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Harmonic Power Flow and the operating characteristics of the Virtual Power Plants

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ABSTRACT

The virtual power plants represent entities to act on the operational characteristics of the system through the aggregation of different types of energy generation sources, facilitating the integration and the reliability of the virtual power to these loads, distribution networks and microgrids, defined as an entity in the energy market through the agent that interacts with the centralized network. By defining the scaling and aggregation parameters of several types of energy generation, the contribution of harmonic components generation in wind and solar energy sources stands out among the technical and economic aspects defined in the analysis of electric power quality to be included in the demand for the virtual power plant.

Index Terms: Virtual Power Plants, Renewable Energy Source, Transmission System, Harmonics, Nonlinear Load, Harmonic Power Flow, Total Harmonic Distortion.

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I. INTRODUCTION

In the last century, we have seen the development of the electric power system incorporating fossil fuel generation far away from its end users, supplemented by high voltage power transmission lines suppressing the demand needed to supply through a power distribution network low voltage to thousands of consumers. This aspect led to several scientific developments directed to the evolution of specific norms, imposing a diversification in the generation of electric energy with power plants aimed at serving decentralized or "distributed" generation (DG).

Distributed generation (DG) guides the production of electricity to places closer to consumers, representing a significant and comprehensive change in terms of electric energy in the expectations of several nations. With this, the possibility of a total revolution in the electric power system, transformed end users of electricity consumers to producers and managers. The term "Distributed Energy Resources" ("DERs") recognizes that distributed assets come in many forms. These include demand response (DR), all forms of distributed generation, and even storage if it can be a reasonable cost, and commercially extended. Greater reliance on DER would be a significant deviation from the current structure of the electrical industry. DERs help the grid by increasing grid reliability and resilience, making the grid less vulnerable to prolonged power failures. More diversified, distributed and renewable electricity system has widely known benefits.

In recent years, there has been another important trend in the electric sector: the emergence of the "Smart Grid". Broadly speaking, this involves two different goals: smart technologies to reform the electrical system and provide consumers with new applications for the fabrication, use and conservation of electricity. The relationship between Smart Grid and DERs involves all domains of the electricity transmission and distribution system.

Virtual Power Plants (VPPs) appear as a magnificent idea that involves aggregating DERs to provide a quantity of resources that can and do serve as a functional equivalent of a traditional power plant. The relationship with the DERs makes the VPP a significant energy potential, acting as a resource equivalent to a conventional plant, and may reduce the demand for fossil fuel power plants, a directive that avoids generating electricity or buying it from less economically attractive markets.

The imposition that the virtual power plants act only to meet the economic requirements has been widely questioned. The virtual power plants are referred to in two reference activities: technical plants and commercial plants, and those of the first type seek to meet the standardization of electric power systems by providing the required energy demand for each load requested by implementing the quantitative and qualitative requirements imposed by incremental variations. In order to meet technical flexibility seeking scalability in the electric energy market, the concept of VPP has also been applied to micro-cogeneration agglomerates, overlapping with massive electric storage (MES) and the provision of benefits between systems and stakeholders.

Growing concern about environmental issues and the advancement of electronic power technology has resulted in the rapid development of energy production using renewable energy sources (RES). These natural resources play an important role in the generation of aggregate energy systems to virtual power plants and one of the most promising energy resources today is wind and solar energy. Wind energy is one of the optimistic sources of energy generation among all RES. Now, day-to-day energy demand is rising rapidly due to population growth and economic development in the world, leading to increased environmental impact on conventional power plants. Therefore, RES should be used to meet energy demand and have community development and to prolong growth [1]. Harmonic load flow calculations can be performed on a deterministic basis, assuming that all relevant parameters are well known and not random. However, such studies provide a certain and static picture of a varied and uncertain situation. In fact, the network configuration usually changes, and its linear and nonlinear loads vary all the time. Moreover, even if they were constant, their parameters are generally not well known [2]. All these characteristics make harmonic distortion a phenomenon that involves uncertainty. Therefore, harmonic power flow studies are important in quantifying the distortion of voltage and current waveforms at various points in a transmission and distribution system. The results are useful for corrective measures and problem solving caused by harmonics.

The analysis of the harmonic power flow is performed basically to determine the existence of dangerous resonant conditions and verify their conformity with the standard harmonic limit [3]. Energy flow calculations are performed more frequently by electric power utilities for static operating conditions such as contingency analysis, system safety assessment, optimized dispatch and dynamic operating conditions such as stability analysis of power systems. A great deal of work was done in the formulation of methods for conducting power flow studies. Energy flow studies usually involve digital computers used as a tool to solve constant load flow equations [4]. The result of a power flow study is the magnitude and phase angle of the voltage on each bus, active and reactive power in each line. Another important information obtained from the study of power flow is the loss of active and reactive power of the system.

II. VPP DEFINITIONS

Virtual Power Plants present their concept [5] based on the fact that these are composed of aggregations of distributed generation units (DGs) allied to a variation of technologies with the functionality of operating with a single source of energy, having the differential of to control the demand of electric power produced by the aggregate units and to manage the flow of electric energy between the different units with the mission of obtaining a better operation of the system.

