Methodological Approach for Evaluating the Impact of Electric Vehicles on Power Distribution Networks

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Abstract. The future of transport will be based on electrical energy, but the transition from fossil fuels will not be easy and will lead to a fundamental change in power distribution networks. The insertion of plug-in-electric vehicles have become a promising solution to reduce CO_2 carbon dioxide emissions. However, the insertion of electric vehicles represents an unexpected increase in the electricity demand, this imposes new challenges for the distribution system operators, due to the uncertainties associated with the electric vehicles charging. This article proposes a practical methodological framework in order to assess the impact of plug-in-electric vehicles on power distribution networks. The proposal includes four levels of uncertainties: electric vehicle model, charging method, state of charge of the battery, and the connection node into the power distribution network. The proposal includes the calculation of power flows, to evaluate voltage regulation and determine the loading of power distribution lines. The results show that when electric vehicles are uncontrolled charge at the hour when the maximum demand occurs, this operating condition might affect the loading of power distribution lines causing the activation of over-current protection relays.

Keywords: Power distribution system · Electric vehicles · Voltage regulation

1 Introduction

The air pollution is the main source of environmental pollution in America. The World Health Organization (WHO) estimates that for every nine deaths in the world one is due to air pollution [1]. According to environmental experts, electric vehicles are able to reduce the burning of fossil fuels, the main source of transportation-induced air pollution. Indeed several governments have been promoting policies regarding electric vehicles in order to implement cost-effective innovations to ensure low pollution [2].

There are about 1200 million vehicles around the world producing 13% of total planet pollution [3]. In the large cities, the vehicles produce 52% of carbon

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dioxide emissions [4], this has led that most automobile companies are focused on the design and make plug-in electric vehicles (PEV) where one of its main aims is to provide to the vehicles large autonomy with short battery charge times.

The high Electric Vehicles penetration impacts the daily electricity demand and might drive to failures on the power distribution networks. There are several challenges that must be overcome in order to adapt the current power distribution networks, therefore, it is required to perform studies for evaluate the impact on the power distribution network and evaluate strategies in order to overcome the main issues regarding to the insertion of electric vehicles in the power distribution networks to establish strategies for conduct an adequate insertion.

The impacts on the power distribution networks produced by the PEVs were analyzed in [5], it is shown that the power distribution networks, might be overloaded, as well as distribution transformers, voltage droops and, power losses might be also increased.

The impact of PEVs on a low voltage power distribution network in a Budapest district in Hungary is presented in [6]. Two loading scenarios are analyzed: uncoordinated and coordinated scenarios considering three PEV penetrations levels, 20%, 40%, and 60%. The study concludes that at 60% PEV penetration level considering uncoordinated load, the power distribution transformers installed along the primary feeder are overloaded; while for the coordinated load scenario, the components of the power distribution network function normally.

The article presented in [7] analyzes the PEV penetration, proposed in the electric mobility roadmap in Singapore, to determine how the electrical network might be expanded considering the impact of electric vehicles and charging infrastructure for PEV. The research work concludes that based on the PEV penetration for the scenarios under study, until 2050, the PEV penetration considering single-phase and three-phase chargers do not represent hazard situations to the power distribution network. However, high-power DC chargers, especially those that can be used for fast PEV charging, require studies considering a more level detail.

In [8] a PEV impact study is carried out in a Seattle residential power distribution network. The study analyzes the voltage stability considering data obtained from 602 Nissan Leafs. For this research work, a PEV penetration level of about 50% was taken into consideration over 75,000 households, with different loading rates. Kernel Density Estimation (KDE) which is a no parametric density estimation technique is applied in order to estimates the battery charge level of each PEV.

In this research work, a novel methodology is presented for the PEVs impact assessment on power distribution networks considering different uncertainties levels. The uncertainties levels that are considered correspond to the randomness where the PEVs can be connected to the network, the type of PEV load (controlled or uncontrolled), vehicle model, and the battery state of charge (SOC). If the PEV battery charges occur during the peak demand, it is defined as uncontrolled load, otherwise, it is defined as a controlled load. Two types of electric vehicles models are considered in this study, with different autonomy levels, a different type of battery, and different charging time. Moreover, the model includes the SOC of the battery, e.g. at least 20% of SOC in order to preserve the battery State of Health (SOH) avoiding an accelerated level of battery degradation occurs. The methodology is implemented using MATLAB software and the MATPOWER toolbox. The paper is organized as follows, Sect. 2 describes in detail the proposed methodology, Sect. 3 presents the case study where the proposed methodology is applied and validated, Sect. 4 presents the results obtained, finally, in Sect. 5 the main conclusions of this research work are presented.

