reasonable costs between 2020 and 2030. The cost of wind energy could be 7 c€·kWh^{-1} with an investment cost between 860 and 920 €·kW^{-1}, while the cost of photovoltaic solar energy would be around 12.9 c€·kWh^{-1} with an investment cost of 0.15 €·W^{-1}.

The present work examines photovoltaic grid-connected systems (PVGCSs), though it can be applied to other distributed generation (DG) technologies. The increase in the distributed-generation capacity means economic profits well as technical benefits [8–10]. In the case of overloaded grids, the proper inclusion of distributed generation would improve the load of the grid and limit the possibility of supply collapses [11–13]. The optimal location and size may serve multiple objectives such as reducing grid losses, updating the net value of production, and the knowledge of the distance to the point of collapse [14–19].

In Spain, PVGCSs have greatly expanded since the year 2004, owing to such regulations as the Royal Decree (RD) 436/2004 [20] and RD 661/2007 [21], though at present there is a lag in the number of new connections [22]. Nevertheless, the rise in electric costs as well as the fall in the price of the peak watt in photovoltaic panels will make photovoltaic installations cost effective by 2016 [23]. In addition, projects such as "Smart City", implemented in Malaga (Spain) are focused on the integration of renewable resources in low- and medium-voltage (LV and MV) distribution grids [24].
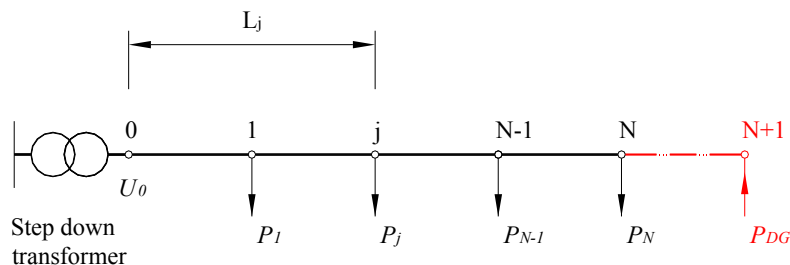
Most PVGCSs are connected to an existing distribution grid. In most cases, to connect a new installation it is required to reinforcement the existing grid or build a new one. In the present work, we propose a solution for increasing the maximum length of existing radial low-voltage feeders in order to encourage the inclusion of new users or DG installations.

The work is structured as follows: Section 2 poses the problem with its previous hypotheses and describes the method of normalized calculation as well as the solution proposed. Sections 3 and 4 present the results and their discussion, respectively, while Section 5 offers the conclusions.

2. Problem Statement

Papaioannou and Purvins [25] consider the DG generators as negative loads in radial LV feeders. In the present work, the study case is similar, but the intent is to increase the length of the distribution grid and therefore improve the connection capacity of the DG. As reflected in Figure 1, we considered a radial grid with any configuration of connected loads, nodes 1 to N, keeping the node 0 for the feed through a step-down transformer. The problem consists of including a new node $N + 1$ where connecting distributed generation and/or new users, implying a lengthening of the distribution grid of LV, according to Equation (1) and Figure 1.

$$\Delta L = L_{N+1} - L_N \tag{1}$$

Figure 1. Radial low-tension distribution grid with increased length to include distributed generation (DG).

2.1. Hypotheses

The hypotheses of operation are established as follows:

- Distribution grid with only one load, *i.e.*, N equal to 1 according to Figure 1, for the simplicity of the grid.
- The level of the previous load implies the maximum intensity reached by the overloads in the line.
- The coefficients for voltage drops, C_t, and resistance increase by temperature in the case of a short circuit, C_R, are fitted to the recommendations of the electric-grid designers [26], commonly 0.8 and 1.5, respectively.
- The maximum length of the grid is limited by the lower intensity of the short circuit, *i.e.*, the maximum length according to the condition of the voltage drop is larger than the maximum length according to the condition of the short circuit.
- The calculations are applied to distribution grids in balanced low voltage and it is considered to be a single-phase equivalent circuit [27].

