Possibilistic Harmonic Load-Flow for Electric Power Systems with Wind Farms

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***Abstract*— This paper is focused on the analysis of the connection of wind farms to the electric power system and their impact on the harmonic load-flow. A possibilistic harmonic load-flow methodology, previously developed by the authors, allows for modeling uncertainties related to linear and nonlinear load variations. On the other hand, it is well known that some types of wind turbines also produce harmonics. The purpose of this paper is to present an improvement of the former method that includes the uncertainties due to the wind speed variations as an input related with power generated by the turbines. Simulations to test the proposal are performed in the IEEE 14-bus standard test system for harmonic analysis, but replacing the generator, at bus two, by a wind farm composed by ten FPC type wind turbines.**

***Index Te rms*— full power converter, harmonics, possibility distribution, power system, uncertainty, wind turbine.**

I. Introduction

ELECTRICITY is a product of particular importance for the progress of society. Meanwhile, an electric power system allows for generating, transforming and transmitting such a product to finally supplying it to the end customers. All efforts and investments of society (e.g., in human resources, physical assets, research and development, etc.) in electric power systems have a common aim "to ensure electricity in sufficient quantity in time and place, with adequate reliability at the lowest cost and controlling that environmental impacts remain within acceptable limits".

To achieve this aim, the scientific and technical community specializing in power engineering has set its expectations in the development of Smart Grids. In this field, there are many issues, only partially resolved or unresolved, which deserve special attention and require intensive research and development. One such issue is related to the connection to the conventional electric power systems of new electricity sources based on renewable resources, e.g., solar, wind, geothermal, etc.

This paper is focused on the analysis of the connection of wind farms and their impact on power quality; i.e., main aspects to be considered when harmonics have to be modeled at the network, including wind farms in its generator fleet, are discussed and developed.

A possibilistic harmonic load-flow methodology, previously developed by the authors, allows for modeling uncertainties related to linear and nonlinear load variations. On the other hand, it is well known that some types of wind turbines also produce harmonics. The purpose of this paper is to present an improvement of the former proposal method that includes the uncertainties due to the wind speed variations as an input related with power generated by the turbines. The new proposal is capable of compute the possibility distributions of the harmonic voltage distortion at all buses of the power system.

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II. Harmonics in Electric Power Systems

A. Fourier Series and Harmonics

Harmonics in power systems are distortions to the voltage and/or current waveforms from their normal sinusoidal shape. The theory to analyze and quantify this type of distortion on the waveform was introduced by the French mathematician and physicist Joseph Fourier in 1822, [1]. Fourier proof that any periodic function on a time interval, can be represented by the sum of a sine function, called fundamental component, and a number of higher order harmonic components, also sinusoidal, whose frequencies are integer multiples of the frequency of the fundamental. Fourier series establish a relationship of function in the time domain and function in the frequency domain [2].

B. Causes of Harmonics in electric power systems

In an ideal electric power system, voltage and current waveforms are perfectly sinusoidal. However, in actual electrical systems there are non-linear components that cause that the waveforms of voltage and current suffer deformations that result in harmonic distortion, see Fig. 1. A nonlinear device is one in which the current flowing through it is not proportional to the applied voltage.

C. Effects of Harmonics in the network

There are several problems related to harmonics, such as:

- Overheating of neutral conductors,
- Overheating of transformers,

- Overloading of capacitors for power factor correction,
- Problems with induction motors,
- Control failures in electronic devices which detect the zero crossing of the voltage wave, and others.

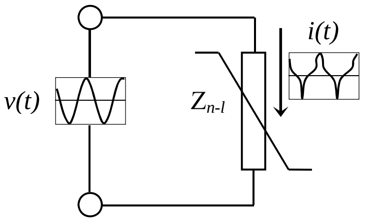


Fig. 1 Current harmonic distortion due to a nonlinear load

III. Modeling to Harmonic Frequency of the Components of a Power System

A. Modeling of Nonlinear Loads

Harmonic modeling of loads is a difficult problem due to the wide variety of nonlinear devices that there are currently in the electrical systems, which also change continuously its operation mode. However, in the frequency domain, the nonlinear loads are usually modeled by harmonic current sources whose amplitudes and phases are dependent on a set of parameters that characterize their behavior to harmonic frequencies and their state of operation.