2 Methodology

The proposed methodology for the PEVs penetration analysis in a power distribution network is shown in Fig. 1.

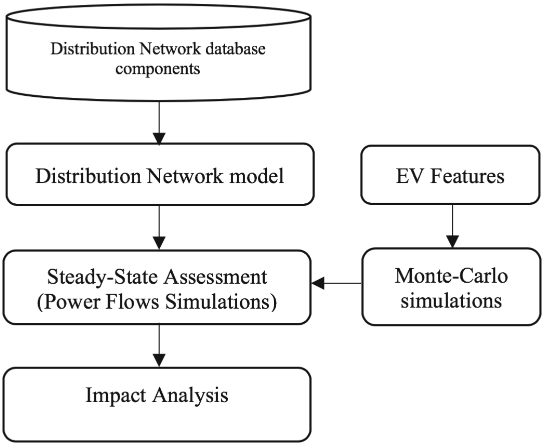

Fig. 1. Proposed methodology

The proposed methodology evaluates the PEV insertion in residential power distribution networks, under different scenarios of penetration. The proposed methodology considers some uncertainties levels, therefore Monte Carlo Simulation method is applied in order to model the uncertainties. As it was mentioned before, the uncertainties levels considered in this research work includes, the PEV connection point in the power distribution network, the PEV charging method (controlled and uncontrolled charging), the type of vehicle connected to the grid node, and finally, the state of charge (SOC) of the battery. Uncertainties levels are defined with the purpose to evaluate the impact of the PEV penetration in the power distribution network.

2.1 Power Distribution Network Database Components

In order to analyze the PEV insertion within a residential feeder in a power distribution network, charging points are added to the households. Equation 1 represents the electricity consumption in a household, including the PEV load to the electrical system. The equation incorporates the increase in electric power demand by each household where: T_D is the total required demand, F_c is the annual growth factor, DMU is the maximum unit demand of each household, and D_{PEV} is the electricity demand required by the PEV charger.

$$T_D = F_c * DMU + D_{PEV} \tag{1}$$

Each node in the distribution network has a power demand profile; the PEVs power demand in each of the nodes is added. The total electricity demand at each node is represented by Eq. 2, where P_{node}, is the total power per node D_{PEV}, is the power demand of the PEVs connected at that node, D_{system}, is the total electricity demand required by households connected at the node and n is the number of PEVs connected to this node. All values are expressed in kW.

$$P_{node} = \sum_{i=0}^{n} D_{PEV\,i} + D_{system} \tag{2}$$

2.2 Power Distribution Network Model

The power distribution network modeling is performed in MATLAB using the MATPOWER toolbox [12], the parameters considered are listed as follows: line impedance, voltage load of the substation, and transformers. The model detailed of the feeder allows to perform the power flow simulations considering PEVs insertion, as a result of the steady-state analysis the following data are obtained voltage droops, power losses, and the loading of each power distribution line. Equations 3–4 are used to obtain the parameters of the distribution network expressed in p.u. (per unit), where: Z_{base}, is the base impedance in Ohms, kV_{base} is the base voltage expressed in kV, S_{base} is the base apparent power in MVA and I_{base}, is the base current in amperes A.

$$Z_{base} = \frac{(kV_{base})^2}{MVA_{base}} \tag{3}$$

$$I_{base} = \frac{kVA_{base}}{kV_{base}} \tag{4}$$

2.3 Monte Carlo Simulations

Figure 2 shows the flowchart to implement Monte Carlo simulations in MATLAB; four uncertainties levels are considered for the PEVs insertion in the power distribution network.

The PEVs with a SOC greater than 60% is considered as a PEV not connected to the grid, the minimum SOC considered in this work is 20%, therefore the PEVs that participate in the electricity demand curve are those that have a

SOC greater than 20% and below 60%. The next uncertainty level is regarding with the PEV Model; this stochastic variable is considered due to there are PEV several models available on the electric vehicles market. Two types of PEVs are considered in this article, the first PEV with high autonomy, 5 passenger capacity, the second type, it is available for one passenger, and less autonomy (city car), the main difference between the two PEVs is the power required by the charger. The charging method is the third uncertainty level. The next paragraph describes in detail the charging methods proposed in the model.