- For the numerical analysis, a LV underground feeder is used according to the normative RD 842/2002 [28] and specific rules of the distribution company [29] (Figure 2).
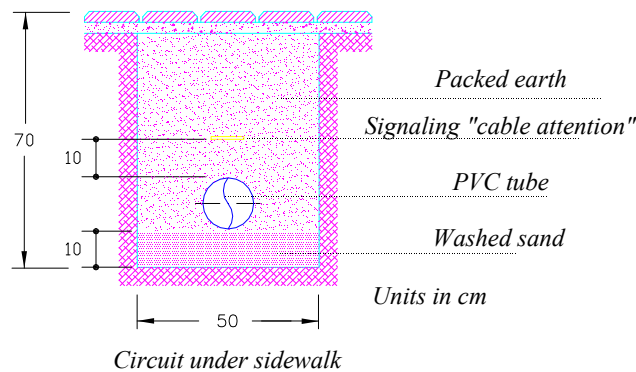

Figure 2. Example of underground distribution grid.

2.2. Normalized Calculation Method

Next, the design procedure for low-voltage distribution grids is described. International design guides were consulted [30], as well as Spanish ones [26]. For the following calculations, the single-phase equivalent circuit of the distribution grid was used (Figure 3). The design procedure is standardized according to the International Electro-technical Committee (IEC) under Spanish regulations according to the normative [28].
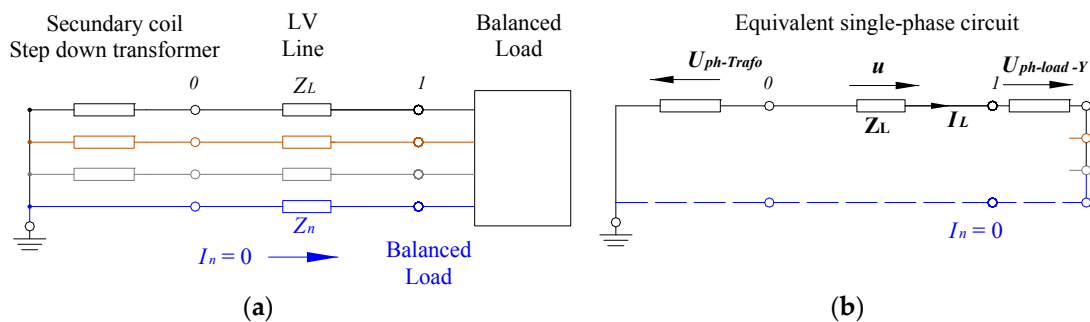

Figure 3. (**a**) Secondary equivalent circuit and the low-voltage (LV) distribution grid; (**b**) single-phase equivalent.

2.2.1. Calculation for Voltage Drop

The maximum voltage drop, *e*, recommended for a distribution grid at LV is established at 5% [22], calculated according to Equation (2):

$$
\begin{aligned}
e &= e\,(\%) \cdot \frac{U_L}{100} \\
e &\geqslant u_L = \frac{P_C}{U_L}\left(R_L + X_L \cdot \tan\varphi\right)
\end{aligned}
\tag{2}
$$

The length limitation established by the condition of the voltage drop, L_{Max-vd}, is determined in Equation (3):

$$
\begin{aligned}
L_{Max-vd} &\leqslant \frac{U_L \cdot e}{P_C \cdot (R_u + X_u \cdot \tan\varphi)} \\
R_u &= \frac{1}{K \cdot S}
\end{aligned}
\tag{3}
$$

where the conductivity, *K*, is determined according to Table 1, since it is a function of temperature of the maximum permanent regime and a function of insulation (Table 2).

Table 1. Conductivity, *K*, as a function of temperature of the permanent regime of the insulation.

Conductor	K_{PVC} ($\Omega^{-1} \cdot$ m $\cdot$ mm^{-2}) at 70 $^\circ$C	K_{XLPE} ($\Omega^{-1} \cdot$ m $\cdot$ mm^{-2}) at 90 $^\circ$C
Copper (Cu)	48	44
Aluminum (Al)	30	28

Table 2. Temperature of the permanent regime according to the type of insulation.

Insulation	T_{rp} ($^\circ$C)
PVC	70
XLPE	90
EPR	90

Notes: PVC stands for polyvinylchloride, XLPE for reticulated polyethylene and EPR for ethylenepropylene.

