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Probabilistic Harmonic Analysis for Waveform Distortion Assessment of Low Voltage Distribution Systems with Plug-in Hybrid Electric Vehicles

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***Abstract* - In this paper, a probabilistic direct method to assess the waveform distortion levels of low voltage distribution systems including plug-in hybrid electric vehicles charging stations is proposed. The method takes into account uncertainties in number of vehicles being charged, charging voltage and current levels, power battery status and capacity, and charging time duration. Numerical applications are performed by applying the proposed probabilistic harmonic analysis to assess the harmonic distortions of a test low voltage unbalanced distribution network.**

***Index Terms*--Electrical vehicle charger, harmonic power flow, Monte Carlo procedure, probabilistic analysis, waveform distortion assessment.**

I. Introduction

The need of transition to sustainable technologies has been driving the growing diffusion of plug-in electric vehicles as transportation systems [1]. Plug-in hybrid electric vehicles (PHEVs) are the immediate answer to sustainability requirements. Recent literature showed that significant greenhouse gas reductions due to PHEV fleet penetration could be obtained ranging from 3.4 to 10.3 billion metric tons carbon dioxide equivalents from 2010 to 2050 [2]. Also, the economics for both the prospective vehicle owner and the electric utility have been shown to be much promising [3]. Problems related to large-scale deployment of PHEVs in the U.S. were investigated in [4] where it was shown that it will have limited impacts on the electric power system in terms of additional generation requirements thanks to the large amounts of underutilized capacity in current electric power systems.

However, while the diffusion of PHEVs represents a step forward in terms of reduction of emissions, at the same time, it embodies a further complexity for the system introducing new challenges in its planning and operation.

One of the main concerns about their penetration is related to the increase of the electrical load in electrical distribution systems, taking into account that a very high number of simultaneous PHEV charger loads is expected in the future grids. This will impact the overall daily load curve as well as peak power, losses and slow voltage variations [5].

A further critical issue is the non-sinusoidal feeding current of the PHEVs battery chargers which are equipped with static converters. This results in load current harmonics (and interharmonics, if present) that are cause of waveform distortions of the network line currents and bus voltages with consequent deleterious effects on the distribution systems components.

Nowadays, there is an impelling need to evaluate voltage and current harmonics in power systems and, particularly, waveform distortion assessment in LV distribution systems including PHEVs has been discussed in various papers of the relevant technical literature where both deterministic and probabilistic approaches have been applied [6 - 14]. The charging behavior of PHEVs is affected by different factors, such as the number of PHEVs being charged, their charging voltage and current levels, power battery start/end status and capacity, and charging time duration etc. All these factors tend to be uncertain if all the PHEVs at an EV charging station or in a residential community are considered, so making the overall charging demand uncertain as well [15]. This makes probabilistic approaches more adequate for the harmonic analysis of power systems including this type of loads.

This paper proposes a probabilistic direct method to assess the waveform distortion levels of LV distribution systems with PHEVs battery chargers. Specifically, the proposed method, based on a Monte Carlo procedure, is able to take into account the aforementioned uncertainties relative to the operating conditions of the battery chargers. Regarding the harmonic currents injected into the network by PHEV chargers, many papers were proposed in the technical literature for their evaluation, some of them based on experimental results [6, 8, 13, 16-18]. In this paper, typical harmonic spectra were used, based on measured data on actual PHEV chargers [13].

The probabilistic harmonic analysis has been then applied to assess the harmonic distortions of the Cigré European LV Unbalanced Distribution Network [19], considering different number and locations of single phase and three phase battery chargers.

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The paper is organized as follows: in Section II the probabilistic approach used for the proposed harmonic analysis is described. Section III reports the results of its application to a LV distribution system. Section IV is devoted to concluding remarks.

II. PROPOSED PROBABILISTIC PROCEDURE

The probabilistic procedure proposed in this paper refers to distribution systems characterized by unbalances of the loads and of other AC system components. Then, the evaluation of the steady-state operating conditions, at fundamental frequency and at harmonics, is effected by applying a three-phase model of the whole power system.

The method, based on a Monte Carlo procedure, is able to take into account both the unbalances of the distribution system and the uncertainties related to the operating conditions of the battery chargers.