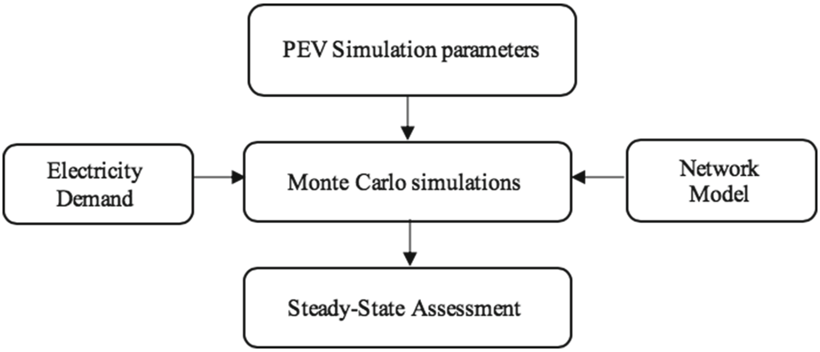

Fig. 2. Monte-Carlo simulation diagram

Non Flexible Load. PEVs start charging as soon as they are connected to the grid. Equation 5 represents the time in which the PEVs start their uncontrolled charge, where $h_{charging}$ is the hour in which the charging process begins and h_{arrive} is the hour when the PEV arrives at the household.

$$h_{charging} = h_{arrive} \tag{5}$$

The total energy consumed by this charging method is considered until the battery reaches its maximum capacity or when the PEV begins a new trip [10].

Flexible Load. The charging process is delayed by a certain time to avoid the peak power demand period. The delay in charging time is based on PEV owner configuration regarding to charge requirements and the time when the charging processing must be complete. Equation 6 represents the charging time for the PEV considering Flexible load where $h_{charging}$ is the start hour for the charging process, h_{arrive} is the PEV arrival hour at household and R is the remaining time to arrive at the time programmed by the user.

$$h_{charging} = h_{arrive} + R \tag{6}$$

The power demand of this charging method is considered until the battery reaches its maximum capacity or when the PEV is disconnected.

Monte Carlo Simulations (MCS) are performed in order to include the uncertainties levels explained above. The total number of vehicles is defined, moreover, the PEV penetration percentage in the power distribution network is defined as the scenario under analysis. The power requirements depend on the PEV model. Once the stochastic variables are defined by MCS, power flow calculations are performed using MATPOWER toolbox, the results obtained include the loading of the power distribution lines, voltage droops, and the demand increase in each node of the power distribution system. It is worth mentioning that MCS uses a uniform distribution for defining uncertainties levels.

2.4 Steady-State Assessment

As it was mentioned before, power flows are calculated by applying Newton Raphson method [9] using MATPOWER toolbox.

In order to perform the analysis, a work day load profile is considered. In addition, the analysis includes different scenarios of PEVs penetration.

The loading of the power distribution lines is calculated by Eq. 7, where *loading* [%], is the loading of the distribution line, S_{branch}, is the apparent power of each section of the power distribution line V_{base}, is the rated voltage network.

$$loading(\%) = \frac{S_{branch}}{V_{base}} * 100 \tag{7}$$

For evaluating the global impact of PEVs penetration in a power distribution network, the following index is proposed, to evaluate the global voltage degradation, which is expressed in Eq. 8, where ∇V, is the variation of the voltage in the power distribution network V_{t0}, is the voltage droop per node without considering PEVs penetration, V_t, is the voltage droop considering PEVs insertion. This variation is related to the PEVs penetration in the power distribution network.

$$\nabla V = \sqrt{(V_{t0} - V_t)_1^2 + (V_{t0} - V_t)_2^2 + \cdots + (V_{t0} - V_t)_n^2} \tag{8}$$

2.5 Impact Analysis

The analysis results include the calculation of the voltage droops, the power demand increase in each node, and the power distribution lines loading, to quantifying the PEVs effects on the primary feeders and their branches. For instance, overloads in the distribution lines might drive the activation of the power distribution system protections such as over-current relays, distribution fuses, and recloser, driving an economic impact on the society.