2.2.2. Over Current, Calculation of Protections and Overloads

Any circuit to be protected from the effects of over currents must comply with the IEC 60364-4-43:2008/Corr.:2008 [31]. These over currents may be originated due to: (i) overloads and (ii) short circuits.

According to the mentioned IEC 60364-4-43:2008/Corr.:2008, to guard against overloads in electrical installations, protection should be coordinated with the channeling of the circuit to be protected. To achieve this, the following conditions must be met:

$$I_B \leqslant I_N \leqslant I_Z \text{ and } I_2 \leqslant 1.45 \cdot I_z \tag{4}$$

where I_B is the intensity of the line, calculated as:

$$I_B = \frac{P_C}{\sqrt{3} \cdot U_L \cdot \cos\varphi} \tag{5}$$

and I_N is the nominal intensity of the protection device. The maximum admissible intensity of the channeling, I_Z, is that by which the conductor and therefore the insulation reaches the permanent regime temperature referred to in Table 2 [32].

If the environmental temperature or the installation conditions of the line are now different from that mentioned in the regulations, correction factors must be applied:

$$I_Z = I_{tb} \cdot Fct \cdot Fci \tag{6}$$

In Equation (4), I_2 is the effective functioning intensity of the protection device. The distribution grids are protected with fuses and, therefore, the effective functioning consists of its fusion, where its value is determined by Equation (7) [33].

$$I_2 = 1.6 \cdot I_N; \; to : \; I_N \geqslant 16 \text{ A} \tag{7}$$

2.2.3. Over Current, Calculation of Protections and Short Circuits

A short circuit is a clear defect, null-defect impedance, which causes high intensities with respect to the intensity of the permanent regime of the line, triggering spikes of dangerous temperatures for the installation. If the design of the installation is correct, a short circuit takes the wire to its maximum short-circuit temperature (Table 3) in 5 s.

Table 3. Short-circuit temperature for each type of insulation.

Insulation	T_{cc} (°C)
PVC	160
XLPE	250
EPR	250

To protect an installation from short circuits, the following three conditions must be fulfilled [26]:

1) $I_{cu} \geqslant I_{PSC-Max}$: The cut-off power, I_{cu}, of the protective element should be at least equal to the short-circuit current at the beginning of the conductor where it is installed, $I_{PSC-Max}$. Most fault currents will be symmetrical three-phase short circuits at the beginning of the installation; it is a function of the characteristics of the transformer at the beginning of the installation.

$$I_{PSC-Max} = \frac{U_{ph}}{Z_L} \tag{8}$$

2) $I_{PSC-min} \geqslant I_{F5}$: The minimum permanent short-circuit intensity, $I_{PSC-min}$, occurs at the end of the line in a phase-neutral fault, and must be greater than the fusion intensity for 5 s for the protection fuse, I_{F5} [33]. Physically, this means that it is within the time limits established for a short circuit (<5 s) and the energy-conservation equations in the adiabatic regime will be valid. The lower short-circuit current will be the one given for the fault in the phase-neutral loop:

$$I_{PSC-min} = \frac{C_t \cdot U_{ph}}{Z_{Loop}} \tag{9}$$

where

$$Z_{Loop} = 2 \cdot Z_L = 2 \cdot \sqrt{\left(\frac{C_R \cdot L}{K \cdot S} \right)^2 + (X_u \cdot L)^2} \tag{10}$$

The length limit, $L_{Max\_I_{F5}}$, for an installation by the above condition is given by Equation (11):

$$L_{Max\_I_{F5}} \leqslant \frac{C_t \cdot U_{ph}}{2 \cdot I_{F5} \cdot \sqrt{\left(\frac{C_R}{K \cdot S} \right)^2 + (X_u)^2}} \tag{11}$$

3) $(K \cdot S)^2 \geqslant I_t^2 \cdot t$ The thermal force admissible in the conductor, $(K \cdot S)^2$, must be greater than the energy that the protection device allows to pass through $I_t^2 \cdot t$; where K is a constant derived from the regulations [32] (Table 4).

Table 4. Value of the short-circuit constant *K*.

