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Measurement of IEC Groups and Subgroups using Advanced Spectrum Estimation Methods

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Abstract *– IEC Standards characterize the waveform distortions in power systems with the amplitudes of harmonic and interharmonic groups and subgroups. These groups/subgroups utilise the waveform spectral components obtained by using a fixed frequency resolution DFT; while this choice represents a good compromise among different aims such as the need of good accuracy, simplification and unification. In some cases the power system waveforms are characterized by spectral components that the DFT with fixed frequency resolution can not capture with enough accuracy. This paper investigates the possibility of a group/subgroup evaluation using advanced spectrum estimation methods: the adaptive Prony, ESPRIT and root-MUSIC methods. The paper presents also the results of applications of these methods to test waveforms and to waveforms obtained from simulations of a real DC arc furnace plant.*

Keywords *– spectrum estimation, waveform distortion analysis, subspace methods, Prony method, ESPRIT method, MUSIC method, discrete Fourier transform, dc arc furnaces*

I. INTRODUCTION

The quality of voltage waveforms is nowadays an important issue for power system utilities, electric energy users and also for the manufactures of electric and electronic equipments. The main reasons are the increasing number of power quality (PQ) problems linked to the modern power electronic devices, the susceptibility of loads to these problems and the incoming new liberalized competitive markets, where the electric disturbances have significant economic consequences. Among PQ disturbances, the proliferation of nonlinear loads connected to power systems has triggered a growing concern with waveform distortions.

As well known, several indices have been used for the characterization of waveform distortions. They generally refer to periodic signals which allow an "exact" definition of harmonic components and require only a numerical value to characterize them. When the spectral components are time-varying in amplitude and/or in frequency (as in case of non-stationary signals), a misleading use of the term harmonic can arise and several numerical values are needed to characterize the time-varying nature of each spectral component of the signal [1-2].

Additionally, Standards and Recommendations contain indices to characterize the waveform distortions in power systems and methods of measurements and interpretation of results. In particular, the IEC Standards [3-4] introduce the specified signal processing recommendations and definitions. They, for practical purpose, define the harmonic (interharmonic) frequency as an integer (not integer) multiple of the fundamental frequency; then, with reference to a Discrete Fourier Transform (DFT) using a time window of ten (50 Hz) or twelve (60 Hz) fundamental periods. They introduce the concept of harmonic and interharmonic groups and subgroups, characterizing the waveform distortions with the amplitudes of these groupings versus time.

The crucial drawback of the DFT method is that the length of the window is related to the frequency resolution. Moreover, to ensure the accuracy of DFT, the sampling interval of analysis should be an exact integer multiple of the waveform fundamental period [5].

In this paper we propose to estimate the IEC groups and subgroups with some advanced spectrum estimation methods: the Prony, ESPRIT and root-MUSIC methods [6–9]. The advanced methods use an adaptive technique firstly successfully applied in [7] only for Prony method application.

The Prony method is a technique that approximates the sampled data with a linear combination of exponentials and has a close relationship to the least squares linear prediction algorithms used for AR and ARMA parameter estimation.

The ESPRIT and the root-MUSIC methods are based on the linear algebraic concepts of subspaces and so have been called "subspace methods". The model of the signal in this case is a sum of sinusoids in the background of noise of a known covariance function.

The novelty of the proposed approach lies in replacing DFT with advanced spectrum estimation methods, which gives more accurate results when analysing strongly distorted waveforms with non-stationary behaviour. Other approaches exist in the literature aiming at avoid or diminish inherent drawbacks of DFT (e.g. wavelets, filters, windowing techniques). Recently, significant improvements have been proposed in [10 –12].

However, the approach presented in this paper presents significant advantages in terms of high accuracy and is tested on waveforms of practical importance, such as the ones of a typical dc arc furnace.

II. PROPOSED APPROACH

The Adaptive Prony, ESPRIT and root-MUSIC methods (for description of methods see Sect. II.A) are compared to DFT on the basis of the values of the IEC harmonic and interharmonic groups/subgroups (Fig. 1).

As well known [3], the amplitudes of the IEC harmonic and interharmonic subgroups G_{sg-n} and C_{isg-n} can be evaluated, respectively, as:

$$G_{sg-n}^2 = \sum_{k=-1}^{1} C_{10n+k}^2 \qquad C_{isg-n}^2 = \sum_{k=2}^{8} C_{10n+k}^2 \tag{1}$$

where C_{10n+k} are the spectral components (RMS value) of the DFT output by using a window width of 10 fundamental periods, in case of a 50 Hz system to which this paper refers.

