

**WAVEFORM DISTORTIONS DUE TO AC/DC CONVERTERS FEEDING
DC ARC FURNACES**

A. BRACALE, G. CARPINELLI

Università degli Studi di Napoli Federico II
Napoli (Italy)

Z. LEONOWICZ, T. LOBOS, J. REZMER

Wroclaw University of Technology
Wroclaw (Poland)

Abstract – The line-commutated converters cause significant harmonic distortions in electrical power systems. They can operate as a six-pulse converter or configured in parallel arrangement for high-pulse operation; twelve-pulse converters are usually used for DC arc furnaces. The DC arc furnaces can cause time-varying power quality disturbances in the feeding network, mainly waveform distortion and voltage fluctuations. In this paper the problem of the waveform distortion assessment of these important disturbing loads is taken into account. The study is performed using computer simulations based on Power System Blockset, that is a tool of Matlab[®], and using a chaos-based model for simulating the dc arc.

1. INTRODUCTION

AC and DC arc furnaces represent one of the most intensive disturbing loads in the sub-transmission or transmission electric power systems; they are characterized by rapid changes in absorbed powers that occur especially in the initial stage of melting, during which the critical condition of a broken arc may become a short circuit or an open circuit.

In the particular case of the DC arc furnaces, the presence of the AC/DC static converters and the random motion of the electric arc, whose non-linear and time-varying nature is well known, are responsible for dangerous perturbations such as waveform distortions and voltage fluctuations. The converters are current controlled in order to limit current fluctuations in the electrodes.

While several papers in the relevant literature analyse the problem of the waveform distortion assessment in three-phase line-commutated current-controlled converters used in AC and DC

motor drives and in HVDC links [1, 2], only few papers analyse the converters behaviour in DC arc furnaces. Recently in [3] this problem has been considered with the aim to outline the interactions between the converter control system and the AC waveform distortions and voltage fluctuations; the dc arc is simulated with a non-linear resistance whose values have been determined on the basis of measurements of the dc arc voltage.

The aim of this paper is to analyse both the waveform distortions caused by the DC arc furnaces on the feeding network and of the effects caused by the feeding network distortions and unbalances on the AC/DC static converter behaviour. In particular, this analysis uses a chaos-based model to represent the dc arc behaviour; in fact, the chaos theory, i.e. the Chua Circuit, has proven to be an accurate and suitable model for assessing waveform distortions [4]. Moreover, in order to better evidence the time-varying nature of the waveform spectral components, Short Time Fourier Transform and high-resolution methods are applied [5, 6]. Particular attention is paid to outline the interactions between the supply voltage quality and the behaviour of the AC/DC converter control system.

2. DC ARC FURNACE IN STUDY

The typical dc arc furnace plant shown in Fig. 1 is considered as test system in this paper. It consists of a dc arc connected to a medium voltage AC busbar with two parallel thyristor rectifiers that are fed by transformer secondary windings with Δ and Y connection, respectively. The AC/DC converters are controlled with a DC current control system.

The medium voltage busbar is connected to the high voltage busbar with a HV/MV transformer whose windings are Y- Δ connected. The system shown in Fig. 1 has the following parameters [4]:

PCC

Rated voltage: 220 kV

Transformer T₁

Rated power: 80 MVA

Rated voltage: 220kV/21kV

V_{cc} 8%

Winding connection: Y- Δ .

Transformer T₂

Rated power: 87 MVA

Rated voltage: 21kV/0,638kV/0,638kV

V_{cc} 10,37%

Winding connection: Δ - Δ -Y

Interphase reactor: 150 μ H

Arc furnace rated current: 96 kA.

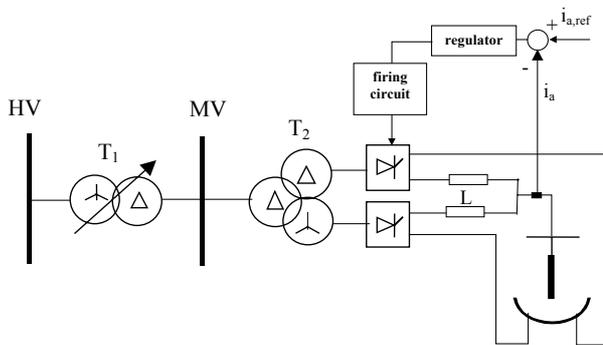


Fig. 1. DC arc furnace plant

In the dc arc furnaces the presence of the ac/dc static converter and the random motion of the electric arc, whose non linear and time-varying nature is known, are responsible for dangerous perturbations, in particular waveform distortions and voltage fluctuations; these perturbations are time-varying. In order to better evidence the waveform distortion problems, neither filters nor reactive compensation devices are initially provided.