Simpler models assume that the harmonic current injected does not dependent of the waveform of the voltage applied on the device, but its magnitude and phase-frequency. For example, thyristor-controlled rectifier, expressions such as (1) can be used to calculate the magnitude and phase of the harmonic currents injected into the system node *j*.

$$\boldsymbol{i}_j^{(h)} = f_h(\boldsymbol{v}_j^{(1)}, v_{dc}, i_{dc}, \beta) \qquad (1)$$

where, $\boldsymbol{v}_j^{(1)}$ is the voltage component to industrial frequency in the node j, v_{dc} and i_{dc} the direct voltage and current at the rectifier output and β the firing angle of the thyristors.

This model can be simplified if the parameter β in (1) is replaced by a function of the active and reactive power of the rectifier, *Prect* ($\approx v_{dc} i_{dc}$) and *Qrect* respectively, and the expression (1) can be rewritten as:

$$\boldsymbol{i}_j^{(h)} = f_h(\boldsymbol{v}_j^{(1)}, P_{rect}, Q_{rect}) \qquad (2)$$

More detailed models have been developed for some of the most important devices based on power electronics; however, such models can be used only when the characteristics of the nonlinear device are well known. This, unfortunately, is not the most common in the case of real electric power systems.

B. Behavior and Models to Harmonic Frequencies of the Main Elements of an Electric Power System

The modeling of the different components of the network, such as lines, transformers, generators, cables, capacitors, etc., is well documented in the literature [3]- [6].

C. Modeling to Harmonic Frequencies of a Wind Turbine

There are several types of wind turbines, among which include: Fixed Speed Induction Generator (FSIG), Doubly Fed Induction Generator (DFIG) and Full Power Converter (FPC). Each type of system has advantages and disadvantages inherent to the technology used, and pursuing the same goal: maximum energy transfer from the wind turbine to the grid, at the lowest cost and ensuring adequate levels of electromagnetic compatibility [7]. However, this paper will deal only the modeling to harmonic frequency of the wind turbine FPC type, as they are widely used in wind farms in Latin America, and also have a characteristic harmonic spectrum by multiples of the grid frequency [8]. Despite the study may be extended in the future to other turbine models.

The basic configuration of a wind turbine type FPC is presented in Fig. 2. The two main components to be modeled to harmonic frequency are the generator and the converter.

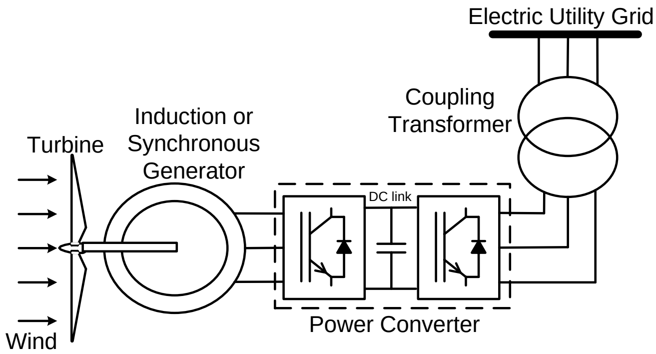


Fig. 2. Configuration of a FPC type wind turbine

Generator: In synchronous generators, the rotating magnetic field established by a harmonic current in the stator rotates at a speed significantly different to that of the rotor. Therefore, to harmonic frequencies the impedance approaches the negative sequence impedance or to the average among sub-transient direct and quadrature axis impedances [4]:

$$X_2 = \frac{X_d'' + X_q''}{2} \qquad (3)$$

In the case of induction generators, the inductance is represented through the locked rotor reactance.