The amplitudes of the harmonic and interharmonic groups G_{g-n} and C_{ig-n} can be evaluated, respectively, as:

$$G_{g-n}^2 = \frac{C_{10n-5}^2}{2} + \sum_{k=-4}^{4} C_{10n+k}^2 + \frac{C_{10n+5}^2}{2} \qquad C_{ig-n}^2 = \sum_{k=1}^{9} C_{10n+k}^2 \tag{2}$$

where C_{10n+k} are the spectral components (RMS value) of the DFT output.

Finally, the results are smoothed over 15 intervals of 10 fundamental periods, that is over the whole interval of very short time measurements [4].

In the next section, firstly some advanced methods for spectral components evaluation are presented (Sect. II.A, II.B, II.C): the adaptive Prony, ESPRIT and root-MUSIC methods. Then, it is shown how the relations (1) and (2) should be modified in the framework of the proposed methods (Sect. II.D and II.E). Finally, the proposed approach will be applied to test waveforms and to waveforms typical for dc arc furnace plant (Sect. III).

A. Adaptive Prony Method

Assuming N data samples $\begin{bmatrix} x_1 & x_2 & \cdots & x_N \end{bmatrix}$ the investigated waveform can be approximated by M exponential functions:

$$y[n] = \sum_{k=1}^{M} A_k e^{(\alpha_k + j\omega_k)(n-1)T_s + j\phi_k} \tag{1}$$

where $n = 1, 2, ..., N$, T_s – sampling period, A_k – amplitude, α_k – damping factor, ω_k – angular velocity, ϕ_k – initial phase.

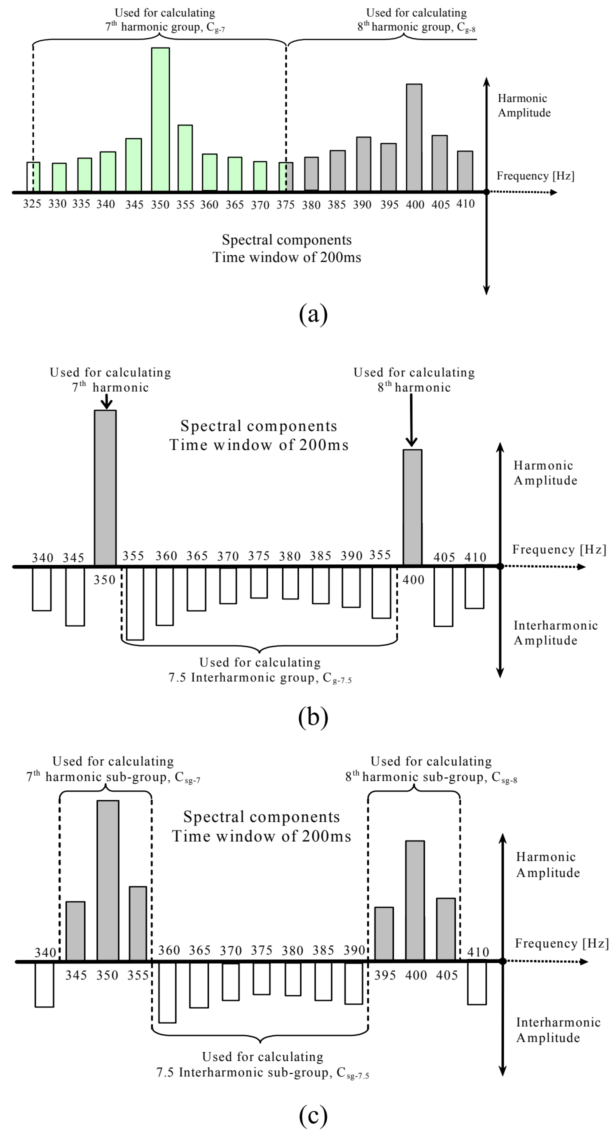


Fig. 1. IEC harmonic ↑and interharmonic ↓ groupings: (a) harmonic groups; (b) interharmonic groups; (c) harmonic and interharmonic subgroups.