Each iteration of the Monte Carlo procedure is characterized by the following steps:

1. The analysis at the fundamental frequency of the LV unbalanced distribution system with PHEVs' battery chargers is performed. This step requires the solution of a three-phase load flow for a given load conditions. In Section II.A, the model to obtain the load PHEV demand is illustrated.
2. For each battery charger, the current harmonics are obtained based on typical spectra (Section II.B).
3. Once known the harmonic injections, the harmonic phase voltages are calculated by the direct solution of a linear equation system which expresses the link between the harmonic phase voltages and harmonic currents through the system harmonic admittance matrices (Section II.C).

The active power absorbed when charging PHEVs at a charging station or in a local residential area is characterized by an appropriate pdf that can be obtained by applying the model proposed in [15] that is briefly recalled in Section II.A. It is assumed a control of the PHEV chargers such as they do not exchange reactive power with the network. Moreover, random behavior of linear loads is accounted by considering for them Gaussian pdf of required active and reactive powers.

The statistical characterization of the harmonic currents injected by charging PHEVs is, then, linked to the statistical characterization of the fundamental component that is a result of step 1 of the Monte Carlo procedure.

It is worth noting that the system analysis at the fundamental frequency at step 1, by means of a three-phase load flow, is of the utmost importance because this analysis provides a complete knowledge of the system phase voltages, allowing the assessment of many power quality indices (e.g., slow voltage variations, unbalances etc…).

A. Probabilistic modeling of charger stations at fundamental frequency

The use of PHEVs is affected by several random factors, therefore a probabilistic modeling is needed. In this paper, the probabilistic model proposed in [15] is applied. This model is able to take into account the main factors determining the PHEV charging behavior: the battery capacity (C_{batt}), the energy consumption (E_m) per km driven and the daily driven kilometers (M_d).

In particular, the battery capacity and energy consumption per km driven depend on the vehicle electrification rate (k_{EV})[1] and, consequently, they are linked to the class of the PHEV vehicle (e.g., micro car, economy car, mid-size car, etc…). The energy consumption per km E_m can be expressed as a function of k_{EV} as:

$$E_m = A \cdot (k_{EV})^B \qquad (1)$$

where the constant coefficients A and B are dependent on the PHEV class.

The model proposed in [15] takes into account the randomness of the parameters influencing PHEV energy consumption. In particular: i) the parameters k_{EV} and C_{batt} are considered correlated and modeled with bivariate normal distributions; ii) according to the PHEV driving pattern statistics reported in [20], the statistical characterization of the PHEV's daily traveled distance is expressed by a lognormal distribution.

Once the vehicle's energy consumption per km and the average daily route are known, it is possible to derive the daily recharge energy required by a single PHEV. This last quantity is also a random variable being a function of random variables.

In the presence of multiple PHEVs charging at a bus of a distribution network, the queue theory can be applied to describe their general charge process. In [15], two different queuing models were considered for two different PHEV charging scenarios: i) charging PHEVs at a charging station and ii) charging PHEVs in a local residential area. The difference between the EV charging station and the residential area is that, in the residential area, the charging slots are privately owned, so the maximum number of customers to be served is limited, compared to the charging station in which the possible number of customers is unlimited. This difference leads to the use of different queue models to describe the charging behavior of PHEVs. In particular, the number n of PHEVs being charged at the same time in a queue follows a discrete distribution.

For an EV charging station, the distribution is:

$$p_n = \begin{cases} \left(\sum_{i=0}^{c-1} \frac{(c\rho)^i}{i!} + \frac{(c\rho)^c}{c!} \cdot \frac{1}{1-\rho} \right)^{-1} & n = 0 \\ \frac{(c\rho)^n}{n!} \cdot p_0 & n = 1, 2, \dots, c \end{cases} \qquad (2)$$

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[1] It represents the fraction of the total energy required by the vehicle that is supplied by the battery energy storage system.

where c denotes the maximum number of customers being served at the same time and ρ is the occupation rate per server.