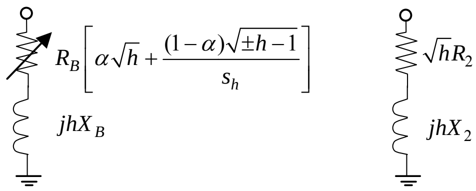
In both cases, the dependency of the resistance with the frequency may be important due to the skin effect and the eddy current losses, therefore this dependence may be considered by increasing the resistance value at the fundamental frequency by $\sqrt{h}$, where h is the harmonic order.

Furthermore, in induction machines the "α" parameter is considered which relates the rotor resistance R_1, with the locked rotor resistance, R_B, by $\alpha = R_1/R_B$, and has a typical value equal to 0.5. On the other hand the slip at harmonic frequency s_h is given by (4).

$$s_h = \frac{\pm h\omega_1 - \omega_r}{\pm h\omega_1} \qquad (4)$$

where ω_r is the rotor speed and the sign + or – depends on the positive or negative sequence of the harmonic order considered.

The models to harmonic frequency for induction and synchronous generators are shown in Fig. 3.



(a) (b)

Fig. 3. Models to harmonic frequency for: (a) induction generators, (b) synchronous generators.

Converter: In a wind turbine FPC type, the electric parameters, variables with the wind speed, are transformed to grid parameters by a converter. The commutation valves used in the converter are Insulated Gate Bipolar Transistors (IGBT) with anti-parallel diodes. On the generator's side, the convert transforms a three-phase AC voltage of variable amplitude and frequency in a constant DC voltage. On the grid's side, the converter is responsible for converting this DC voltage into an AC voltage phase, with constant amplitude and frequency (exactly like the power grid where the unit is connected).

Using digital signal processors, the vector control is performed in the converter (PWM technology). The control algorithms are diverse and depend on the manufacturer, but always looking for the optimum use of turbine-generator. In Fig. 4 the characteristic curve of wind speed versus electrical power generated from a commercial generator of 2 MW is shown.

Although a characteristic function of the harmonic behavior of a wind turbine-generator type FPC has not been fully defined (eg., similar expressions to those defined in (1) and (2) for a converter), it is possible to find information such as that presented in Table I, and that relates to the harmonic current, I_h, injected by the generator, as a percentage of the fundamental frequency current, I_1, (50 or 60 Hz). Values such as those reported in Table I are normally provided by the manufacturer and are obtained from the electric power quality tests.

Thus, using information such as that of Fig. 4 and Table I, it is possible to model the harmonic current that injects a wind turbine-generator according to the wind speed, in this case a wind generator 2 MVA.

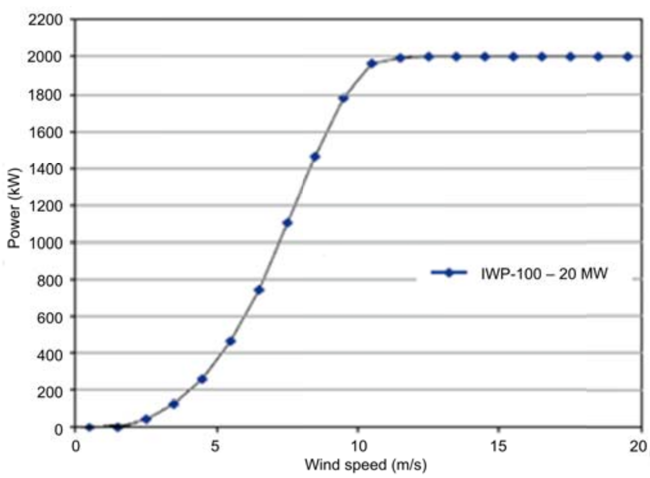


Fig. 4. Power curve vs. wind speed for a commercial generator FPC type of 2MW.