Insulation	Copper (Cu)	Aluminum (Al)
PVC	115	74
XLPE	135	87
EPR	135	87

2.3. Proposed Variation to the Calculation Method

As a hypotheses, the line length is equal to the maximum length given by the condition of the short circuit, Equation (11), and smaller than the maximum length admissible from the voltage drop condition (Equation (3)). The aim is to increase the capacity of the installation in terms of the short circuits limits, thus improving the maximum length of the installation and therefore the capacity of the

distribution line to connect new users and/or GD. The solution proposed in the present work is to increase the neutral section in the final segment of the distribution grid (Figure 4). Specifically, in the case presented, the neutral conductor will be doubled, thereby duplicating the initial section.
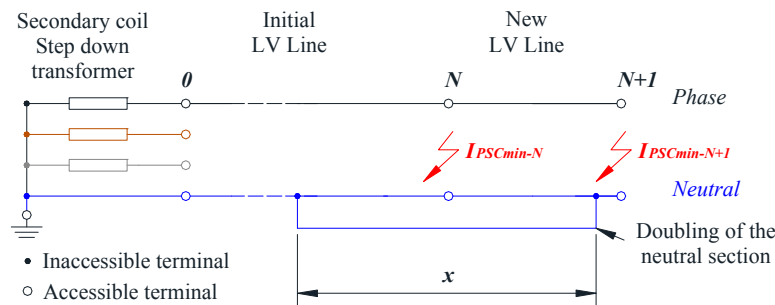

Figure 4. Radial distribution grid of modified LV.

Figure 4 shows that the distribution grid now includes N + 1 nodes and has increased its length, as L_{N+1} is greater than L_N. The impedance of any phase-neutral fault loop and thus the intensity of the corresponding short circuit depends on the length, x, which requires that the neutral conductor doubles. As established in the hypotheses, if the minimum short circuit at node N takes the minimum value (I_{F5}) then, any lengthening desired of node N + 1 will be require a lengthening of the doubled neutral conductor, as reflected in Equation (12).

$$R_{ph} + R_n = \frac{C_R \cdot L_{N+1}}{K \cdot S} + \left[\frac{C_R \cdot (L_{N+1}-x)}{K \cdot S} + \frac{C_R \cdot x}{K \cdot 2 \cdot S} \right] \xrightarrow{Operand} R_{ph} + R_n = 2 \cdot C_R \cdot R_u \cdot \left(L_{N+1} - \tfrac{x}{4} \right)$$

$$X_{ph} + X_n = X_u \cdot L_{N+1} + \left[X_u \cdot (L_{N+1} - x) + X_u \cdot \tfrac{x}{2} \right] \xrightarrow{Operand} X_{ph} + X_n = 2 \cdot X_u \cdot \left(L_{N+1} - \tfrac{x}{4} \right) \tag{12}$$

$$Z_{Loop}(x) = 2 \cdot \left(L_{N+1} - \tfrac{x}{4} \right) \cdot \sqrt{(C_R \cdot R_u)^2 + (X_u)^2} \Rightarrow I_{PSCmin}(x) = \frac{C_t \cdot U_{ph}}{Z_{Loop}(x)} \geq I_{F5}$$

The minimum length of the neutral line doubling, x_{min}, must be such that on lengthening the line from L_N to L_{N+1}, the fault in any modified phase-neutral loop is greater than or equal to the initial fault without modification; where, according to the hypotheses, takes the value of I_{F5}.

$$I_{PSCmin}(x_{min}) \geq I_{F5} \rightarrow Z_{Loop}(x_{min}) \leq Z_{Loop}(0)$$

$$2 \cdot \left(L_{N+1} - \tfrac{x}{4} \right) \cdot \sqrt{(C_R \cdot R_u)^2 + (X_u)^2} \leq 2 \cdot L_N \cdot \sqrt{(C_R \cdot R_u)^2 + (X_u)^2} \tag{13}$$

$$x_{min} \geq 4 \cdot (L_{N+1} - L_N)$$

On the other hand, the maximum length of the neutral doubling, x_{Max}, must be less than L_{N+1}, and the fault of any phase-neutral loop is lower than or equal to I_{F5} (Equation (14)).