One feature is the flexible representation of a Distributed Energy Resource Portfolio (DER) that can be used to contract in the wholesale market and to provide services to the system operator, together with an information and communication system with centralized control over aggregation of GDs, controllable loads and storage devices. An aggregation of DERs including different DER technologies, reactive loads and storage devices which, when integrated, have similar flexibility and control capability to large conventional plants. The Virtual Power Plants control system acts to classify dispatchable and non-dispatchable DGs, energy storage elements and controllable loads accompanied by information and communication technologies to form a single imaginary plant that plans, monitors operation, and coordinates energy flows among its components, minimize generation costs, minimize greenhouse gas production, maximize profits and improve trade within the electricity market, as well as, promote the direct performance of the maximization of electric power composite quality in the flow of power between the manageable aggregate units associated to the harmonic power flow as a significant and promising part in structuring the functionalities expected by the control systems.

III. POWER QUALITY ECONOMICS

The intermittent nature of a volatile characteristic without definition of a reserve margin in the origin of generation of renewable energy sources (RE), specifically solar and wind energy, has an impact on the bases of operations and organization of the system, including voltage and frequency, harmonics and power quality (PQ) in general, and influences the overall performance of the electric power network as the distribution network (DN). Inverters connected to RE sources, nonlinear client loads and electronic energy devices introduce harmonics into the distribution network that cause transformer overheating, tripping of circuit breakers, and shortens the life of connected equipment [24-27]. Therefore, harmonics are one of the attributes, among the deficiencies of the most dominant electrical power systems that need to be kept to a minimum to guarantee the PQ of the network. Significant technological innovation research and development work is done by various agencies and institutions around the world to investigate and mitigate harmonics in power system networks.

They conclude from their results that the impacts of harmonic costs are not as quantified and complete as to determine the cost impacts of disruptions. The cost to end users occurs when harmonic currents increase the normal load and increase the losses of electric power to the load in their distribution systems. Higher losses reduce the system's power capacity, including conductors, transformers and motors. An example of losses are hysteresis losses, the electrical material develops losses that relate directly to the waveform frequency of the magnetic flux, including the effect of harmonics. These losses, called eddy current losses, are generated by the currents induced in the ferromagnetic core when it is traveled by a time-varying magnetic flux. The variation of the magnetic flux produces an electric field along a closed path (Faraday's Law), and since this path has an associated electrical conductivity, current rings (through the passing relation) are formed. The increased load generates heat and accelerates the aging of power equipment such as transformers and motors. Other harmonic cost impacts include noise and vibration, reduced motor torque, reduced power factor, reduced performance of television sets and relays, and inaccurate readings of watt-hour induction meters. Virtual power plants and utilities incur costs for harmonic currents similar to end-user costs.

They experience voltage distortions that affect the operation of their equipment and cause greater loss of energy in overhead conductors, underground cables and transformers. Increasing the load from the harmonic currents also accelerates the aging of utility transformers and generators. The main aspect that influences the concessionaires, with respect to the impact offered by the harmonics in the electric energy systems, is that it generally reduces its transformers and generators by up to 25% because of the additional heating of the harmonics. Some utilities are setting harmonic limits for their clients based on the IEEE Standard 519-1992. Others are installing special recipe meters to charge their customers for harmonics. Utilities and end users can spend from $ 4,000 to $ 5,000 or more to conduct the engineering study to analyze harmonic problems at their facility and determine cost-effective solutions.

IV. ECONOMICS TERMS OF VIRTUAL POWER PLANTS

The Virtual Power Plant (VPP) has become the focus of one of the highest levels of influence in recent years. A VPP is a complete yet flexible representation of a portfolio of Distributed Energy Resources (DER), ie: distributed generation, determination of required demand and storage of electricity [29]. One of the main activities of a VPP is the provision of (almost) real-time balancing services, for example: provision of reserve regulatory power to the TSO, providing active network management services to the DSO or minimizing the unbalance costs of a commercial part To operate this (almost) real-time coordination activity in an optimized way and constant updating of procedures and goals aimed at operational improvement, VPP is necessary to maintain a dynamic list of order of merit, based on several relevant specific and characteristic aspects, of all DER participants [30].

To make optimal decisions based on this list, the merit order should be based on the actual marginal cost (or marginal benefit in the case of demand response, where decision makers analyze the relevance of cost and output variables such as units of demand produced, to develop the information systems of how profitability behaves based on incremental changes in these variables.) of the individual DER units. The marginal electricity costs of most types of DER are directly related and affected by that of the local context and thus suffer variation over time. For example, the marginal cost of producing electricity for cogeneration is directly related to the amount of heat demanded by the unit at a given moment: when the demand for heat is high, the marginal cost for the production of electricity is low and vice-versa. Generally, VPPs consist of a large number of generators, responsive loads, and storage units. The marginal cost level of the units participating in the VPP may vary over time.

Hence the dynamic nature of the VPP merit request list. There is a class of DER units for which, under circumstances, the marginal cost level can not be determined unambiguously. The control system looks for bid / offer strategies based on the marginal cost for flexible DER units in VPPs that use marginal cost mechanisms to establish dynamic lists of merit order. From the microeconomic point of view, DER units are presumed to participate in a competitive market. This hypothesis holds that, generally, the number of DER units in a VPP is relatively high and its volumes traded are of the same order of magnitude. A competitive market is not characterized in its fundamental formation based on speculative or arbitrary values, and the best (dominant) development structure for each participant is to optimize its own utility, actually offering its marginal cost.