TABLE I
CHARACTERISTIC HARMONIC OF A WIND GENERATOR FPC

Harmonic Order	5	7	11	13	17	19	23	25
I_h/I_1	0.5	0.54	0.21	0.10	0.13	0.19	0.19	0.02

IV. POSSIBILISTIC HARMONIC LOAD FLOW

A. Uncertainty management

Most real-world decisions are made within an environment in which: goals, constraints, possible actions (solution space) and consequences are not precisely known. To deal quantitatively with imprecision usually techniques and concepts of probability theory are employed. However, it must be considered, that when uncertainty is modeled by using probability density functions, PDFs, implicitly it is accepted that the imprecision of whatever nature can be compared with randomness, an assumption which may be questionable. I.e., in many situations, the decision maker cannot measure or express an explicit function for all determinant parameters within a decision process. This because of various reasons, e.g., incomplete information, insufficient knowledge, lack or inaccuracy of models, or that the involved cost to acquire the lacking information is high regarding the improvement in results. Therefore, in those situations, it could be advisable to appeal to other types of information, namely: experience, intuition, ideology, beliefs, feelings, etc., i.e., options with a degree of subjectivity, but not of arbitrariness.

Fuzzy sets and possibility theories provide a formal framework to model vague relationships or concepts, such as, big, polluting, economic, satisfactory, adequate, etc. Definitions for the formal treatment of the fuzzy sets and possibility distributions can be found in [9] and applications to the specific problem of harmonic analysis in [10]- [14].

B. The possibilistic harmonic load-flow

Through the references [10] - [14], a complete formulation for calculating the harmonic load-flow, considering uncertainties in the input parameters, has been presented. Such uncertainties are modeled by possibility distributions. Reader is advised to review such references to achieve a better understanding of the methodology briefly described below.

In the possibilistic harmonic load-flow, a set of n_p uncertain input parameters, which completely describes the magnitudes and compositions of the loads and harmonic sources, in the whole network, are described with its corresponding possibility distributions $\mu_{\hat{P}_k}(p_k)$, $k = 1\ldots n_p$.

In a more general case, the set of n_p parameters is organized in subsets of nodal parameters that are related among them due to well-defined physical relationships (e.g., active and reactive power due to linear, nonlinear devices, capacitors, etc., must add up to the total active nodal load). Mentioned physical relationships can be expressed through a system of $n_d < n_p$ equations. In this way, n_d dependant parameters can be expressed in terms of the remaining independent parameters $n_i = n_p - n_d$, as follows:

$$\begin{aligned} p_{n_i+1} &= g_1(\mathbf{P_i}) \\ &\vdots \\ p_{n_i+n_d} &= g_{n_d}(\mathbf{P_i}) \end{aligned} \qquad (5)$$

where $\mathbf{P_i} = [p_1, p_2, \ldots, p_{n_i}]$. Here it is assumed, without loss of generality, that the first n_i nodal parameters are independent, and that (5) are the expressions for the dependent ones. Moreover, if the possibility distribution functions are compatible and all of them are equally reliable, then the standard fuzzy intersection operator, [10], can validly be applied to obtain the joint distribution functions, for each node; i.e.:

$$\mu_{\hat{\mathbf{P}}_\mathbf{i}}(\mathbf{P_i}) = \min_{\left\{\begin{smallmatrix} p_{n_i+1}=g_1(\mathbf{P_i}) \\ \vdots \\ p_{n_p}=g_{n_e}(\mathbf{P_i}) \end{smallmatrix}\right.} \left\{ \mu_{\hat{P}_1}(p_1), \mu_{\hat{P}_2}(p_2), \ldots, \mu_{\hat{P}_{np}}\left(p_{n_p}\right) \right\} \qquad (6)$$

Moreover, from a deterministic viewpoint, the harmonic voltage, v_j, at node j is generally a function of the n_p parameters, then:

$$v_j = f_j\left(p_1,.., p_{n_i}, g_1(p_1,.., p_{n_i}),.., g_{n_e}(p_1,.., p_{n_i})\right) \qquad (7)$$

