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COMPARISON OF DIFFERENT PARAMETERS FOR THE ANALYSIS OF ELECTRICAL POWER SYSTEMS UNDER NONSINUSOIDAL CONDITIONS

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Abstract – In modern power systems the hypothesis of pure sinusoidal waveforms is less and less realistic. The removal of this hypothesis has both theoretical and practical consequences. Some classical electrical quantities lose their physical meaning and do not provide useful information. On the other hand, new parameters may be introduced in order to characterize a system under nonsinusoidal conditions. A relevant feature of such parameters should consist in the measurement of the non-fundamental power and in the evaluation of the distortion introduced by loads. This paper presents analytical and experimental considerations about classical and new parameters suitable for the analysis of nonsinusoidal systems. Some tools like Fault Function, Amplitude Harmonic Distortion, Distortion Power and Instantaneous Power Harmonics are proposed in this paper for the first time. The considered parameters may be divided in two general classes: single-harmonic based parameters and global parameters.

Keywords: harmonics, measurement systems, nonsinusoidal systems.

1. INTRODUCTION

The classical electrical quantities used in power systems were introduced to deal with sinusoidal waveforms. New parameters suitable to characterize electrical systems even under nonsinusoidal conditions should be introduced for both theoretical and practical reasons.

As far as theoretical aspects are concerned, every electrical or electronic system may be approached starting from Maxwell Equations, but the analysis would be too complicate, since infinite parameters should be considered. Therefore some hypotheses are commonly introduced in order to reduce the required parameters. Typical restrictive hypotheses imply that the waveforms are periodical and sinusoidal; the loads are linear and constant. The removal of these restrictions allows to extend the analysis to more generalized situations.

In particular, the proliferation of non-linear and time-variant loads makes the hypothesis of pure sinusoidal voltage and current less and less realistic.

In fact, important changes have occurred in the last years [1]. Personal Computers and power electronics equipment, such as Adjustable Speed Drives, Controlled Rectifiers, Arc and Induction Furnaces, spread in industrial and commercial environments. Due to the finite source impedance, the distortion and the unbalance of such loads propagate through the Point of Common Coupling (PCC) that feeds several loads and create disturbances for the utility and the end-user's equipment.

Accordingly, users should be charged depending on their actual harmonics, along with their active and reactive fundamental power.

Since the traditional instrumentation designed for the sinusoidal waveform is no longer suitable, new metering facilities should be developed. They should be based on microprocessors, Analog-to-Digital Conversion (ADC), Data Acquisition (DAQ), and Digital Signal Processing (DSP). Moreover they should be able to manage quantities and parameters suitable for nonsinusoidal analysis.

Some classical electrical quantities lose their physical meaning or they are not able to provide any useful information.

Many authors tried to extend the significance of such quantities to more general situations. According to other authors these attempts are doomed to fail, since the new conditions are not simply the extension of the sinusoidal ones. Therefore new parameters should be specifically defined.

This paper presents theoretical and experimental considerations about classical and new parameters for measurement and analysis on nonsinusoidal systems. Some parameters were already proposed in literature, other ones are proposed for the first time.

An useful quantity should feature: the evaluation of the electrical state of a system, the classification of the loads, the identification of the actual distorting sections, the metering of the power exchange that is not limited to only one frequency and of the direction.

The parameters are divided in two general classes: Single-Harmonic-Based (SHB) parameters and global parameters. The global parameters concentrate the information about several harmonics.

2. GENERAL MODEL OF THE POWER SYSTEM

An electrical system under nonsinusoidal conditions can be modelled by means of the measurable electrical quantities, as shown in fig. 1.

The equivalent circuit in fig. 1 may be applied for each load connected to the PCC, but it is valid for more general configurations.

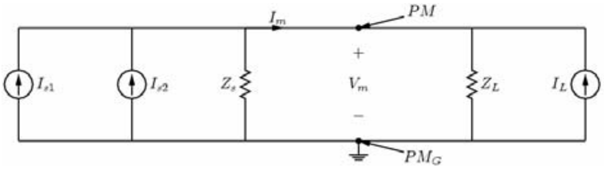

Fig. 1. Equivalent circuit for voltage and current measurement on a generic power system.