These optimal local developer aspects lead to a list of merit requests that result in optimal allocation at the global level. The DERs that are best suited, by virtue of the merit requirements themselves, to respond to a given event are the first to be selected to do so. Economic analysis encompasses the determination of momentary marginal costs provided by distributed generators and the momentary marginal benefits of demand-responsive resources. Showing the existence of a bid development training spectrum and determining the position of certain real-world RER configurations on this spectrum. Initially, it seeks to identify the true growth potential of the system due to the relevant characteristics in the virtual plant. It is through scalability that one can find out if the formation of the virtual plant could generate the necessary billing to return the investment made at the beginning of the operation. Scalability is also one of the criteria most analyzed by investors. Mutual funds and other traders observe very carefully the scalability of the systems to be aggregated. They are able to reduce uncertainty levels and more accurately assess business returns over the next few years. Considering the mechanism of current entrepreneurship, scalability has been increasingly valued. A set of results over ten years in terms of capital described per unit value of each quota is presented in figure 1, characterizing the scalability and stability of the investment.

Figure 1: Stock Chart.

V. Power System Quantities under Nonsinusoidal Conditions

Based on the analysis of the harmonic distortions in the electric energy systems, some basic elements of the electric power system such as rms, power (reactive, active, apparent) [12,33], power factor, and phase sequences are defined for the fundamental frequency context in a pure sinusoidal condition, considering a linear network with periodic voltage, in general, it is possible to write for distorted voltages and currents:

$v(t) = V_o+V_{1m}+\sin(\omega t + \phi_1) + \sum_{h=2}^{\infty} V_{hm} \sin(h\,\omega t + \phi_h)$ (1)

$i(t) = I_o+I_{1m}+\sin(\omega t + \theta_1) + \sum_{h=2}^{\infty} I_{hm} \sin(h\,\omega t + \theta_h)$ (2)

Consider a voltage *v(t)* and current *i(t)* expressed in terms of its RMS harmonic components,

$v(t) = \alpha_o + \sum_{k=1}^{\infty}[\alpha_k \sin(k\,\omega_o + \phi_k)]$ (3)

$i(t) = c_o + \sum_{k=1}^{\infty}[c_k \sin(k\,\omega_o + \theta_k)]$ (4)

The active and reactive power is given by flowing equations:

$P = \alpha_o\, c_o+\sum_{k=1}^{\infty}[\alpha_k\, c_k \cos(\theta_k - \phi_k)]$ (5)

$Q = \sum_{k=1}^{\infty}[\alpha_k\, c_k \sin(\theta_k - \phi_k)]$ (6)

The apparent power level is given by equation:

$S = \sqrt{(\sum_{k=1}^{\infty} \alpha_k^2).(\sum_{l=1}^{\infty} \alpha_l^2)}$ (7)

In the case of sinusoidal *v(t)* and *i(t)*, the *S* is become:

$S^2 = P^2+Q^2$ (8)

However in non sinusoidal case equation (6) does not hold well, the discrepancy is termed as distortion (D):

$D=\sqrt{S^2 - P^2 - Q^2}$ (9)

The RMS value of a pure sinusoidal voltage wave form (VRMS) is defined by:

$V_{RMS} = V_{1RMS}$ (10)

Where,

$V_{1RMS}=\sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_{1max}^2\, sin^2(\omega t).dt}$ (11)

$V_{1RMS} = \frac{V_{1max}}{\sqrt{2}}$ (12)

The RMS value of a non-sinusoidal voltage waveform ($V_{NS.RMS}^2$) is defined as:

$V_{NS.RMS}^2 = \frac{1}{2\pi}\int_0^{2\pi} v^2(t).dt$ (13)

$V_{NS.RMS}^2 = \frac{1}{2\pi}\int_0^{2\pi}[V_{1max}\ \sin(\omega t + \varphi_1) + V_{2max}\ \sin(2\omega t + \varphi_2) + \cdots + V_{nmax}\ \sin(\omega t + \varphi_n)].dt$ (14)

Where, φ_n is phase angle of n harmonic, and n is rang of harmonic.

$V_{NS.RMS}^2 = \frac{V_{1max}^2}{2} + \frac{V_{2max}^2}{2} + \cdots + \frac{V_{nmax}^2}{2}$ (15)

Simplifying the above equation results in:

$V_{NS.RMS} = \sqrt{\frac{V_{1RMS}^2+V_{2RMS}^2+\cdots+V_{nRMS}^2}{2}}$ (16)

The total harmonic distortion (THD) quantifies the thermal effect of all the harmonic.