Therefore, according to the extension principle, [9], the possibility distribution of v_j can be written as:

$$\text{pos}(v_j) = \max_{\left\{\begin{smallmatrix} f_j(\mathbf{P})=v_j \\ p_{n_i+1}=g_1(\mathbf{P_i}) \\ \vdots \\ p_{n_p}=g_{n_e}(\mathbf{P_i}) \end{smallmatrix}\right.} \left[\min\left\{ \mu_{\hat{P}_1}(p_1), \ldots, \mu_{\hat{P}_{np}}\left(p_{n_p}\right) \right\} \right] \qquad (8)$$

and the α-cuts (for definition see [9]) of the possibility distribution of the harmonic voltage magnitude, $\hat{V}_j$, may be determined by solving the following optimization problems:

$$\begin{aligned} \underline{v}_j^{(\alpha)} &= \min\left[f_j\left(p_1,.., p_{n_p}\right) \right] \\ \overline{v}_j^{(\alpha)} &= \max\left[f_j\left(p_1,.., p_{n_p}\right) \right] \end{aligned} \qquad (9)$$

Both subject to:

$$\begin{cases} \underline{p}_1^{(\alpha)} \le p_1 \le \overline{p}_1^{(\alpha)} \\ \vdots \\ \underline{p}_{n_p}^{(\alpha)} \le p_{n_p} \le \overline{p}^{(\alpha)} \\ p_{n_i+1} = g_1(p_{n_1}..p_{n_i}) \\ \vdots \\ p_{n_i+n_d} = g_{n_d}(p_{n_1}..p_{n_i}) \end{cases} \qquad (10)$$

For reasons of space, the possibilistic harmonic load-flow algorithm is not presented in this paper, but the reader can find it in figure 4 of reference [12].

C. Fuzzy Modeling of Linear and Non-linear Loads

The methodology to calculate the possibilistic harmonic load-flow is summarized above. However, for its suitable implementation, it is important to establish an appropriate set of parameters p_k, k=1…n_p, to describe the information available with regard some features of loads and wind generators, thus allowing to compute the admittances from node to ground, and the harmonic currents injected at the node.

Main steps for developing a nodal model are: 1) define the circuit which models the harmonic load behavior, 2) select a set of fuzzy parameters describing the available information with respect to the composition and magnitude of loads and wind generators (these parameters are called model parameters, and differ from the electric circuit parameters identified in the first step), 3) establish the relationships between model and the circuit parameters.

General model of the aggregated load for harmonic analysis: several studies suggest the electric circuit shown in Fig. 5, [13], as a suitable model for harmonic load-flow calculation; where each branch represents the sum of loads with similar characteristics. This model also allows the inclusion of the wind generator as an RL branch and a harmonic current source:

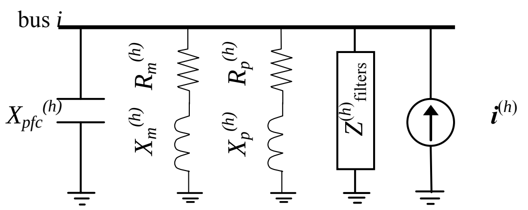


Fig. 5. General model of the aggregated load at a node of the PS

where $X_{pfc}^{(h)}$ models capacitors for power factor correction. $R_m^{(h)}$ and $X_m^{(h)}$ model rotating machinery. $R_p^{(h)}$ and $X_p^{(h)}$ model passive loads and small engines. $\boldsymbol{i}^{(h)}$ models harmonic currents injected by nonlinear devices (rectifiers, inverters, etc.); and filters model the RLC circuits installed to filter harmonics.

Fuzzy parameters: The circuit parameters in the load model of Fig. 5 are uncertain and, in principle, could be described through their possibility functions. In practice, however, the available information usually refers to other characteristics of the load, the wind generator, and the environment, e.g., total active and reactive power, the percentage of it due to nonlinear devices, the wind speed, etc. Table II shows the model parameters, which are usually available in practice. These model parameters, together the appropriate expressions, allow to compute the parameters of the circuit in Fig. 5.