3 Case Study

3.1 PEV Characteristics

Two PEV models are implemented to analyze the impact of PEV in a power distribution network, the Nissan Leaf model [11] and Renault Twizy [12], the characteristics are summarize in Table 1. This research work considers a sample of 1200 vehicles, considering PEVs penetration index ranging from 10% to 40%, two PEVs models are selected and they are distributed randomly in the power distribution network under study.

Table 1. Electric vehicles features

Battery main features	Nissan leaf	Renault twizy
Storage capacity	24 [kWh]	6.1 [kWh]
Type of charger	220/110 [V]	220/110 [V]
Power charger	3.3 [kW]	4.6 [kW]
Time of charge	8 [Hours]	3.5/6 [Hours]
Autonomy	389 [km]	100 [km]

3.2 Charging Scenarios

Two charging scenarios are evaluated to determine the impact of PEVs on a residential power distribution network. The A scenario corresponds to uncontrolled charging, in this scenario each PEV starts its charging when the PEV is connected to the grid, without considering the load profile i.e. if all PEVs are connected to the grid considering this charging method, it will cause a significant overload in the power distribution network lines because PEVs might start its charging at the peak power demand period. Scenario B corresponds to flexible charging where the PEVs start its charging during the lower demand period (00:00 to 07:00). The main aim is to obtain a battery SOC about 100% at 07:00.

MCS method uses random distribution to place the PEVs in the test Feeder under study, considering the following penetration rates; 10%, 20%, 30%, and 40%, with the purpose to evaluate the behavior of the power distribution network under different PEVs penetration rates.

3.3 Distribution Network Characteristics

Figure 3 shows the distribution network under study, corresponding to the IEEE 34-Bus Test Feeder. The configuration of the electrical system, as well as the main grid characteristics such as conductor size, line impedance, distance, between branches, power demand by each node, among others are available in the reference [13].

Figure 4 shows a typical demand curve for the residential sector, where its maximum demand is presented from 19:00 to 21:00 h. Notice, Power Distribution networks are designed for a lifespan about 25 years [14], therefore the loading increase due to PEVs charging at peak hours period might decrease the Power Distribution networks lifespan. Moreover, it is worth mentioning that the batteries might be considered as a distributed generator, however, in this study, the power injected from the PEVs batteries is not considered.

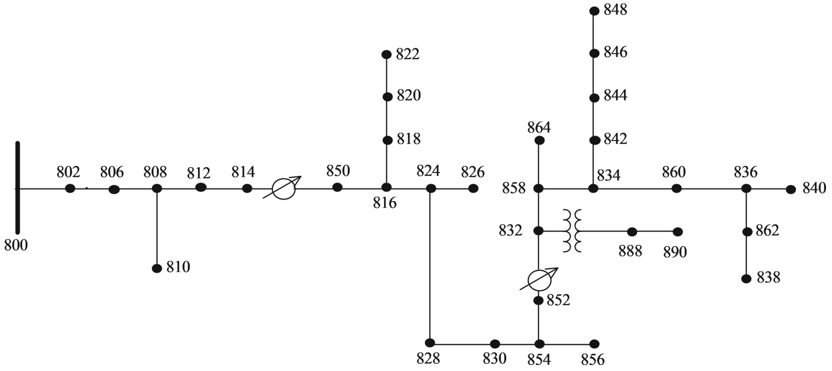

Fig. 3. IEEE 34-Bus test feeder

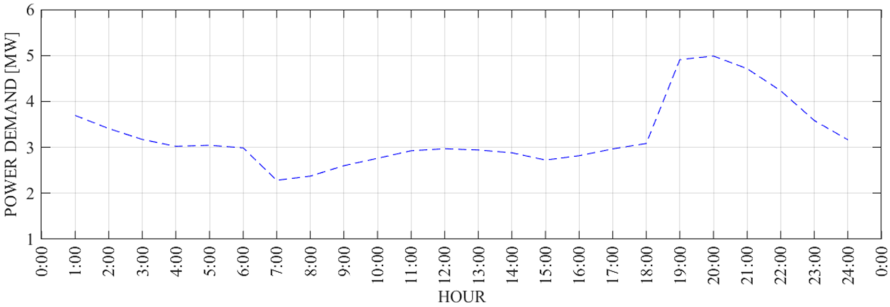

Fig. 4. Residential electricity demand curve

4 Analysis Results

This section presents the results obtained applying the proposed methodology on the IEEE 34-Bus Test Feeder considering a residential load profile using the formulation described in Sect. 2. Four uncertainty levels include; PEV charging method, electric vehicle model, battery charge level (SOC), and the distribution of PEVs in the nodes of the power distribution network. Moreover, 4 PEVs penetration scenarios are evaluated, as it was mentioning before in Sect. 3. The simulations performed take into account a total of 1200 vehicles, the number of vehicles based on fossil fuel depends on the PEVs penetration level.