The Toeplitz matrix created from samples makes it possible to determine the vector of coefficients ***a*** of the characteristic polynomial:

$$z^M + a_1 z^{M-1} + \ldots a_{M-1} z + a_M = 0 \tag{2}$$

The roots of the characteristic polynomial define the Vandermonde matrix:

$$\mathbf{Z} = \begin{bmatrix} \mathbf{z}_1^0 & \cdots & \mathbf{z}_{M-1}^0 & \mathbf{z}_M^0 \\ \mathbf{z}_1^1 & \cdots & \mathbf{z}_{M-1}^1 & \mathbf{z}_M^1 \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{z}_1^{M-1} & \cdots & \mathbf{z}_{M-1}^{M-1} & \mathbf{z}_M^{M-1} \end{bmatrix} \tag{5}$$

Vector of complex values **H** can be calculated from:

$$\mathbf{Z} \cdot \mathbf{H} = \mathbf{X} \tag{6}$$

where:

$\mathbf{X} = \begin{bmatrix} x_1 & x_2 & \cdots & x_M \end{bmatrix}$.

Parameters of exponential components for k=1, 2,…,M can be calculated from:

$A_k = |\mathbf{h}_k|$ - amplitude, $\alpha_k = f_s \cdot \ln|\mathbf{z}_k|$ - damping factor,

$\omega_k = f_s \cdot \arg(\mathbf{z}_k)$ - angular velocity, $\phi_k = \arg(\mathbf{h}_k)$ - initial phase.

The Adaptive Prony method is a modified version of the Prony method that has been proposed in [7]. The basic idea of Adaptive Prony method consists in applying the Prony method to a number of "*short contiguous time windows*" inside the ten period of fundamental component. The lengths of these short time windows are variable. This variability ensures the best fitting the signal variations along the ten fundamental periods of the waveform. The most adequate short contiguous time windows are obtained by minimizing the waveform estimation error.

B. Adaptive ESPRIT-method

The original ESPRIT algorithm [5] is based on naturally existing shift invariance between the discrete time series, which leads to rotational invariance between the corresponding signal subspaces.

The assumed signal model is the following:

$$y[n] = \sum_{k=1}^{M} A_k e^{(j\omega_k n)} + w[n] \tag{3}$$

where $w[n]$ represents additive noise. The eigenvectors **U** of the autocorrelation matrix of the signal define two subspaces (signal and noise subspaces) by using two selector matrices $\boldsymbol{\Gamma}_1$ and $\boldsymbol{\Gamma}_2$.

$$\mathbf{S}_1 = \boldsymbol{\Gamma}_1 \mathbf{U} \quad \mathbf{S}_2 = \boldsymbol{\Gamma}_2 \mathbf{U} \tag{4}$$

The rotational invariance between both subspaces leads to the equation:

$$\mathbf{S}_1 = \boldsymbol{\Phi} \mathbf{S}_2 \tag{5}$$

where:

$$\boldsymbol{\Phi} = \begin{bmatrix} e^{j\omega_1} & 0 & \cdots & 0 \\ 0 & e^{j\omega_2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e^{j\omega_M} \end{bmatrix} \tag{6}$$

The matrix $\boldsymbol{\Phi}$ contains all information about *M* components' frequencies. Additionally, the TLS (total least-squares) approach assumes that both estimated matrices **S** can contain errors and finds the matrix $\boldsymbol{\Phi}$ as minimization of the Frobenius norm of the error matrix. Amplitudes of the components can be found in similar way as with Prony method, using equation (3).

The analysis of non-stationary signals requires a similar approach as in short time Fourier transform (STFT). The time varying signal is broken up into minor segments with the help of the temporal window function and each segment (with overlapping) is analysed.

In this paper the adaptive techniques proposed in [10] has been applied also to this method. In order to obtain the Adaptive ESPRIT method, once again we apply the ESPRIT method to a number of "*short contiguous time windows*" inside the ten fundamental period. Since the ESPRIT method does not provide any phase estimation of the spectral component, the short contiguous time windows are obtained by minimizing the error between the actual waveform energy content evaluated in time domain and the estimated waveform energy content obtained by using the spectral components in the frequency domain.