Relationships between the model parameters and the aggregated load parameters: For each harmonic frequency, nonlinear loads are represented by current sources at their respective nodes, and link the model parameters by means of expressions as (1) and (2). In addition, the model for the harmonic current injected by a wind turbine corresponds to that presented in Section III.

Regarding linear loads, detailed expressions which relate the model parameters with the elements of the aggregate circuit of Fig. 5, are presented in the Appendix (Section 8) of reference [12].

TABLE II
FUZZY PARAMETERS TO ESTIMATE THE HARMONIC NODAL MODEL

Parameter	Description
$\upsilon_{wind,j}$	Wind speed (mps) at node *j*
$P_{t,j}^{(1)}$	Active power at fundamental frequency at node *j*
$Q_{t,j}^{(1)}$	Reactive power at fundamental frequency at node *j*
$K_{p,j}$	Composition factor of passive loads (fraction of the passive load in the total active bus load) at node *j*
$pf_{p,j}$	Power factor of passive loads at node *j*
$K_{m,j}$	Composition factor of motive loads (fraction of the motive load in the total active bus load) at node *j*
$pf_{m,j}$	Power factor of motive loads at node *j*
$K_{nl,j}$	Composition factor of nonlinear load(s) (fraction of the nonlinear load in the total active bus load) at node *j*
$pf_{nl,j}$	Power factor of nonlinear load(s) at node *j*
Kf	Installed factor, which can be estimated from the rated motor power factor, pfm, i.e., *Kf*=1/pfm. (typically, *Kf*= 1.2)
X_{LR}	Locked rotor reactance in pu (typically $0.15pu \le X_{LR} \le 0.25pu$)
fq_{LR}	Quality factor of the locked rotor circuit. From experience, this value is approximately 8
$ang_{nl,j}^{(h)}$	Phase angles of the harmonic currents injected at node *j* (for the aggregate model several small and medium power devices)
$Q_{pfc,j}^{(1)}$	Reactive power due to the capacitors for power factor correction, at fundamental frequency, at node *j*

V. Case Study

D. Description of the Electric Power System

The test system is presented in Fig. 6. Main parameters of the power system are summarized in [15]. Furthermore, in Fig. 7 of reference [12], the values of the parameters (which are known with uncertainty) to model aggregated harmonic loads and sources are presented. I.e. these uncertain parameters are modeled through triangular possibility distributions, and the values reported in [10] and [12] are the same employed for this case study. The only difference is that a 20 MW wind farm of ten generators, each one of 2 MW, is included at the generation bus 2. Moreover, it is assumed that wind speed is known with uncertainty, and that it can vary between 5 mps and 20 mps. Under other wind speed conditions, the generators are turned off, due to security reasons.

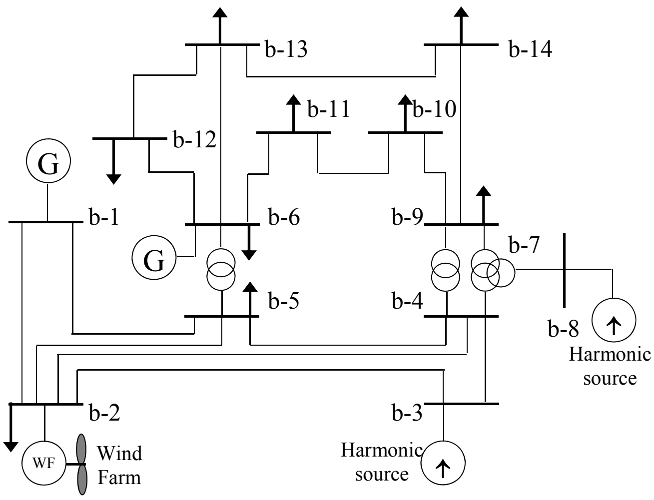


Fig. 6. IEEE 14-bus standard test system for harmonic analysis.