For a residential area, the distribution is:

$$p_n = \begin{cases} \left(\sum_{i=0}^{c} \binom{N_{max}}{i} \cdot (c\rho)^i + \sum_{i=c+1}^{k} \frac{N_{max}! \cdot (c\rho)^i}{(N_{max}-1)! \cdot c! \cdot c^{i-c}} \right)^{-1} & n = 0 \\ (c\rho)^n \cdot \binom{N_{max}}{i} \cdot p_0 & n = 1, 2, \dots, c \end{cases} \quad (3)$$

where k is the maximum number of customers being served or waiting in the queue, and N_{max} is the maximum number of possible customers to be served.

After establishing the distributions of the main factors that determine the charging behavior of PHEVs, a Monte Carlo procedure can be applied to obtain their total charging demand samples.

The procedure starts with the random generation of n, that is the number of PHEVs that are charged at the same time according to distribution (2) or (3). Then, for each PHEV, the following steps are implemented:

1. Randomly select the class of the PHEV according to its market penetration probability;
2. Randomly generate the parameter k_{EV} and, then calculate the energy consumption per kilometer E_m;
3. Randomly generate the driven distance M_d and, then, calculate the required recharge energy D_E using the value of E_m calculated at step 2;
4. Randomly generate the service time T for charging the PHEV, that is statistically characterized by the exponential distribution with mean T_μ, as: $T = -T_\mu \cdot \ln(U)$, where U is a uniformly distributed variable in the range (0,1).
5. Calculate the average charging current of the PHEV by:

$$I_1 = min\left(\frac{D_E}{V_n \cdot T}, I_{max}\right) \quad (4)$$

where V_n is the charging nominal voltage and I_{max} is the maximum charging current.

Once the charging current I_1 is calculated for all the PHEVs (by repeating steps 1-5 for all the PHEVs), the total charging demand P of the n vehicles that are charged at the same time is obtained by the relation:

$$P = \sum_{i=1}^{n} V_n I_{1,i} \quad (5)$$

with $I_{1,i}$ is the fundamental charging current of the i^{th} PHEV calculated at step 5.

The procedure is repeated a sufficient number of times to obtain a good estimate of the probability of the output variables according to a stated accuracy.

B. Probabilistic modeling of charger stations at harmonics

The PHEV charger is modelled by the harmonic current source. Once the PHEV charger is turned on, the harmonic currents injected into the network follow a typical harmonic spectrum. In this paper, the harmonic current spectrum data measured from several PHEV chargers reported in [13] has been considered.

Table I illustrates the harmonic spectra of measured PHEV chargers reported in [13].

TABLE I - HARMONIC CURRENT SPECTRA OF MEASURED PHEV CHARGERS [13]

h	$I_{h-spectrum}$	
	Mag [%]	*Angle* [deg]
1	100.0	15.5
3	8.864	111.8
5	2.452	-73.4
7	0.891	38.6
9	0.911	-114.5
11	0.870	-69.5

The PHEV chargers harmonic model follows the model proposed in [21]. The h^{th} harmonic current of a single PHEV charger has a magnitude equal to:

$$I_h = I_{fund} \cdot \frac{I_{h-spectrum}}{100} \quad (6)$$

where $I_{h-spectrum}$ are the values of the typical spectrum reported in Table I and I_{fund} is the amplitude of the fundamental current absorbed by each PHEV charger.

Assuming that the fundamental frequency current has a phase angle of θ_1[2], the phase angle of the h^{th} harmonic current θ_h is given by [21]:

[2] Assuming that the PHEV's charger does not absorb reactive power, the phase angle θ_1 coincides with the phase of the supply voltage.

$$\theta_h = \theta_{h-spectrum} + h \cdot (\theta_1 - \theta_{1-spectrum}) \qquad (7)$$

where $\theta_{h-spectrum}$ and $\theta_{1-spectrum}$ are the spectrum values of Table I. The value of the phase angle of the fundamental current, needed to apply (7), can be determined as a result of the system analysis at the fundamental frequency performed by the three-phase load flow.

As illustrated in the previous section, the amplitude I_1 depends on the power required by the charging point that is a random quantity. So, the amplitude of the fundamental current and, from eq. (6), the amplitude of the harmonic currents absorbed by the charging point result to be random variables.

The current phase angle, instead, is not considered as a random variable; this is because the PHEV chargers always draw harmonic currents at approximately the same phase angle with respect to the supply voltage [13].