In this scheme, for each load, only one point of the net is accessible for the measurement: the Point of Measurement (PM). Fig. 1 also shows the reference ground for the measured voltage (PM_G)

All the elements on the right side of the PM act as a Norton equivalent source. The current generator I_L models the distorting effect of the considered load. The impedance Z_L represents the linear behavior of the same load.

I_{s1}, I_{s2} and Z_s include all the elements on the left side of the measuring point. The generator I_{s1} is the power source of the system. It is a pure sinewave at the fundamental frequency (50 or 60 Hz). For symmetry considerations, also this power supply was modelled with a Norton rather than with a Thevenin equivalent circuit.

I_{s2} includes the non-linear effects of all the loads, except Z_L, connected to the power supply, along with the components at non-fundamental frequency that the supply could insert in the system.

Z_s is the parallel of all the impedances on the left side of PM. It includes the internal impedance of the power supply.

Practically, only V_m and I_m can be measured (at the PM), producing an apparent power S_m.

3. SINGLE HARMONIC BASED PARAMETERS

The SHB analysis applies for the situation shown in fig. 2. Each parameter refers to one harmonic that normally is not the fundamental. With this simplification the system is absolutely linear.

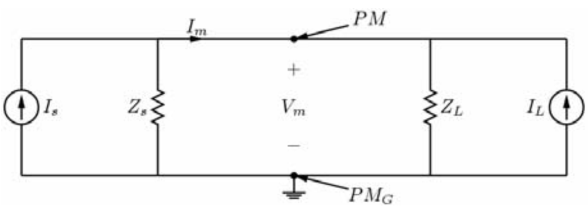

Fig. 2. Equivalent circuit for SHB measurement.

The measured voltage is:

$$V_m = k_p \cdot I_s + k_p \cdot I_L \quad (1)$$

where k_p is the parallel of the two impedances:

$$k_p = \frac{Z_s \cdot Z_L}{Z_s + Z_L} \quad (2)$$

More in general k_p is a fundamental parameter of the electrical network: it is the parallel of all the existing impedances. The influence of each equivalent current generator depends on such parameter.

However this influence also depends on the phase φ between I_s and I_L:

$$|V_m| = |k_p|\sqrt{|I_s|^2 + |I_L|^2 + 2|I_s||I_L|\cos\varphi} \quad (3)$$

The measured current is:

$$I_m = \frac{k_p}{Z_L} \cdot I_s - \frac{k_p}{Z_s} \cdot I_L \quad (4)$$

3.1. Fault function

When every quantity in Fig.2 is known, several criteria may be adopted in order to classify the weight of a source for the presence of a harmonic component.

A reasonable and widespread parameter is the amplitude of the harmonic current I_L, which actually differs from I_m.

We think that is very useful to consider not only the amplitude of I_L, but the detrimental effect on the actual circuit and in particular on the voltage V_m, since V_m supplies all the loads. The "fault" could be related to a V_m percentage given by the Fault Function F:

$$F = \frac{|I_L|}{|I_s|} \quad (5)$$

In practice, when a particular harmonic is recognized, a load should pay for a percentage given from the product:

$$|V_m| \cdot \left(1 + \frac{1}{F}\right) \quad (6)$$

Since the measured voltage $|V_m|$ depends on φ too, and k_p that is the same for each load, a user could determine the φ that minimizes the effect of his own I_L. For example, if $I_L = -I_s$ then $V_m = 0$, even for $I_L \neq 0$.

3.2. Active power

It is well-known that the active power represents an energy flow. This physical meaning is valid only for the fundamental frequency.