E. Results

The aim of simulation is to compare the results obtained both cases: *i)* the case in which the generator at bus 2 corresponds to a synchronous machine that does not inject harmonics into the network (this case corresponds with that reported in reference [12]), and *ii)* the proposed case in this article, in which generator at bus 2 is replaced by 10 FPC-type wind generators, each one of 2 MW.

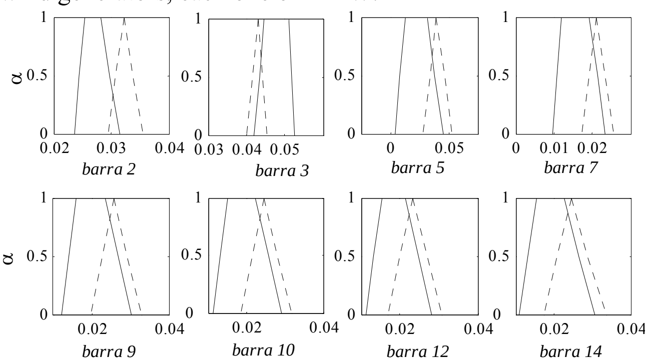


Fig. 7. Per unit 5th order harmonic voltage magnitude at buses 2, 3, 5, 7, 9, 10, 12 and 14. Dotted lines indicate the Possibility functions obtained in [12]; i.e. case *i*. Continuous lines indicate the Possibility functions obtained in case *ii*, i.e., by considering the wind farm at bus 2, and assessing the influence of the variability of the wind speed between the interval [5 mps – 20 mps].

F. Discussion

From results presented in Fig. 7, it can be concluded that the wind farm connection impacts over the 5th harmonic voltage magnitudes at all buses of the power system. In particular, in most of the buses, there is a decrease in the harmonic distortion, surely due to phasorial cancellation between the harmonic currents flowing through the network. However, this situation is different at bus 3, where the harmonic voltage distortion increases considerably and reaches levels that can be intolerable from the electromagnetic compatibility point of view.

It can also be noted that obtained possibility distributions, in the case *ii*, are trapezoidal. This is the result of modeling the uncertainty related to the wind speed as an interval, unlike the other uncertain parameters which are modeled with triangular possibility distributions. It is therefore concluded that involve uncertainty in the wind speed; i.e., an input parameter, has a considerable effect on the uncertainties associated with the harmonic voltage magnitudes, i.e., the outputs of the possibilistic harmonic load-flow.

VI. Conclusions

This work has been focused on including the wind-turbine FPC type within the methodology for calculating the possibilistic harmonic load-flow. The methodology is able to consider the uncertainties due to the deficiency of information regarding harmonic sources and the magnitude and composition of linear loads; i.e., wind turbines, nonlinear devices, and conventional loads.

The Possibility Theory has been selected to model uncertainty, because it seems to be an interesting alternative for situations where the information is too vague to define reliable probability distributions; a common situation in the context of harmonic studies.

The possibilistic harmonic load-flow has shown flexibility allowing in a simple way to include wind farms as harmonic sources. In fact, the reformulated method has been proven in the IEEE 14-bus standard test system for harmonic analysis.

In order to evaluate the performance of the proposal, a comparison with previously published simulations, in which wind farms were not considered, was performed in this article. Obtained results show that involve uncertainty in the wind speed has a considerable effect on the uncertainties associated with the computed harmonic voltage magnitudes, therefore this uncertainty must be considered when harmonic studies must be developed.

It is hoped that the methodology developed contributes to the solution of real problems related with harmonics in electric power systems. For example, problems such as decision making under uncertainty, harmonic filter design, harmonic filters and capacitors location, analysis of the impact of the connection wind farms, among others.

In future work, research efforts must be conducted for the development of harmonic models for other types of wind turbines, e.g., DFIG type wind turbines, and its inclusion in the possibilistic harmonic load-flow method.

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