1) Power factor of the fundamental [14,38]

$pf_1 = \frac{P_1}{S_1}$ (17)

Active power of up to three harmonics:

$P_x = V_x I_x cos(\varphi_x - \gamma_x)$, x = 2, 3,…, N (18)

$P_y = V_y I_y cos(\varphi_y - \gamma_y)$, y = 2, 3,…, N (19)

$P_z = V_z I_z cos(\varphi_z - \gamma_z)$, z = 2, 3,…, N (20)

• Reactive power of up to three harmonics:

$Q_x = V_x I_x sin(\varphi_x - \gamma_x)$, x = 2, 3,…, N (21)

$Q_y = V_y I_y sin(\varphi_y - \gamma_y)$, y = 2, 3,…, N (22)

$Q_z = V_z I_z sin(\varphi_z - \gamma_z)$, z = 2, 3,…, N (23)

• Apparent power of up to three harmonics:

$S_x = V_x I_x$, x = 2, 3, …, N (24)

$S_y = V_y I_y$, y = 2 , 3, …, N (25)

$S_z = V_z I_z$, z = 2, 3, …, N (26)

• Power factor of up to three harmonics:

$pf_x = \frac{P_x}{S_x}$, x = 2, 3,…, N (27)

$pf_y = \frac{P_y}{S_y}$, y = 2, 3,…, N (28)

$pf_z = \frac{P_z}{S_z}$, z = 2, 3,…, N (29)

Total harmonic distortion of the phase current

$(THD)_I = \frac{\sqrt{I^2 - I_1^2}}{I_1}$ (30)

• Total harmonic distortion of the phase voltage

$(THD)_V = \frac{\sqrt{V^2 - V_1^2}}{V_1}$ (31)

2) Three-phase systems with nonsinusoidal and unbalanced conditions.

For each time interval *i*, the effective voltage and current are recorded; moreover, the fundamental component is separated from the total harmonics component [36], that is

$V_{ei}^2 = V_{e1i}^2 + V_{eHi}^2$ and $I_{ei}^2 = I_{e1i}^2 + I_{eHi}^2$

Where $V_{eHi} = \sqrt{\sum_{h\neq1}^{\infty} V_{ehi}^2}$ and $I_{eHi} = \sqrt{\sum_{h\neq1}^{\infty} I_{ehi}^2}$

The total effective apparent Power squared is

$S_e^2 = 9V_e I_e = \frac{9}{v^2}\sum_{i=1}^{v}(V_{ei})^2 \sum_{i=1}^{v}(I_{ei})^2 = \frac{9}{v^2}[\sum_{i=1}^{v}(V_{e1i}^+)^2 \sum_{i=1}^{v}(I_{e1i}^+)^2 + \sum_{i=1}^{v}(V_{e1i}^+)^2 \sum_{i=1}^{v} I_{eHi}^2 + \sum_{i=1}^{v} V_{eHi}^2 \sum_{i=1}^{v}(I_{e1i}^+)^2 +$

i=1vVeHi2i=1vIeHi2

The first term is due to the contributions of the fundamental voltage and current and hás exactly the same terms as Equation.

$\frac{9}{v^2}\sum_{i=1}^{v}(V_{e1i}^+)^2 \sum_{i=1}^{v}(I_{e1i}^+)^2 = (\overline{P_1^+})^2 + (\overline{Q_1^+})^2 + (\overline{S_{1u}})^2 + D_{1R}^2$

The second term is due to the interaction between the fundamental voltages and the harmonic currents

$\frac{9}{v^2}\sum_{i=1}^{v}(V_{e1i}^+)^2 \sum_{i=1}^{v} I_{eHi}^2 = (\overline{D_l})^2 + D_{1R}^2$

With

$\overline{D_l} = \frac{1}{v^2}\sum_{i=1}^{v} 3\, V_{e1i} I_{eHi}$ and $D_{lR} = \sqrt{\frac{9}{v}\sum_{1\leq n<m\leq v}^{v}(V_{e1m} I_{eHn} - V_{e1n} I_{eHm})^2}$

Being the current distorion power and the randomness current distortion power, respectively. The third term is due to the interaction between the harmonic voltages and the fundamental currents

$\frac{9}{v^2}\sum_{i=1}^{v} V_{eHi}^2 \sum_{i=1}^{v} I_{e1i}^2 = (\overline{D_v})^2 + D_{vR}^2$

With

$\overline{D_l} = \frac{1}{v^2}\sum_{i=1}^{v} 3\, V_{eHi} I_{e1i}$ and $D_{VR} = \sqrt{\frac{9}{v}\sum_{1\leq n<m\leq v}^{v}(V_{eHm} I_{e1n} - V_{eHn} I_{e1m})^2}$

Being the voltage distortion power and the randomness voltage distortion.

The fourth term is due to the interaction between the harmonic voltages and the harmonic currents

$\frac{9}{v^2}\sum_{i=1}^{v} V_{eHi}^2 \sum_{i=1}^{v} I_{e1i}^2 = (\overline{S_H})^2 + D_{HR}^2$

With

$\overline{S_H} = \frac{1}{v^2}\sum_{i=1}^{v} 3\, V_{eHi}\, I_{eHi}$ and $D_{HR} = \sqrt{\frac{9}{v}\sum_{1\leq n<m\leq v}(V_{eHm}\, I_{eHn} - V_{eHn} I_{eHm})^2}$

The harmonic active power $\overline{P_H}$ and the non-active harmonic power $\overline{N_H}$ make up the total harmonic apparent power $\overline{S_H}$. Finally, the apparent power squared can be resolved using the expression

$S_e^2 = \left(\overline{S_1^+}\right)^2 + (\overline{S_{1u}})^2 + (\overline{D_l})^2 + (\overline{D_V})^2 + (\overline{S_H})^2 + D_R^2$

Where

$$D_R = \sqrt{D_{1R}^2 + D_{lR}^2 + D_{VR}^2 + D_{HR}^2}$$

In the total randomness power.