Therefore, assuming that the voltage supplying all the chargers in the charging station or in the residential area is the same, the amplitude of the h^{th} harmonic current injected into the network, where the charging station or residential area is connected, is the sum of the amplitude of the harmonic currents injected by each single PHEV charger operating at the same time; in accordance, the phase angle of the h^{th} injected harmonic current results equal to the one calculated by (7).

C. The probabilistic harmonic direct method for an unbalanced network

The main objective of this Subsection is the determination of the distributions of voltage harmonics at the busses of the distribution network that charges the PHEVs. Considering that the distribution network is unbalanced and that the PHEV chargers can be single-phase, a multi-phase analysis has to be performed.

In this paper, we adopted a direct harmonic multi-phase and multi-source power flow as proposed in [22].

However, it should be noted that a probabilistic analysis is required to account for the randomness of power required by charging stations or chargers in residential areas (see Section II.A) and, therefore, for the randomness of harmonic injections (see Section II.B).

To describe the applied method, let us refer to:

$$\bar{\boldsymbol{I}}_{\boldsymbol{h}} = \dot{\boldsymbol{Y}}_{\boldsymbol{h}} \cdot \bar{\boldsymbol{V}}_{\boldsymbol{h}} \qquad (8)$$

where $\bar{\boldsymbol{I}}_{\boldsymbol{h}}$ and $\bar{\boldsymbol{V}}_{\boldsymbol{h}}$ are the vectors of the injected phase currents and of phase voltages, respectively, at the *h*th harmonic order. $\dot{\boldsymbol{Y}}_{\boldsymbol{h}}$ is the network admittance matrix, at the *h*th harmonic order, whose dimension is 3*N*x3*N*, being *N* the number of busses.

The matrix $\dot{\boldsymbol{Y}}_{\boldsymbol{h}}$ can be built considering appropriate models of the network components. The application of the model reported in Section II.B allows determining the values of $\bar{\boldsymbol{I}}_{\boldsymbol{h}}$; then, the harmonic voltages can be obtained by solving eq. (8).

To account for randomness of the involved variables, a Monte Carlo procedure can be applied and the distribution of the harmonic phase voltages, as well as of harmonic indices, can be obtained.

III. CASE STUDY

The proposed Probabilistic Harmonic Analysis presented in Section II has been applied to the low-voltage distribution grid of Fig. 1.

The grid refers to the Cigré European LV Distribution Network reported in [19]. The network, operating at nominal voltage of 400 V, includes 41 busses, 37 lines and it is connected to a 20 kV MV grid. Three MV/LV transformers of 500, 150 and 300 kVA supply, respectively, residential (R), commercial (C) and industrial (I) lines. The details of linear loads and network data are reported in [19].

The grid has been modified by including non-linear loads constituted by the PHEV charging systems.

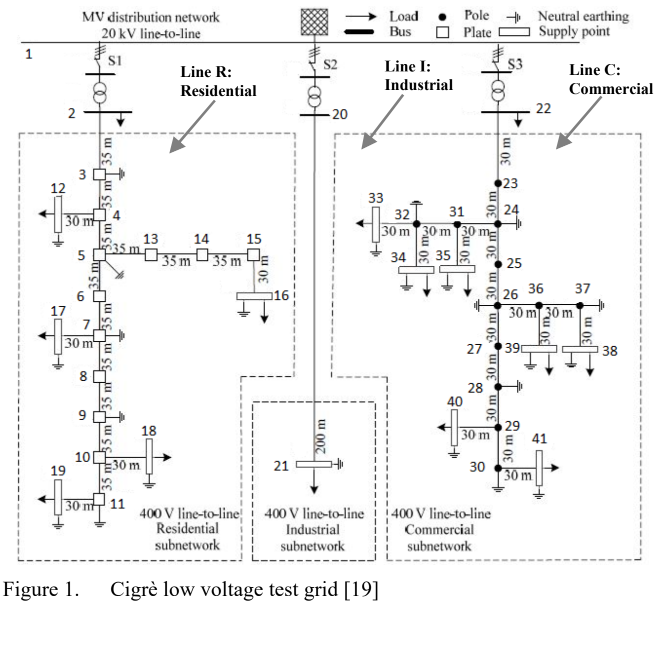


Figure 1. Cigrè low voltage test grid [19]

With respect to the residential area, the busses with PHEV chargers are reported in Table II. Table II also reports the number of single-phase charging points (V_n=230 V and I_{max}=16 A), for each location. Chargers are supposed to be equally distributed among the three phases.