C. Adaptive root-MUSIC (Multiple Signal Classification) method

The MUSIC method [5] involves projection of the signal vector onto the entire noise subspace. Matrices of eigenvectors of the autocorrelation matrix $\mathbf{R}_x$ can be divided into signal and noise matrices:

$$\mathbf{E}_{signal} = \begin{bmatrix} \mathbf{e}_1 & \mathbf{e}_2 & \cdots & \mathbf{e}_p \end{bmatrix} \tag{7}$$

$$\mathbf{E}_{noise} = \begin{bmatrix} \mathbf{e}_{p+1} & \mathbf{e}_{p+2} & \cdots & \mathbf{e}_M \end{bmatrix} \tag{8}$$

and, similarly, two matrices of eigenvalues $\Lambda_{signal}, \Lambda_{noise}$ can be built. It is possible then to rewrite $\mathbf{R}_x$ as:

$$\mathbf{R}_x = \mathbf{E}_{signal} \Lambda_{signal} \mathbf{E}_{signal}^{*T} + \mathbf{E}_{noise} \Lambda_{noise} \mathbf{E}_{noise}^{*T} \tag{9}$$

MUSIC method uses only the noise subspace for the estimation of frequencies of sinusoidal components, while ESPRIT method uses only the signal subspace. $\mathbf{E}_{noise}$ can be used to form the polynomial:

$$\hat{P}^{-1}(z) = \sum_{i=p+1}^{M} E_i(z) E_i^*(1/z) \tag{10}$$

which has p double roots lying on the unit circle. These roots correspond also to the frequencies of the signal components. This method of finding the frequencies is therefore called root-MUSIC.

After the calculation of the frequencies, the powers of each component can be estimated from the eigenvalues and eigenvectors of the correlation matrix [5].

The most adequate contiguous short time windows are obtained by minimizing the error between the actual waveform energy content evaluated in time domain and the estimated waveform energy content obtained by using the spectral components in the frequency domain. This approach results in the Adaptive MUSIC method.

D. Calculation of the short harmonic and interharmonic subgroup amplitudes

As previously evidenced, all advanced methods recalled in the previous Sections permit the evaluation of the spectral components of distorted waveforms inside some "short contiguous time windows" along ten periods of fundamental component.

Then, the need to define corresponding "short time harmonic and interharmonic subgroups" arises; they can be defined as the subgroups calculated for a short time window. With reference to the j[th] short contiguous time window, they are given by:

$$G^2_{ssg-n}(j)=\sum_{k=1}^{M_{nsg}} G^2_k(j), \qquad C^2_{issg-n}(j)=\sum_{k=1}^{M_{nisg}} C^2_k(j) \tag{15}$$

where M_{nsg} is the number of spectral components inside the frequency interval [n f_I–7.5, n f_I+7.5] Hz and M_{nisg} is the number of spectral components inside the frequency interval]n f_I+7.5, (n+1) f_I-7.5[Hz. The need to enlarge (with reference to the IEC intervals) the frequency ranges for both harmonic and interharmonic grouping evaluation derives from the absence in the advanced method application of the DFT fixed frequency resolution.

E. Calculation of the harmonic and interharmonic subgroup amplitudes

Once known the "*short time harmonic and interharmonic subgroups*" for all windows inside an interval of ten fundamental periods, the harmonic and interharmonic subgroup amplitudes can be calculated properly by averaging of all the abovementioned short harmonic and interharmonic subgroup amplitudes; it results in:

$$G^2_{sg-n}=\frac{\sum_{j=1}^{N_W} N_W(j)G^2_{ssg-n}(j)}{N_W}, \qquad C^2_{isg-n}=\frac{\sum_{j=1}^{N_W} N_W(j)C^2_{issg-n}(j)}{N_W} \tag{16}$$

where N_W is the number of samples inside ten fundamental periods,

and $N_W(j)$ is the number of samples in the j[th] short contiguous time window.

Finally, the results can be averaged over 15 intervals of ten fundamental periods in order to obtain the results referred to the very short time measurements.

III. NUMERICAL APPLICATIONS

Several numerical experiments were performed. Here, reference is made only to the results of a test waveform and of the current and voltage waveforms at MV busbar of the simulated dc arc furnace plant shown in Fig.2 [13].

In the next two sections, the IEC method, the Adaptive root-MUSIC method, the Adaptive ESPRIT method and the Adaptive Prony method, will be indicated, respectively, as IECM, ARM, AEM and APM.

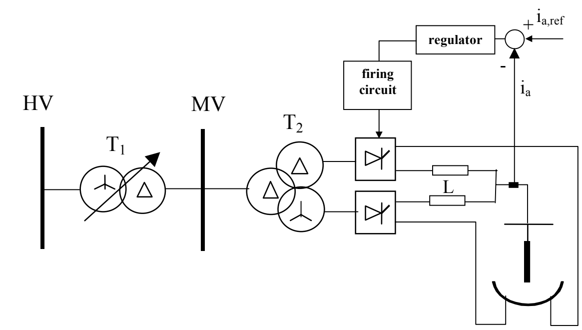


Fig. 2 – Scheme of the DC arc furnace.