The measured P_m (namely, the P_m derived from V_m and I_m), if I_L has a zero phase displacement and $I_s = |I_s| e^{-j\varphi}$, is:

$$P_m = |k_p|^2 \cdot \left\{ |I_s|^2 \frac{R_L}{|Z_L|^2} - |I_L|^2 \frac{R_s}{|Z_s|^2} + |I_s| \cdot |I_L| \cdot \right.$$

$$\left. \cdot \left[\left(\frac{R_L}{|Z_L|^2} - \frac{R_s}{|Z_s|^2} \right) \cos\varphi - \left(\frac{X_L}{|Z_L|^2} - \frac{X_s}{|Z_s|^2} \right) \sin\varphi \right] \right\} \quad (7)$$

Thus P_m is the sum of three terms:

$$P_m = P_s - P_L + P_\varphi \quad (8)$$

where P_m and P_s are the active powers that each source would generate without the other one. P_φ is the oscillating component of P_m; it is related to P_s and P_L but it oscillates with φ.

When there is only one source, the sign of P_m follows the direction of the distortion power and its value is significative. With additional sources, the sign shows only that a source exists, but it could be lower than the active power indicates.

Therefore the sign of P_m doesn't provide any indication about the main harmonic source.

Actually, the relationship between power and current (or voltage) is not linear: the power of the sum is different from the sum of the powers.

The parameter F regulates the amplitude of the oscillations, but P_m may refer to very different F.

The function $P_m(\varphi)$ is a sinusoidal waveform. Obviously, the harmonic strength depends not only on generator values but also on the impedances Z_s e Z_L. Anyway a user can be charged because he connects impedance (since he already pays for the relative active and reactive power).

Further information could be derived from the knowledge of Z_s e Z_L, but it is practically impossible. Moreover it should be done for every interesting frequency.

It is useful to remember that usually active power is calculated by means of digital samples. Therefore, the length and the type of the adopted window affect the measured value.

3.3 Critical parameters

Since the parameters F shows the contribution of a load on a harmonic, it is necessary to individuate the situations that could lead to unreliable information.

From the above considerations it is evident that the phase affects every possible evaluation of P_m and F. The effect is more effective when the absolute value of P_φ is greater.

The maximum and the minimum of the function P_φ can be found for critical values of the phase φ_{cr}:

$$\varphi_{cr} = \arctan\left(\frac{R_s |Z_L|^2 - R_L |Z_s|^2}{X_L \cdot |Z_s|^2 + X_s \cdot |Z_L|^2} \right) \pm \pi \quad (9)$$

F_{cr} (critical) is the minimum value of F for which (7) is zero.

Two distinct φ_{cr} can be derived from (9). The first φ_{cr} provides $P_m=0$ with P_s-$P_L>0$, the other one with P_s-$P_L<0$. In these values of φ, P_φ reaches its maximum. In these cases, F_{cr} gives $P_m=0$, namely:

$$F_{cr} = \frac{\pm |b| \pm \sqrt{b^2 + 4\dfrac{R_s \cdot R_L}{|Z_s|^2 \cdot |Z_L|^2}}}{2\dfrac{R_S}{|Z_s|^2}}$$

(10)

where b is

$$b = \pm \frac{\sqrt{\left(R_s|Z_L|^2 + R_L|Z_s|^2\right)^2 + \left(X_L|Z_s|^2 + X_s|Z_L|^2\right)^2}}{|Z_L|^2 |Z_s|^2} \quad (11)$$

Therefore the amplitude of the oscillations of the active power is $|P_\varphi|=|k_p b I_s I_L|$.

The solutions are ever real (and different) but two of them are negative (the ones with the minus before the root). One positive solution F_{cr} is valid for P_s-$P_L>0$ (F'_{cr}), the other one for P_s-$P_L<0$ (F''_{cr}), but obviously the φ_{cr} changes.

By introducing the well-known approximation

$$\sqrt{1+x} = 1 + \frac{1}{2}x + \frac{1}{8}x^2 + ... \quad (12)$$

and arresting it to the first order, the lower F_{cr} in (10) may be rewritten as:

$$F_{cr} = \frac{R_L |Z_s|^2}{\sqrt{\left(R_s|Z_L|^2 + R_L|Z_s|^2\right)^2 + \left(X_L|Z_s|^2 + X_s|Z_L|^2\right)^2}} \quad (13)$$

It is important to stress out that the function $I_L = f(I_s)$ is linear:

$$I_L = F_{cr} \cdot I_s \quad (14)$$

for all the currents.