With respect to the commercial feeder, a charging station is supposed to be connected at bus #34 and the number of charging points is reported in Table II.

TABLE II
PHEV CHARGING SYSTEMS.

Bus number	Line	Number of charging points 230V-16A
#7	Residential	35
#16		20
#34	Commercial	20

In order to take into account the differences in PHEV parameters, such as k_{EV}, C_{batt} and E_m, the PHEVs are divided into 4 classes (Micro-car, Economy car, Mid-size car and SUV). All data referred to the PHEV parameters and necessary to apply the procedure illustrated in Sec. III are reported in [15]. The lognormal distribution parameters that statistically describe the daily distance traveled by PHEV is obtained by assuming a mean value of 60 km and standard deviation of 30 km. The queue model parameters used in this numerical application are also reported in [15].

Several numerical simulations were performed. For the sake of conciseness, only the following two case-studies are illustrated in detail:

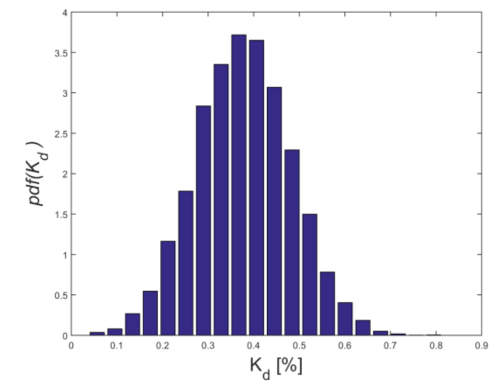
Case 1: the network linear loads are all balanced as reported in [19].

Case 2: an unbalance of 30% between the phase power of the linear loads have been considered.

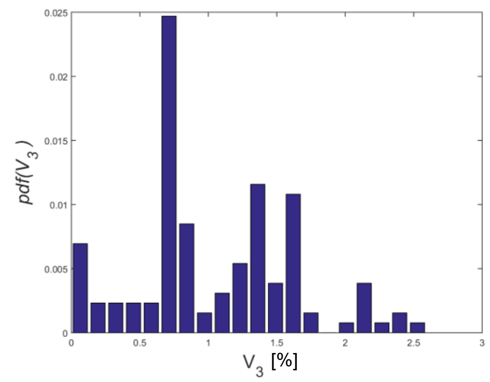
A. Case 1

In this case the network linear loads are all balanced as reported in [19].

A Monte Carlo simulation was performed (Number of trials= 10000) to account for randomness in PHEV charging and to determine the distribution of phase voltages at fundamental frequency and at harmonic frequencies. As an example of the obtainable results, Fig. 2 shows the pdf of the unbalanced factor at bus #16 and of the amplitude of the 3rd voltage harmonic at phase 2 of bus #15.



(a)



(b)

Figure 2. Probability density function of the unbalanced factor at bus #16 (a) and of the amplitude of the 3rd voltage harmonic at phase 2 of bus #15 (b)

Figs. 3 show the mean values of fundamental phase voltage and of the unbalance factor (K_d) at all busses resulted by the application of the proposed method.

Fig. 3.a evidences that, for almost all busses, the mean value of the fundamental voltage is within the range of normal operating conditions. Only a few busses experience a mean value of the fundamental voltage lower than 0.9 p.u., that, in many

standards, is the minimum admissible value of voltage. Thanks to the balancing of the load powers on the three phases, a low value of the unbalance factor is obtained as shown in Fig. 3b.

Fig. 4 and Fig. 5 show the mean values assumed by the 3rd and 5th voltage harmonics at each network bus, while Fig. 6 shows the mean value of voltage THD at all busses.

By the analysis of Figs. 4-6, it appears also that the main contribution to the THD of voltage is due to the 3rd voltage harmonic as it was expected due to the presence of single-phase charging systems. Being each line connected to the 20 kV distribution network through its own transformer, the harmonic pollution in the industrial line (nodes #20 and #21), where there are not PHEV chargers, is negligible.