4.1 Load Distribution Through Primary Feeder

Figure 5 shows the load demand increase in each node due to the insertion of PEVs in the network. As an illustrative example Fig. 5 shows the peak power demand at 20h00 for the residential network under study, considering a 10% of PEVs penetration level, the power demand increases from 5598 kW to 5956 kW. Considering a 20% of PEVs penetration level, the power demand increases about

706.1 kW, considering 30% of PEVs penetration level, the power demand increase about 1072 kW, this increased cause loading problems because the loading of line 1 is over 100%. Notice, the proposed methodology is able to distribute the PEVs load through the power distribution network in randomness way.

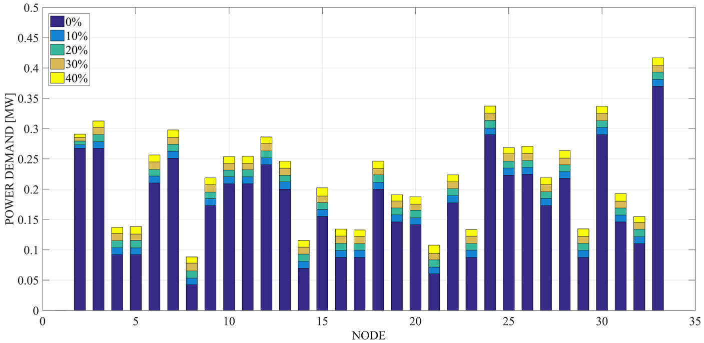

Fig. 5. Electricity demand by node

4.2 Voltage Droop Through Nodes of Primary Feeder

Figure 6 shows the voltage profile in p.u. by each node considering different PEVs penetration levels. The voltage droops must not exceed the threshold of 0.95 p.u. allowed for power distribution networks, considering 30% of PEVs penetration level, the maximum voltage droop is 0.972 in p.u. The voltage profile is not affected due to the robustness of the power distribution network, however, the method is able to identify the nodes where there are voltage droops that do not fulfill the requirements of grid codes.

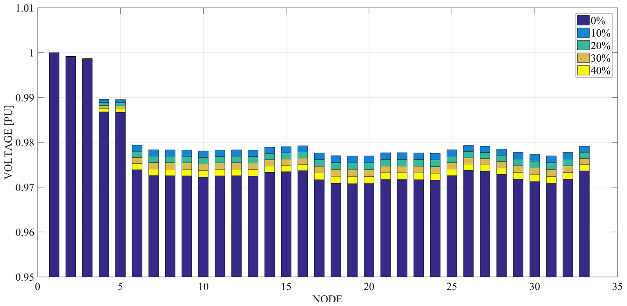

Fig. 6. Voltage droop by node

4.3 Loading of Power Distribution Lines

The power demand increase in each of the nodes causes an increase in the power flow of power distribution lines, in Fig. 7 the loading of the power lines is shown considering the PEVs penetration scenarios under study. The loading of the three first segments close to the substation without consider PEVs insertion are 85%, 81%, and 77% respectively. Considering a 10% of PEVs penetration, the loading of the power distribution line increases about 90.56% in the first section, while, considering a 20% of PEVs penetration level, the loading of the main section increases about 96.92%, when 30% of PEVs penetration level is simulated, the loading of the power distribution line exceeds its maximum capacity by 2.05%, which might cause the activation of over-current protection, therefore, expenditures occur in terms of monetary cost and, social impact.