$$x_{Max} \leq L_{N+1}$$

$$I_{PSCmin}(x_{Max}) \geq I_{F5} \rightarrow Z_{Loop}(x_{Max}) \leq Z_{Loop}(0) \tag{14}$$

$$2 \cdot \left(L_{N+1} - \tfrac{x_{Max}}{4} \right) \cdot \sqrt{(C_R \cdot R_u)^2 + (X_u)^2} \leq 2 \cdot L_N \cdot \sqrt{(C_R \cdot R_u)^2 + (X_u)^2}$$

Finally, the maximum value that the line can increase from L_N to L_{N+1} is determined by operating in the inequality of Equation (14), giving:

$$L_{N+1} \leq \frac{4}{3} \cdot L_N \tag{15}$$

3. Results

Normalized calculation was applied as was the variation proposed for an underground LV distribution grid installed in conduit, according to the regulation [28] (Figure 2). The conductors used are made of aluminum, with insulation strength of 0.6/1 kV, and XLPE insulation; the sections used in this case study are 150 mm^2 and 240 mm^2, according to the particular norms of the distribution company [29].

3.1. Length Line Calculation by the Normalized Method

The study begins by calculating for overloads and it is considered that the line will be the maximum of its capacity for overloads, then, the minimum length line is calculated from the conditions of the voltage drop and short circuit.

3.1.1. Overloads

For the calculation of the maximum admissible intensity and of the corresponding correction factors, the Complementary Technical Instruction ITC-BT-07 of the regulation of low voltage RD 842/2002 is used [28]. According to Equation (6), the diameter of the fuse fit the normative IEC 60269-1:2006 [33]. The fuses must meet the conditions of Equation (4). For each line section, the largest fuse that fulfilled these conditions is selected (Table 5). Thus, it fulfills the hypotheses of Section 2 and the load can reach the maximum intensity to overloads in the line.

Table 5. Overload conditions. Results of Equation (4).

Section (mm^2)	I_{tb} (A)	Fc	Iz (A)	I_N (A)	I_2 (A)	$1.45I_Z$ (A)
150	230	1	230	200	320	333.5
240	305	1	305	250	400	442.25

3.1.2. Voltage Drop Condition

According to Table 5, the line is limited by the capacity of effective functioning of the fuse. Thus, the nominal power admitted by the line is adjusted to the nominal intensity of the fuse for each section. The nominal power for each case (Equation (16)) and the maximum length from voltage drop condition (Equation (3)) are shown in Table 6.

$$P_C = \sqrt{3} \cdot U_L \cdot I_N \cdot \cos\varphi \tag{16}$$

Table 6. Voltage drop. Results of Equation (3).

Section (mm^2)	K_{AL} (90 $^\circ$C)	U_L (V)	e (V)	P_C (W)	tg'	X_u ($\Omega \cdot$ m^{-1})	L_{Max-vd} (m)
150	28	400	22	1.10×10^5	0.75	1.0×10^{-4}	255
240	28	400	22	1.38×10^5	0.75	1.0×10^{-4}	284

3.1.3. Short-Circuit Protection

1) $I_{cu} \geqslant I_{PSC-Max}$: The maximum intensity of short circuit, symmetrical three-phase fault, is given at the beginning of the distribution grid and it depends on the power of the distribution transformer. Here, has been considered a transformer of 630 kVA, where a fault will take an intensity of value (Equation (17)):

$$I_{PSC-Max} = \frac{U_L}{\sqrt{3} \cdot Z_{CC}} \xrightarrow{S=630 \text{ kVA}} I_{PSC-Max} \approx 24 \text{ kA} \tag{17}$$

$$I_{Pcu} \geqslant 24 \text{ kA}$$

2) $I_{PSC-min} \geqslant I_{F5}$: As can be seen in Table 7, this condition limits the maximum length of the distribution line (Equation (11)), as this is less than the maximum length per voltage drop (Equation (3)).

3) $(K \cdot S)^2 \geqslant I_t^2 \cdot t$ This condition of the short circuit is fulfilled. Further details are not given, since the length of the distribution line is not affected by this condition.

Table 7. Short-circuit conditions. Results of Equation (11).