VI. HARMONIC POWER FLOW

The formulation of the harmonic power flow [34] problem differs from the fundamental load flow because it includes harmonic generating loads. Detailed load models for line switched circuits and non-linear resistors are included. The terminal voltages of the defined non-linear loads are represented by their Series and are related to their input currents by these models.

The non-linear loads [13] are analyzed as current sources connected to the power distribution system. The initial prediction of injected currents and terminal voltages for non-linear loads [35] if harmonic distorted energy generation sources are obtained from the model data based on specified loads and sources. Because reactances are frequency dependent, the energy distribution system has both self and mutual for the fundamental and also for each harmonic frequency of the current injected. Although these admittance matrices only relate the currents in a given frequency at the same frequency, the response of the system voltage to a harmonic frequency may be related to the current injected at a different frequency.

In addition, the voltage distortion caused by injected harmonic currents will affect the injected current, necessitating an iterative solution. The Newton-Raphson iterative method is reformulated to include frequencies. Additional equations are needed to solve the harmonic node voltages. The equations are based on the current law of Kirchhoffs and conservation of apparent power, where appropriate.

The harmonic power flow formulation extends these equations to include nonlinear resistors and variety of parameter combinations for line-switched circuits not included in the development.

Considering that the detailed formulation of the equations is beyond the scope of this study, the general results are stated here for completeness. For a node system n with m nonlinear buses, the linear buses are numbered from a to m - 1. The oscillating bus is the numbered linear bus. Non-linear buses are numbered from m to n. The odd harmonics do not triplen from five to L are considered.

The active and reactive power balance is:

$[\Delta W] = [J^{(1)}\ J^{(5)} \ldots J^{(L)}][\ \Delta V^{(1)}\ \Delta V^{(5)} \ldots \Delta V^{(L)}]^T$

Where $[\Delta W] = \begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}$, $[\Delta V^{(k)}] = \begin{bmatrix}\Delta\delta^{(k)}\\ \Delta|V^{(k)}|\end{bmatrix}$, and the superscript k indicates harmonic order. The Jacobian fundamental, $J^{(1)}$, is the same as the square matrix in equation.

$P_n = \sum_{k=1}^{N} |V_n V_k Y_{nk}| \cos(\theta_{nk} + \delta_k - \delta_n)$ (32)

$Q_n = -\sum_{k=1}^{N} |V_n V_k Y_{nk}| \sin(\theta_{nk} + \delta_k - \delta_n)$ (33)

Partial derivatives of equations (32) and (33) evaluated with k^{th} harmonic the values of the frequency components are used to construct the Jacobian harmonic $J^{(k)}$.

The non-linear device models use two state variables, α and β. The change in state variables to an iteration are defined to be

$[\Delta\phi] = [\Delta\alpha_m\, \Delta\alpha_{m+1} \ldots\ \Delta\alpha_n \mid \Delta\beta_m\, \Delta\beta_{m+1} \ldots\ \Delta\beta_n]$

The k^{th} harmonic current injected at node t has real and imaginary parts $g_{t,r}^{(k)}$ and $g_{t,i}^{(k)}$, respectively, where m≤t ≤n. The partial derivatives of nonlinear device currents with respect to nonlinear device state variables at the k^{th} harmonic are:

$$H^{(k)} = \text{diag}\begin{bmatrix} \frac{\partial g_{t,r}^{(k)}}{\partial \alpha_t} & \frac{\partial g_{t,r}^{(k)}}{\partial \beta_t} \\ \frac{\partial g_{t,i}^{(k)}}{\partial \alpha_t} & \frac{\partial g_{t,i}^{(k)}}{\partial \beta_t} \end{bmatrix}$$

The harmonic jacobian that relates the k^{th} and J^{th} harmonics is indicated by $YG^{(k,j)}$ and is defined as

$$YG^{(k,j)} = \begin{cases} Y^{(k,k)} + G^{(k,k)}, k = j \\ G^{(k,j)}, k \neq j \end{cases}$$

where $Y^{(k,k)}$ is an array containing partial derivatives of the k^{th} harmonic of injection currents with respect to the k^{th} harmonic bus voltages derived from the system admittance matrix. The partial derivatives of the k^{th} harmonic device currents with respect to the J^{th} harmonic applied voltages are derived from the nonlinear device models and form the matrix

$$G^{(k,j)} = \begin{bmatrix} O_{2(m-1),2(m-1)} & O_{2(m-1),2n} \\ O_{2n,2(m-1)} & diag\begin{bmatrix} \frac{\partial g_{t,r}^{(k)}}{V_t^j \partial \theta_t^{(i)}} & \frac{\partial g_{t,r}^{(k)}}{\partial V_t^{(i)}} \\ \frac{\partial g_{t,i}^{(k)}}{V_t^j \partial \theta_t^{(j)}} & \frac{\partial g_{t,i}^{(k)}}{\partial V_t^{(j)}} \end{bmatrix} \end{bmatrix}$$

where, $V_t^{(k)}$ and $\theta_t^{(k)}$ are the k^{th} harmonic voltage magnitude and phase angle at the t^{th} bus, $O_{i,j}$ is an ixj matrix of zeros, and m≤ t ≤n.