In correspondence with the critical parameters φ_{cr} and F_{cr}, P_φ reaches its maximum and its minimum and $P_m=0$.

The sign of P_m is reliable only in the interval defined by the two possible critical values:

$$F'_{cr} < F < F''_{cr} \quad (15)$$

The fault of a source I_L can't be extended beyond the lower F_{cr}.

The formulae (10) and (13) represent an analytical expression for F_{cr}, but they could be experimentally determined. Indeed, it is constant for every value of current generators. Therefore F_{cr} is the ratio of the measured variation of two generators (one must be the considered load) that maintain $P_m = 0$.

3.4. Influence of the critical parameters on the Fault Function

When a real P_m is measured, there is a particular relationship $I_L=f(I_s)$, different from the critical case $P_m=0$. This relationship is:

$$|I_L| = \frac{\pm|I_s||b| \pm \sqrt{|I_s|^2 b^2 + 4\frac{R_s}{|Z_s|^2}\left(\frac{|I_s|^2 R_L}{Z_L^2} - \frac{P_m}{|k_p|^2}\right)^2}}{2\frac{R_s}{|Z_s|^2}} \quad (16)$$

The second sign must be positive. It is significative to consider $P_m<0$, namely the load seems to be responsible for the distortion. Using the linear approximation as in (13):

$$F = F_{cr} + f \cdot \frac{P_m}{|I_s|^2} + F_0 \quad (17)$$

The parameter f is another parameter of the actual power system and it may be viewed as an incremental fault function:

$$f = \frac{(Z_s + Z_L)^2}{\sqrt{\left(R_s|Z_L|^2 + R_L|Z_s|^2\right)^2 + \left(X_L|Z_s|^2 + X_s|Z_L|^2\right)^2}} \quad (18)$$

The general expression for F in (17) includes the F_{cr} and other two terms: a term depends on f and it is proportional to P_m/I_s^2. Such term confirms that a high active power P_m may be produced not only by a high I_L, but also by a high I_s. So the actual value of P_m has no significance.

As far as the term F_0 is concerned, the first sign in (16) should be assumed to be negative, in order to consider the minimum fault for the user I_L. In this case $F_0=0$. Otherwise, if the first sign is positive, F_0 is constant, equal to:

$$F_0 = \frac{|b||Z_s|^2}{R_s} \quad (19)$$

3.5. Classical powers and power factor

Active power (P), reactive power (Q), apparent power (S) and power factor (P_F) are important and traditional SHB parameters. Their recent definitions may be found in [1]. However they have physical meaning only for the fundamental frequency.

The active power might be related to a flow of energy for each single harmonic. Anyway, since the influence of φ is relevant and this energy is useful only for some particular devices, it should be considered along with the fundamental active power as a global parameter:

$$P = P_1 + P_H \quad (20)$$

where P_1 is the active power for the fundamental and P_h is the sum of the active power for other components [1]. The harmonic powers may be simply added because they refer to different frequencies.

3.6. Extension to three-phase systems

Most parameters used in single-phase power system can be extended to three-phase systems. This can be done by applying the Clarke-Park transforms. This approach is well-known in literature. For this reason, in this paper only single-phase parameters were introduced.

4. GLOBAL PARAMETERS

4.1. Total Harmonic Distortion

The Total Harmonic Distortion (THD) of the voltage is

$$THD = \sqrt{\frac{\sum_{i=2} |V_i|^2}{|V_1|^2}} \quad (21)$$

Analogously, it may be defined for the current. It is a very popular parameter and it is used in many standards [1].

The variance of THD follows daily, weekly, and seasonal patterns. We recorded these patterns for our Department. Time series and cumulative histograms allow to estimate the probability distributions.

THD is very effective to show the overall deviation of a distorted wave from its fundamental.