Section (mm²)	U_L (V)	C_t	C_R	I_N(A)	I_{F5} (A)	X_u ($\Omega \cdot m^{-1}$)	$L_{Max-IF5}$ (m)
150	400	0.8	1.2	200	1250	$1.0 \cdot 10^{-4}$	243
240	400	0.8	1.2	250	1650	$1.0 \cdot 10^{-4}$	272

3.2. Line Length Calculation with the Variation Proposed for the Grid Design

As reflected in Table 7, the condition of minimum short circuit limits the maximum length of the distribution line under the hypotheses of Section 2 and according to Equation (11). With the doubling of the neutral section (Equation (12)), the length of the exploitaion of the distribution line can lengthen up to what is established in Equation (15) (Table 8). This alternative design implies an increase in the line length more than 20%.

Table 8. Admissible line length with the doubling of the neutral conductor section. Results of Equation (12).

Section (mm²)	$L_{Max-IF5}$ (m)	Line Length Increment (%)
150	323	27% $\leqslant$ 33% (Equation (15))
240	329	21% $\leqslant$ 33% (Equation (15))

4. Discussion

The solution proposed would be applied to any installation where the maximum length reached by a voltage drop is greater than the maximum length reached by the least short circuit of the grid. Although, for greater simplicity, the calculation example was developed for a radial distribution grid with a single load, that is, with regard to Figure 1, it corresponds to the case in which N is equal to 1; and where the load implies the 100% of the thermal load capacity of the line.

From this standpoint, the length of the short circuit is increased, with margins sufficient to undertake the implementation of new users and/or DG in the line. This configuration does not use a new output of the step-down transformer; this is considered an advantage by being their limited number.

The fact of considering the same section for the neutral conductor as for the phases is to improve the logistics and installation of the distribution grid, as only one section was used for all the poles of the three-phase grid.

5. Conclusions

This paper proposes a simple solution, adjusted to the relevant regulations and embodied in a radial distribution grid of Spanish low voltage, to improve the interconnection of distributed generation, usually grid connected photovoltaic systems.

The solution proposed, *i.e.*, the partial doubling of the neutral section, can increase the length of the use of a low voltage distribution generation by up to 20%. This would improve the connection capacity of distribution grid installations as well as photovoltaic grid-connected systems, since in most cases these installations are installed over previously constructed distribution grids.

Abbreviations

C_R	Coefficient of resistance
C_t	Coefficient of voltages
e	Voltage drop, in V
F_C	Correlation factor for intensity, in A
F_{ci}	Correction factor for installation
F_{ct}	Correction factor for temperature
I_B	Intensity of the circuit to protect, in A
I_{cu}	Cut-off power of the protection device, in A
I_{F5}	Fusion intensity for a fuse in 5 s, in A
I_L	Intensity of the line, in A
I_n	Neutral current, in A
I_N	Nominal intensity of the protection device, in A
I_{PSC}	Permanent intensity of the short circuit, in A
I_{tb}	Intensity consulted from normalized tables in A
I_Z	Maximum intensity of the normalized channeling, in A
K	Conductivity of the conductor, in $\Omega^{-1} \cdot mm^{-2} \cdot m$
L_j	Total length from node 0 to node j, in m
P_C	Calculated power, in W
P_N	Nominal power, in W
S	Section of a conductor, in mm^2
R_L	Resistance of a line, in Ω
R_n	Neutral resistance, in Ω
R_{ph}	Resistance of a phase, in Ω
R_u	Unit resistance, in $\Omega \cdot m^{-1}$
φ	Difference between voltage and phase intensity, in rad
$\cos\varphi$	Power factor of value 0.8 in this research
U_{ph}	Voltage between phase and neutral, in V
U_L	Line voltage, in V
X_L	Inductive impedance of the line, in Ω
X_n	Inductive impedance of the neutral, in Ω
X_{ph}	Inductive impedance of the phase, in Ω
X_u	Unit inductive impedance, in $\Omega \cdot m^{-1}$
Z_{CC}	Short-circuit impedance of the distribution transformer
Z_L	Line impedance, in Ω
Z_{LOOP}	Impedance of the phase-neutral loop, in Ω

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