A. Test Waveform

The signal under consideration is composed of a harmonic component of amplitude 1 pu at fundamental frequency of 50 Hz and an interharmonic component of amplitude 0.1 pu at frequency 57.4 Hz.

For this case-study the unique harmonic and interharmonic subgroup whose amplitude is different from zero is the first harmonic subgroup and its amplitude $G_{sg,1}$ is equal to 1.005 p.u..

In Table 1 the amplitudes of the harmonic subgroups $G_{sg,1}$ $G_{sg,2}$ and of the interharmonic subgroup $C_{isg,1}$ are reported. The different processing techniques are also compared with an extension of IEC grouping to high resolution spectral analysis performed directly on a 3 s time window without the 15 intermediates step on ten periods of fundamentals [10]. This technique will be named as IEC3sM.

From the analysis of the Table 1 it clearly appears that IEC method suffers from the leakage problems due to the presence of the interharmonic component. Moreover, the IEC3sM does not solve completely this problem. In fact, it gives a not negligible error on the harmonic subgroup $G_{sg,1}$

and a non zero amplitude for the interharmonic subgroup $C_{isg,1}$.

All the adaptive techniques and in particular the Adaptive Prony method perform very well.

Table I. Test waveform: harmonic subgroup amplitudes evaluated over 3s interval by using the different techniques.

	G_{sg-1}	C_{isg-1}	G_{sg-2}
IEC3sM	1.0035	0.0532	0.0000
IECM	1.0031	0.0677	0.0071
ARM	1.0046	0.0000	0.0000
AEM	1.0047	0.0000	0.0000
APM	1.0050	0.0000	0.0000

B. DC Arc Furnace Waveforms

The investigated waveforms originate from the simulation of a real dc arc furnace plant, which scheme is shown in Fig. 2. To simulate the dc arc behaviour a chaotic model has been applied [13].

In order to compare different adaptive techniques (ARM, AEM and APM) with the IEC method the current and voltage waveforms at MV busbar of the dc arc furnace have been analysed.

The following filters have been applied:

a) a bandstop Butterworth IIR filter cuts out the main (50 Hz) component;
b) bandpass Butterworth IIR filters have been applied for selected subgroups.

In Table 2 (Table 3) the most significant harmonic subgroup amplitudes of the current (voltage) waveforms are reported. The most correctly estimated interharmonic subgroup amplitudes of the current (voltage) waveforms are reported in Table 4 (Table 5).

From the analysis of the Tables from 2 to 5, it clearly appears that with reference to the current and voltage harmonic subgroup amplitudes G_{sg11} and G_{sg-13} (Tables 2 and 3), ARM, APM and AEM give higher values than the ones obtained by using the IEC method. On the contrary, the IEC method gives values of the current and voltage harmonic subgroups G_{sg-12} significantly greater than the ones obtained with all the adaptive techniques.

With reference to the current and voltage interharmonic subgroup amplitudes (Tables 4 and 5), all the adaptive methods (ARM, AEM and APM) give values lower than the ones obtained by using the IEC method. Moreover, as foreseeable, the results obtained by using the subspace-based methods (ARM and AEM), in most cases, are similar.

The lower values of the IEC harmonic subgroups G_{sg11} and G_{sg-13} as well as the higher values of the IEC harmonic subgroups and of the IEC harmonic subgroup G_{sg-12} are probably due to the spectral leakage present in the DFT-based algorithm. A part of the harmonic subgroup G_{sg11} and G_{sg-13} energy content is dispersed on contiguous harmonic and interharmonic subgroups.

The different processing techniques have been also compared with the technique based on the extension of IEC grouping to high resolution spectral analysis performed on 3 s (IEC3sM).

As an example, Fig. 3 reports the amplitudes of the same harmonic and interharmonic subgroups obtained with different techniques for the MV current waveforms.

From the analysis of the Fig. 3 it should be noted that the problem of spectral leakage due to the presence of the characteristic harmonics of the twelve pulse bridge is partially reduced by using the IEC3s method.