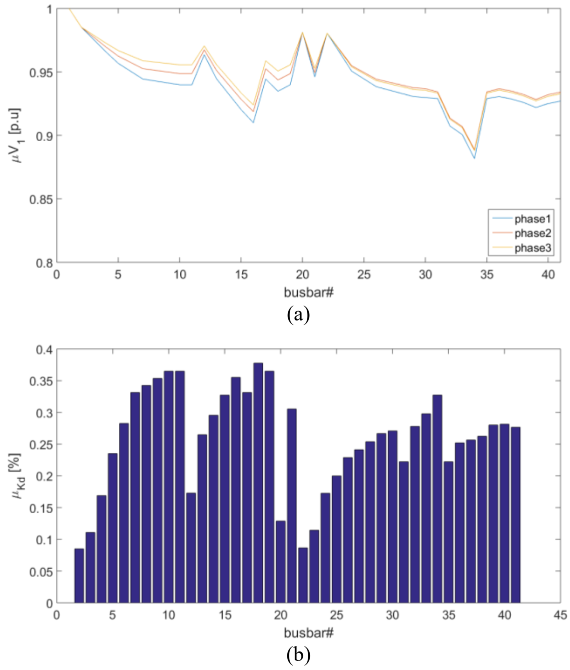


Figure 3. Mean value of the fundamental phase voltage (a) and mean value of the unbalance factor at all network busses (b)

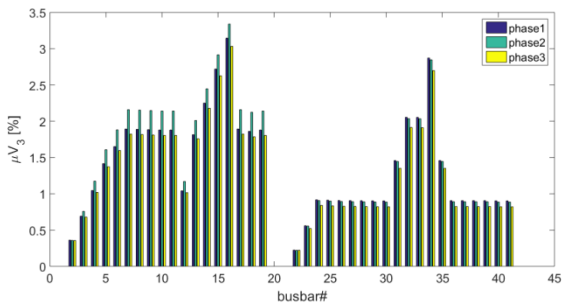


Figure 4. Mean value of the 3rd voltage harmonic at all busses

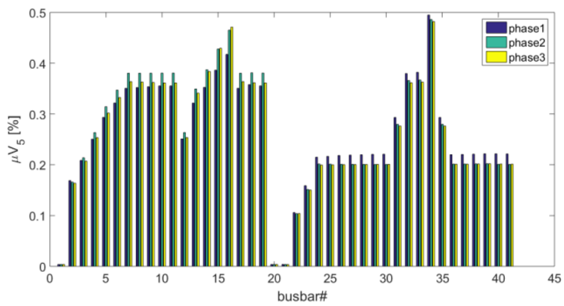


Figure 5. Mean value of the 5th voltage harmonic at all busses

B. Case 2

In this case, to take into consideration the influence of unbalances on the harmonic distortion levels, unbalanced loads have been assumed at each grid's bus.

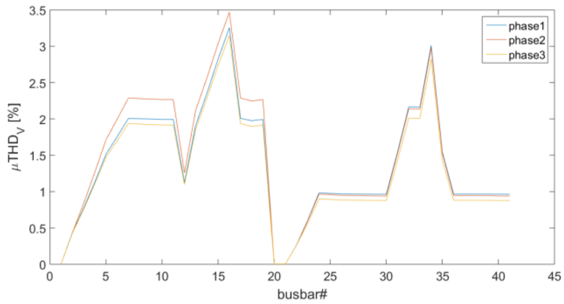


Figure 6. Mean value of the THD of voltage at all busbars

In particular, the total power of the three phase loads values indicated in [19] have been assumed by imposing different values in each of the three phases of the network busses. The power at phase p=3 was increased of 30% and the power at phase p=1 was decreased of 30% respect to the nominal value.

With reference to the charging systems, the same configuration of case 1 has been considered (see Table II).

Figs. 7 show the mean values of fundamental phase voltage and of the unbalance factor (K_d) at all busses. As expected, the greatest voltage drop arises in phase p=2 where the voltage amplitude at some busses assumes values lower than 0.9 p.u.. Moreover, the presence of unbalanced loads causes an increase of the unbalanced factors with respect to those observed in case 1, which in this case assume mean values close to 1%. Fig. 8 and Fig. 9 show the mean values assumed by the 3rd and 5th voltage harmonics at each network bus, while Fig. 10 shows the mean value of voltage THD at all busses. The harmonic levels are similar to those obtained in case 1. The distortion at phase 2 appears more significant; this is due to the lower amplitude of the fundamental voltage.