If h harmonics in addition to the fundamental are considered, the set of 2n(l +h) + 3m nonlinear equations in matrix form is

$$\begin{bmatrix} \Delta\bar{W} \\ \Delta\bar{I}^{(1)} \\ \Delta\bar{I}^{(5)} \\ \vdots \\ \Delta\bar{I}^{(L)} \end{bmatrix} = \begin{bmatrix} \bar{J}^{(1)} & \bar{J}^{(5)} & \cdots & \bar{J}^{(L)} & 0 \\ \overline{YG}^{(1,1)} & \overline{YG}^{(1,5)} & \cdots & \overline{YG}^{(1,L)} & \bar{H}^{(1)} \\ \overline{YG}^{(5,1)} & \overline{YG}^{(5,5)} & \cdots & \overline{YG}^{(5,L)} & \bar{H}^{(5)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \overline{YG}^{(L,1)} & \overline{YG}^{(L,5)} & \cdots & \overline{YG}^{(L,L)} & \bar{H}^{(L)} \end{bmatrix} \begin{bmatrix} \Delta\bar{V}^{(1)} \\ \Delta\bar{V}^{(5)} \\ \vdots \\ \Delta\bar{V}^{(L)} \\ \Delta\phi \end{bmatrix} \quad (34)$$

These equations are solved in much the same way as the fundamental load flow equations of the previous section are solved. An initial guess is made at the harmonic voltages and nonlinear device state variables. The power and currents are evaluated with the estimated values. Changes in voltages and state variables are computed from equation (34). With each iteration, the voltage and state variable estimates are up dated with the computed values until the change in power and currents decay to the specified tolerance.

The solution speed and memory requirements depend heavily on the system because of the large number of sparsely populated matrices.

VII. MATHEMATICAL FORMULATION OF AN ALGORITHM

The Algorithm is based on dispatch unit governance in order to track the production of intermittent units and dispatch full power according to contracts with the DSO (distribution system operator), depending on the requests placed in the VPP [9]. The model developed is valid for an arbitrary number of controllable and intermittent generators as well as their location in the distribution network. While the entire network, with its appropriate loads and intermittent sources, has the same time versus energy characteristics in all case studies (including the base case), the algorithm changes its settings according to the specific demands and lists the fundamental parameters to establish a better level of energy quality based on values of harmonic distortion provided. the monitoring and planning systems can create scenarios that use slightly different versions of the same algorithm, whose cumulative characteristics can be summarized below. The flowchart of the VPP algorithm is shown in Figure 2.