4.2 Amplitude Harmonic Distortion

Obviously, THD is intrinsically non-linear. It means that, if the THD produced by a single device is known, it is hard to exploit this value to foresee the THD of a system with two sources of distortion or with a background distortion. To overcome this problem, we introduced the new parameter Amplitude Harmonic Distortion (AHD):

$$AHD = \frac{\sum_{i=2} |V_i|}{|V_1|} \quad (22)$$

The use of AHD allows to obtain the total effect produced by several devices, simply by summing the contribution produced by a single device.

Also AHD is not totally linear. In fact, the total AHD of two devices is influenced by the phase of the equivalent current generators (see (3)). This phase is different for each harmonic. The AHD may be simply summed for devices that produce harmonics at different frequencies.

It is possible to conclude that AHD is linear, if the average effect on a set of situations is considered.

In order to confirm the validity of the index, we developed a Virtual Instrument that is able to estimate it for a device, also in a non-ideal electrical environment, through the statistical mean of n samples (with and without the device).

The AHD was measured in several cases: for example, when two device of the same type are connected to the same line, the AHD was about twice. Moreover, an empirical formula was derived: it foresee the AHD value for a line with any type of load, through the knowledge of the AHD of all non-linear loads that influence that line.

4.3. Indices for location of distorting sources

Many authors proposed parameters that are useful not only to quantify the deviation of electrical quantity from a reference situation, but also, and especially, to identify the source generating the detrimental effects. We define it Power-Quality Indices (PQI).

The main PQIs that have been tested to provide sound information are summarized in [3]. They are:

$$\eta = \frac{THD_I}{THD_V} \quad (23)$$

$$\xi_{slq} = \frac{P_{m_\Sigma}}{P_{m_{\Sigma+1}}} \quad (24)$$

$$\xi_{HGI} = \frac{\left|I_{\Sigma_L}\right|^2}{\left|I_{\Sigma s}\right|^2} \quad (25)$$

$$v_k = \frac{1}{3}\left(\frac{\xi_{slq_k}^{-1}}{\xi_{slq_s}^{-1}} + \frac{\xi_{HGI_k}}{\xi_{HGI_s}} + \frac{\eta_k}{\eta_s}\right) \quad (26)$$

They are global parameters not only because they include several harmonics. In fact, v_k is more effective if it is simultaneously measured for each line k leaving a PCC.

It is interesting to stress out that PQIs are heavily based on active power and THD. For ξ_{slq} and ξ_{HGI} the considerations about (7) and (8) are still valid. Since η may provide incorrect indication for particular value of load impedance, it is still valid that pure impedances can't be charged for harmonics.

Anyway, the index v_k should be able to average other PQIs and to compensate the different reasons that cause each single index to fail in assessing the responsibility. This was confirmed by some experimental tests.

4.4. Extension of reactive and apparent powers

Many new definitions of reactive (Q) and apparent (S) power were proposed but they aren't able to extend relevant property.

S, according to the definition in [1], can be resolved in five terms:

$$S^2 = S_1{}^2 + P_H{}^2 + D_I{}^2 + D_V{}^2 + D_H{}^2 \quad (27)$$

where S_1 is the fundamental apparent power. The last three terms are other relevant global parameters: the current distortion power D_I, the voltage distortion power D_V and the harmonic distortion power D_H. Their definitions are, respectively:

$$D_I = V_1 \cdot I_H = S_1 \cdot THD_I \quad (28)$$

$$D_V = V_H \cdot I_1 = S_1 \cdot THD_V \quad (29)$$

$$D_H = \sqrt{S_H^2 - P_H^2} \quad (30)$$

In typical situations, $D_I > D_V$. A relevant property of S is that the power loss in the feeder is a nearly linear function of S^2.

We think that the correlation existing between D_I and D_V could provide some indication about the direction of the harmonic flow.

In fact, in fig. 2 the total power produced by components at different frequencies (D_{VI}) is composed by D_I and D_V. The same quantities may be expressed in time-domain: d_{VI}, d_V and d_I.

The power that derives from components at different frequencies produces a "sum" distortion $d_{VI}(h_i+h_1)$ at higher frequency and a "difference" distortion $d_{VI}(h_i-h_1)$ at lower frequency. Each distortion is:

$$d_{VI}(h_i \pm h_1) = d_I(t) \pm d_V(t) \quad (31)$$

When the distortion power comes from the supply (or equivalent circuit) to the load it might be associated to the sum of D_I and D_V. In the opposite direction it is more similar to their difference.