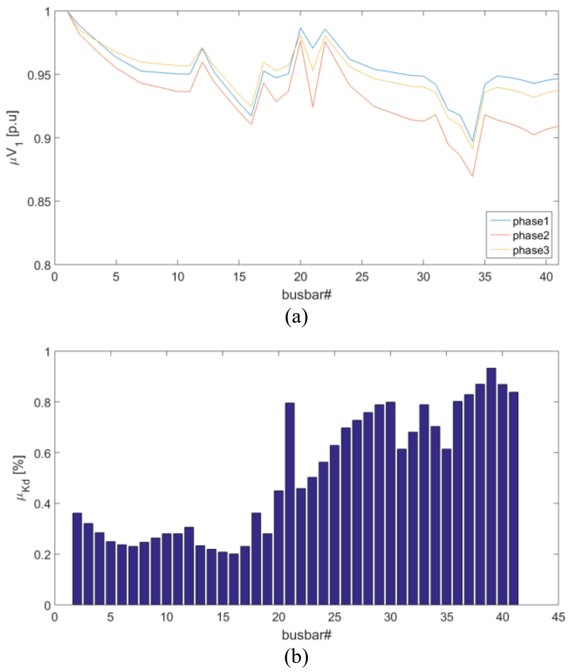


Figure 7. Mean value of the fundamental phase voltage (a) and of the mean value of the unbalance factor at all network busses (b)

IV. Conclusion

In this paper, a method was proposed to assess in a probabilistic field the waveform distortion levels of a low voltage distribution system including PHEV battery chargers. The analysis was conducted in a probabilistic framework in order to take into account the uncertainties relative to the operating conditions of the battery chargers.

A direct method was applied for the multi-phase and multi-source harmonic power flow. Results of numerical simulations allowed analyzing harmonic levels in a LV unbalanced distribution grid including PHEV chargers also evidencing their influence on unbalance factor.

For a more accurate analysis of the impact of single-phase and three-phase PHEV chargers on real distribution systems, studies are in progress for developing a model for three-phase analysis (at fundamental and at harmonics) of four wire distribution networks in which the presence of the neutral conductor is explicitly considered.

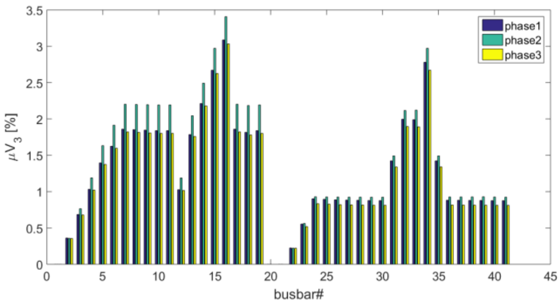


Figure 8. Mean value of the 3rd voltage harmonic at all network busses

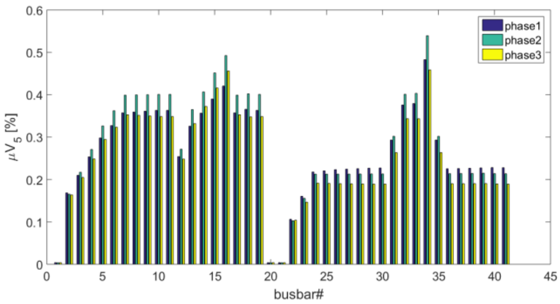


Figure 9. Mean value of the 5rd voltage harmonic at all network busses

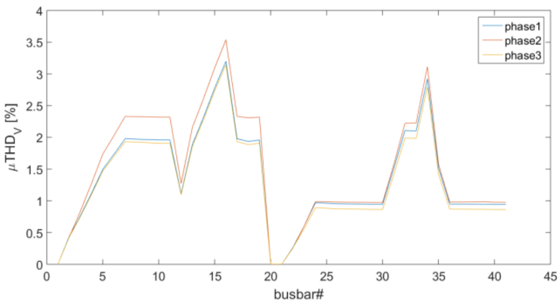


Figure 10. Mean value of the voltage THDv at all network busses.

V. ACKNOWLEDGMENT

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