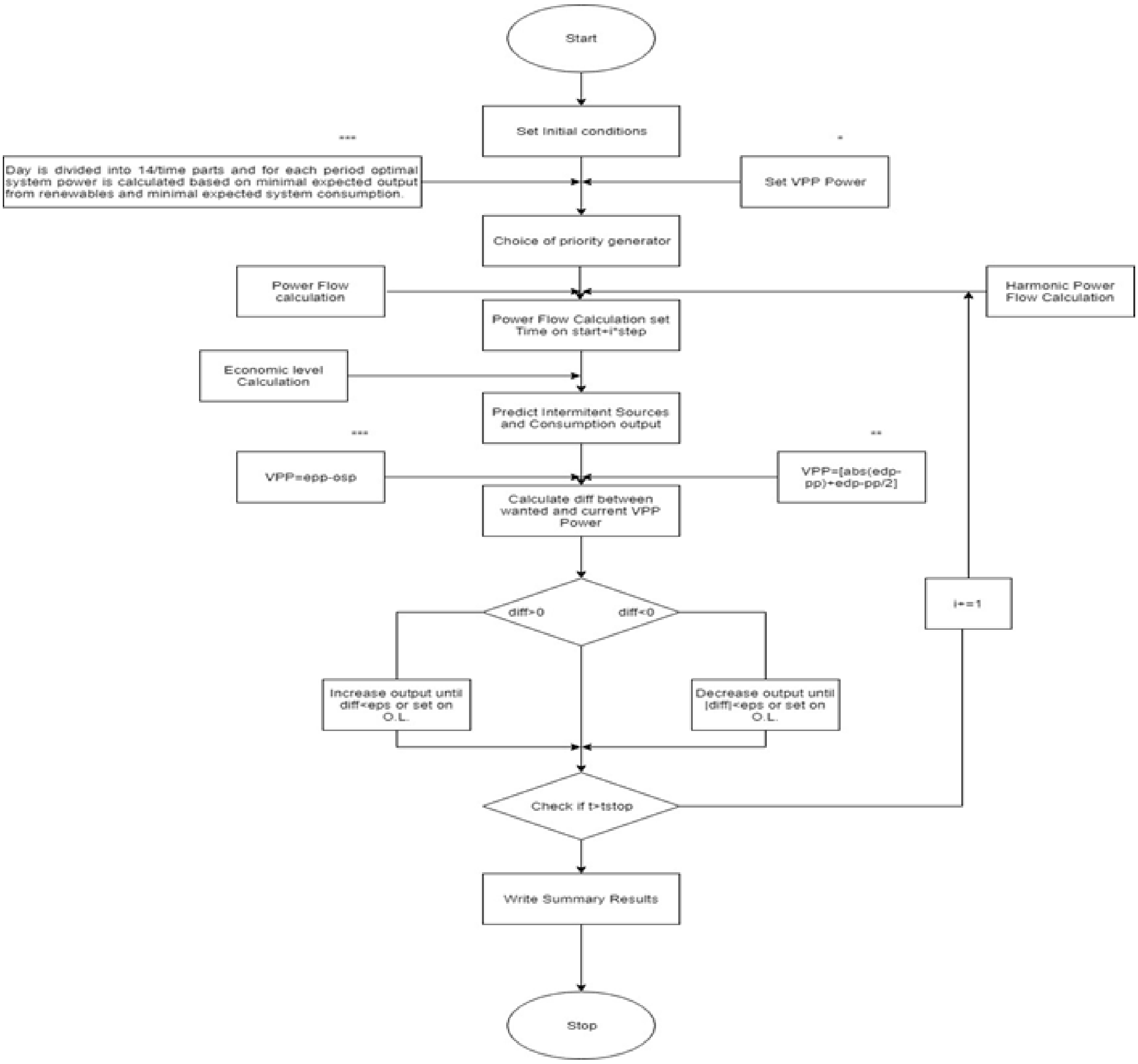

Figure 2: The flowchart of the VPP algorithm.

1) Starting, stopping and passing time in units of time are being transported to an algorithm through a basic graphical user interface of the corresponding script. By default, the values of the previously mentioned variables are started with previously set values (which corresponds to a sampling time of 10 minutes). Also the epsilon value that the algorithm uses to optimize the dispatch accuracy of controllable generators is initially set to a fixed value as well as the initial dispatch conditions for each controllable generator that is adjusted.

2) From the start time, after each start + i × step and finally with the stop time, a LoadFlow calculation is performed along with the harmonic power flow, and the relevant aspects relating to the calculation of the economic level show the differential conditions of each generating unit to be incorporated into the system in order to reach the specified goals for economic development.

3) The assumption is that an algorithm, based on past experience and statistical data, has a perception of network consumption expectancy in future periods with minor or major error. The similar type of approach can also be used for active power output from intermittent sources, based on the weather forecast. Error, for both meteorological conditions (lighting, wind) and consumption forecast is solved with normal distribution (Gaussian), which is the most common practice in the description of load uncertainty or wind energy, where $\sigma > 0$ is the standard deviation, and μ is the expected value, read from the external file (forecast) for this case.

4) Based on the actual iteration values and predicted iteration values after the active, an algorithm calculates the difference between the desired active power in the next step and the currently generated power: diff = power - (TotGen + wt - wtold + pv - pvold).

5) The final step is to optimize the output of controllable generators, by increasing or decreasing the output of controllable generators, depending on the diff > 0 or diff < 0: the desired power of the VPP is currently higher than the output of the generators be increased. If the desired power is unachievable, the dispatch is set to the maximum level. In two other cases, the desired power can be achieved by manipulating the primary unit, or by configuring the main unit to the maximum level and by manipulating the secondary unit. The PmO, PMO, SmO and SMO main motor unit regulators denote the minimum and maximum active power available from the primary and secondary generator, respectively. PG and SG are calculation parameters, while power and ren are the current power of VPP and renewable output, respectively. Differences in VPP steering solution could be depicted in a flowchart diagram (figure 2). In scenarios, blocks that differentiate the control logic are marked by *, ** and *** respectively.

VIII. SIMULATION

The impact of harmonic distortions due to the integration of potentially disturbing loads that has a participation in the analysis of harmonic power flow [37] and influence the evaluations considered in the variables of formation of the management algorithm of the electric power system integrated to the virtual power plant can be measured in 13.8 [kV], which is a function of the connection of a new load to an industrial consumer in the foundry sector, considering the representation of the main loads connected to the Interconnected Distribution System (IDS) in 13.8 [kV].

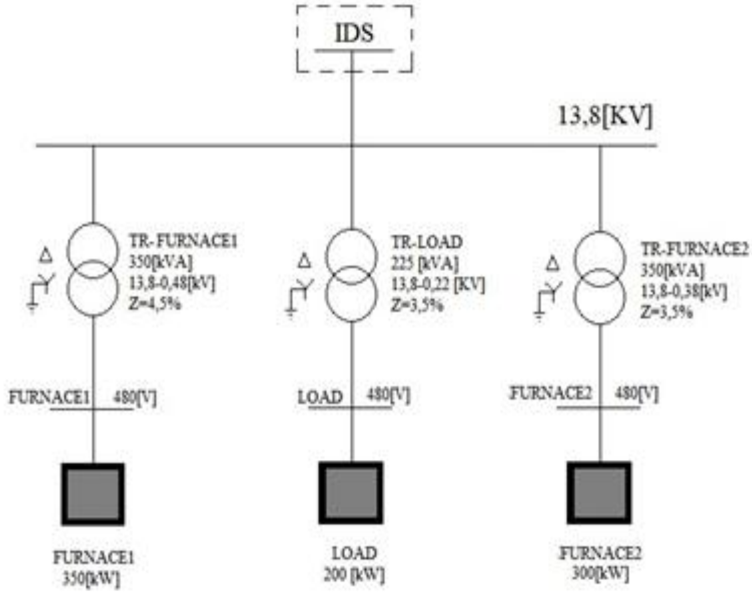

Figure 3: Loads connected to the distribuition system.