Table II. Dc arc furnace current waveform: harmonic subgroup amplitudes evaluated over 3s interval by using the different techniques.

	G_{sg-11} [A]	G_{sg-12} [A]	G_{sg-13} [A]
IECM	172.76	12.19	132.28
ARM	180.03	1.19	138.28
AEM	183.43	1.20	139.39
APM	181.10	1.07	135.39

Table III. Dc arc furnace voltage waveform: harmonic subgroup amplitudes evaluated over 3s interval by using the different techniques.

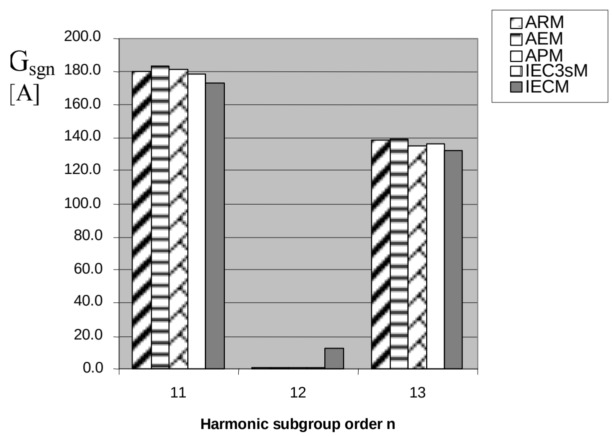
	G_{sg-11} [V]	G_{sg-12} [V]	G_{sg-13} [V]
IECM	335.30	26.83	333.89
ARM	351.12	2.68	348.45
AEM	352.26	2.71	349.24
APM	347.70	2.42	348.65

Table IV. Dc arc furnace current waveform: interharmonic subgroup amplitudes evaluated over 3s interval by using the different techniques.

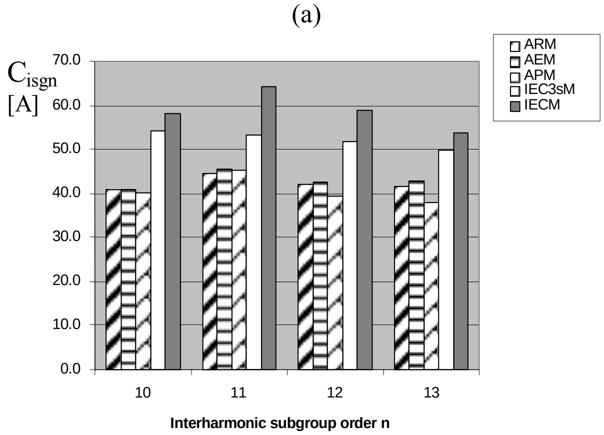
	C_{isg-10} [A]	C_{isg-11} [A]	C_{isg-12} [A]	C_{isg-13} [A]
IECM	58.27	64.17	58.83	53.87
ARM	40.75	44.57	41.98	41.67
AEM	40.84	45.39	42.57	42.72
APM	40.29	45.16	39.35	37.77

Table V. Dc arc furnace voltage waveform: interharmonic subgroup amplitudes evaluated over 3s interval by using the different techniques.

	C_{isg-10} [V]	C_{isg-11} [V]	C_{isg-12} [V]	C_{isg-13} [V]
IECM	109.33	129.43	143.69	139.57
ARM	97.12	90.21	101.75	109.34
AEM	96.19	91.68	103.34	110.65
APM	86.77	84.48	99.51	108.39



(a)



(b)

Fig. 3. Dc arc furnace current waveform: some harmonic (a) and interharmonic (b) subgroup amplitudes.

IV. CONCLUSIONS

In this paper selected advanced spectrum estimation methods are proposed for the evaluation of the harmonic and interharmonic groupings. The techniques are based on the application of Prony, ESPRIT and root-MUSIC methods to a number of short contiguous variable windows inside the ten fundamental periods imposed by IEC Standards as time interval to which the grouping have to be referred. The number and the duration of the short windows are obtained by applying an adaptive algorithm based on the minimization of the estimation error.

The application of the proposed techniques to test defined waveforms and waveforms deriving from simulations of an actual plant has shown very accurate harmonic and interharmonic subgroup estimation.

Even if the use of the IEC Standard technique represents a good compromise among different aims such as the need for good accuracy, simplification and unification, the new proposed approach appears particularly useful for its very high accuracy also in case of particularly complex signals. However, their computational cost is certainly higher than the one of the DFT-based methods.

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