Unfortunately, when the phase difference between D_I and D_V is close to 180°, thus sum and difference may be confused.

4.5 Instantaneous power harmonics

The Fourier transform of the instantaneous power $p_i(t)=v(t)\cdot i(t)$ is $P_i(\omega)=V(\omega)*I(\omega)$, with $P_{i(rms)}=S$. The harmonic analysis of P_i is normally ignored, but, in our opinion, it could be useful.

Odd harmonics can exist only with distortions. So the comparison between even and odd harmonics is meaningful. For example, a relevant parameter is given by the ratio odd/total harmonics (OTR) of P_i:

$$OTR = \frac{\sum_h P_i(2h+1)}{\sum_h P_i(h)} \quad (32)$$

In the same way, other indices may be defined (for example, considering the square of the harmonics).

Actually, it is interesting to stress that also the power factor P_F is based on comparison of two power harmonics ($h=0$ and $h=2$). Accordingly, the analysis of P_i allows to introduce the new concept of harmonic distribution of P_F.

In accordance with the principles of the Physics, it is possible to observe that under nonsinusoidal conditions, the power may be dissipated (active power P), may be stored and returned (reactive power Q), may be transformed in other forms of energy, namely at different frequencies (distortion power D).

Each harmonic of P_i is due to several voltage and current components and corresponds to different types of power, even if there are some overlaps (that exist between active and reactive power too). Non-distorting loads concentrate the power mostly to even harmonics (the dc for a good P_F).

5. MEASUREMENT SYSTEMS

The parameters and algorithms presented in the above paragraphs need to be applied to suitable systems, that should not be identical for every kind of analysis. We imagined three different experimental setups. Each setup is useful for specific parameters.

5.1 Global analysis on power system

We developed a distributed measurement system that allows to process and record electrical quantities for several days. Electrical quantities are conditioned by a power unit and acquired by an Analyzing Recorder Yokogawa AR1100A. A PC controls the system through the LAN or Internet with a GPIB-ENET interface.

Harmonic analysis is carried out by classical FFT algorithm, but for harmonic extraction a time-domain approach based on software PLL (Phase Locked Loop) was preferred. It improves the efficiency, reduces the leakage and avoids considering useless frequencies. Uncertainty evaluation of proposed algorithms was performed with the methods presented in [2].

5.2 Analysis on simulated system

The SHB parameters may be effectively analyzed by means of the simulation (SPICE or SIMULINK) of the circuits in fig. 1 and fig. 2.

The same analysis may be carried out on a real circuit. Since this circuit works at low voltage (less than ±20 V), it is possible to use arbitrary waveform generators as current generators. The IEEE-488 interface allows to control the generators in order to perform automatic measurement. Anyway, due to fixed impedances, the available configurations are limited.

5.3 Simulation of distorting load

The global analysis needs loads that introduce several harmonics at the same time. The test on power system does not allow to control and foresee the disturbances. To overcome this problem, we are developing a controllable harmonic source. It is based on the high-frequency connection/disconnection of loads by means of controlled switches. This facility may be inserted in the low voltage simulated circuits or, with some difficulties, in a power distribution system.

6. CONCLUSION

Several parameters for the analysis of nonsinusoidal system were investigated.

A general scheme was adopted in order to derive the indices from the elements of an equivalent circuit.

The single-harmonic-based parameters are related to each harmonic. The fault function was introduced in order to provide a criterion for the harmonic distortion produced by a load. It was shown that the significance of active power is restricted between critical values of fault function and phase.

Amplitude Harmonic Distortion was proposed as an alternative to Total Harmonic Distortion. It allows to add up the effects of several harmonic sources.

An useful interpretation of the distortion powers was shown too.

The new concept of instantaneous power harmonics was introduced. It associates the harmonic components of the instantaneous power to different kinds of physical energy.

Three distinct experimental approaches was proposed to test different classes of parameters.

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