The Figure 4 shows respectively the harmonic spectrum resulting from the current shown in figure 3, noting the characteristic harmonic components especially in the full load operating condition. The results of the simulation presented were performed by the electromagnetic transient program (ATPDRAW).

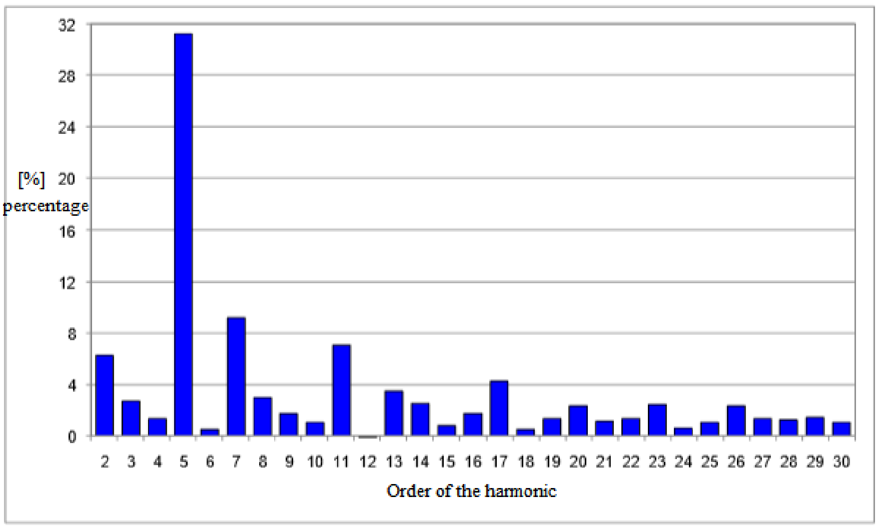

Figure 4: Harmonic spectrum.

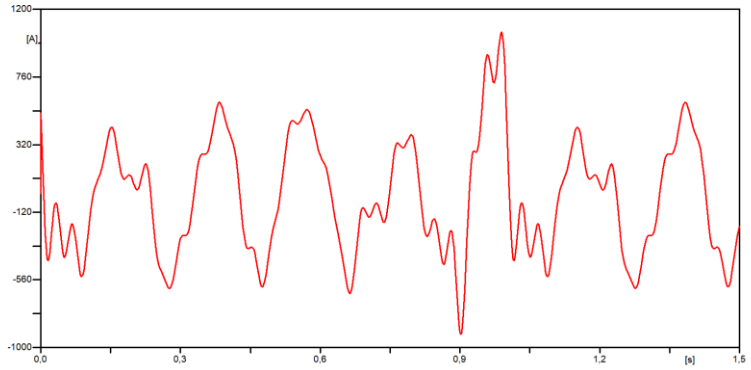

Figure 5: Load current.

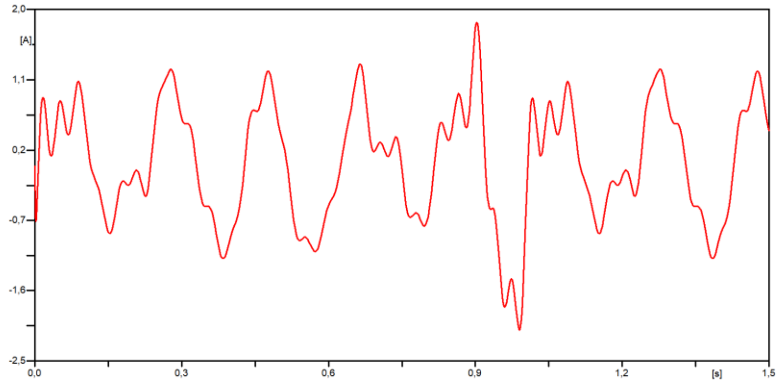

Figure 6: IDS current.

The analysis of the harmonic power flow shows the variation of the harmonic distortion propagated in the common coupling point, which can reflect as the main influence of the impact of loads to be coupled in the virtual power plant, being able to be quantified in function of variables and parameters made available in the operations of the entire electric energy system made up of several sources of harmonic distortion, such as these loads presented and power inverters in renewable energy sources, making it possible to include in the computer systems managers the improvement through the best aspects of energy quality available.

CONCLUSION

Among the main aspects related to this article are the impacts of the penetration of renewable energy sources in voltage buses, voltage THD and order values of three harmonics are investigated for a virtual plant using a Newton Raphson method based on the harmonic power flow . From the method studied, it can be observed that the addition of RES in the network directly impacts the RMS value of voltage, harmonic order and THD factor. The fundamental voltage is improved and depends on the energy penetration of the RES system; also the RES injection has a significant impact on the harmonic reduction and the value of THD. Other research cases related to multiple sources of renewable energy connected to the grid and aggregated to the virtual power plant are currently under investigation and preparation for future improvements in electric power systems that seek reliability and, above all, electric power quality, to interact directly with the conditions of economic variation of the generating structures to be incorporated to the system, defining real parameters expressed in editable variables and adhering to the general algorithm of the system control of the system greater level of potential in economic growth and with that greater reliability to the generation system with quality of electric energy formed by the Virtual Power Plant.

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