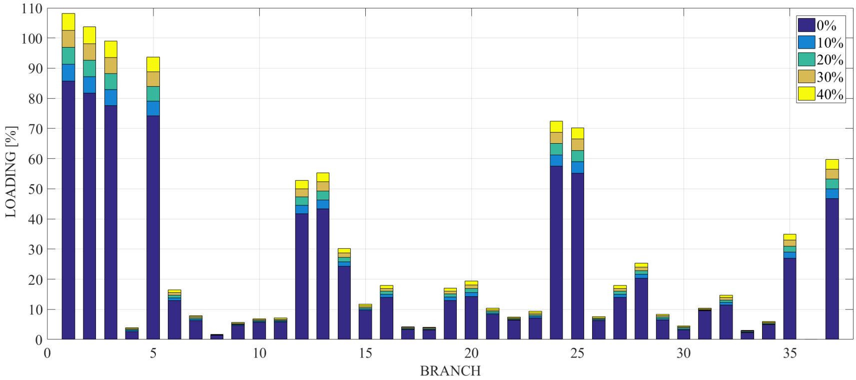

Fig. 7. Loading of power distribution lines

The power distribution network under study shows several loading problems in the power distribution lines when the index penetration is greater than 30%, at peak power demand hour, there are several PEVs connected to the power distribution network considering uncontrolled charging method, moreover, the SOC of the batteries is less than 60%. The large number of PEVs connected to the power distribution network is due to the feeder modeled contains a residential load profile.

The peak power demand hour contains the highest number of PEVs connected to the network. Because of the feeder under study, it is modeled as a residential power distribution network.

The impact of PEVs insertion is shown in Fig. 8 into the daily power demand curve, considering 30% of the penetration index. The bars in blue color represent the actual daily power demand without considering PEVs, while the bars in orange represent the increase in demand value by hour caused by the 30% insertion of PEVs in the power distribution network. Notice, there is an increment of about 1068 kW at the peak demand corresponding to PEVs insertion.

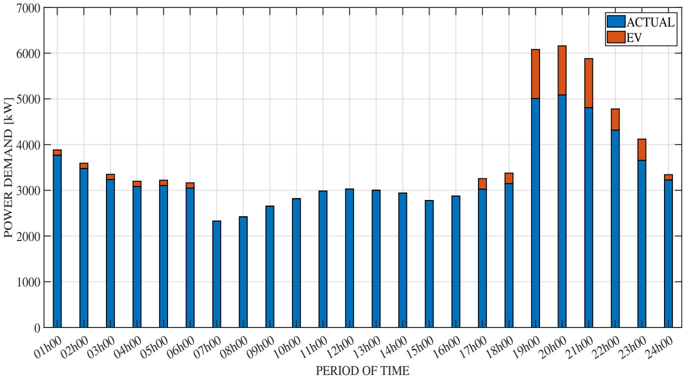

Fig. 8. Electricity demand curve considering 30% of PEVs penetration

4.4 Voltage Profile

Table 2 shows the voltage profile degradation as a function of PEVs penetration rate, considering Eq. 8 proposed in Subsect. 2.4. The Voltage profile droops about 0.992 p.u. considering 10% of PEV penetration index, while the voltage profile droops close to 0.968 p.u when the PEV penetration index is 40%. Although the voltage degradation index of the power distribution system under study fulfills the threshold established into the grid codes, the proposed index is able to represent the status of the power distribution network.

Table 2. Voltage profile degradation

PEV penetration level	Voltage profile degradation
10%	0,992 p.u.
20%	0,984 p.u.
30%	0.976 p.u.
40%	0.968 p.u.

5 Conclusions

The take-up of PEVs is expected to accelerate rapidly in the future, driven by consumer demand and government policies aimed at tackling climate change, the PEVs insertion impose several challenges in the future power distribution systems. In this context, this research work presents a practical methodological framework in order to assess the impact of PEVs in the power distribution networks. The proposal considers 4 uncertainties levels associated with randomness where the PEVs can be connected to the power distribution network, PEVs model, PEVs charging method and, the level of charge battery (SOC). The methodology is implemented and validated using the IEEE 34-Bus Test Feeder, the results demonstrate that the proposal is able to evaluate the impact of the PEVs on power distribution networks. Four PEVs penetration scenarios are considered. Considering a 30% penetration index the activation of over-current protections relays occurs. In addition, it is demonstrated that the proposed methodology is able to identify the feeder sections that need to be reinforced and allows to analyze the loading index of distribution network elements, moreover, a voltage degradation index is presented in order to determine if the voltage regulation requirements, established into the grid codes are fulfillment.

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