3. DC ARC FURNACE MODEL

In this paper, the simulation of the DC arc furnace plant has been developed by means of Power System Blockset, a toolbox of Matlab[®].

A chaos-based model for the dc arc furnace has been used.

In fact, in [4] it has been shown that the DC arc voltage waveform has the irregular behaviour that characterizes every chaotic phenomenon. This has been demonstrated with the analysis of proper

delay plots and the evaluation of the largest Lyapunov exponent.

Some chaos based models have been analysed (Rossler, Chua and Lorenz models) in literature; in this paper, the Chua model has been employed due to its usefulness for waveform distortion forecasting.

The Chua model is based on the following equations:

$$\dot{x} = \begin{cases} \alpha(y - b_2x - (b_2 - a_2)), & \text{if } x < -1 \\ \alpha(y - a_2x), & \text{if } -1 \leq x \leq 1 \\ \alpha(y - b_2x - (a_2 - b_2)), & \text{if } x > 1 \end{cases}$$

$$\dot{y} = x - y + z$$

$$\dot{z} = -\beta y \quad (1)$$

In (1) x, y and z are the state variables and a₂, b₂, α and β the model parameters, whose values have to be set as the most suitable for dc arc simulation. In particular, in this paper the optimal procedure proposed in [4] to set the parameters of the arc model has been applied.

With reference to the AC/DC converter control system, a DC current control system is usually employed. It clearly influences the time variations of the AC side current and voltage waveforms spectral content.

The current control system can be composed by a DC current control loop and a phase lock-loop (PLL) [3].

The DC current control loop acts such that, firstly, the actual output current of the converter is smoothed by a first-order time-delay element. Then, the filtered values are compared with the reference current. The so obtained error is the input of a PI controller that allows the evaluation of the delay control angle for the thyristors.

The PLL provides the reference system for the thyristor control angles of the converters. For this purpose the actual bus voltages are transformed in orthogonal components to evaluate the phase angle which is, in turn, compared with the control variable. The resulting deviation is smoothed and is the input of a PI controller. After comparison with the power system frequency, the control variable (phase angle) is generated by an integrator.

In [3] each of the DC arc furnace converters is provided of a separate current control system.

As an alternative, the reference angle for the thyristor control of the converters can be obtained by filtering the supply three-phase voltage waveforms. Moreover, both AC/DC converters can be controlled with only one current control system.

4. SOME CONSIDERATIONS ON DC ARC FURNACE WAVEFORM DISTORTIONS

The analysis of the current and voltage waveforms on the AC side of a DC arc furnace reveals an aperiodic behaviour, in spite of the converter dc current control. This is due to the strong non-linear and time-varying nature of the dc arc.

From a theoretical point of view, an aperiodic behavior could involve voltage and current spectral components (harmonics and interharmonics) that can be time-varying both in amplitude and frequency.

In the particular case of the numerical simulation of the DC arc furnaces, harmonics with time varying amplitudes can be forecasted due to the presence of the AC/DC converters and interharmonics can arise according to the DC arc model and behaviour.

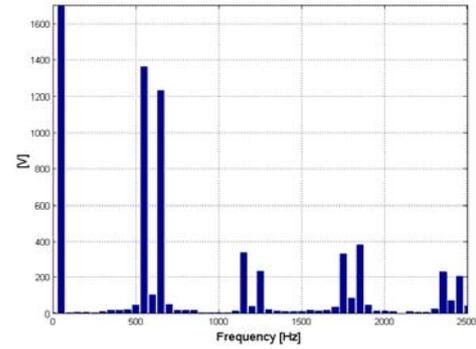
As well known, a method for studying waveform distortion indices for time-varying signals in power systems is the short-time Fourier transform (STFT) where the Fourier transform is applied to a windowed signal [7].

The main problem in applying the STFT is the choice of the window length, having in mind that this choice constraints also the frequency resolution.

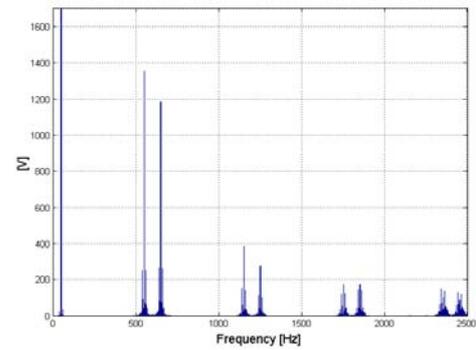
In particular, the choice of a short time window can cause the presence of unexpected spectral components, for instance uncharacteristic harmonics or a direct component, as shown in Fig.2 a) where a 20 ms time window has been used; moreover, it can exalt the desynchronisation effects, mainly in presence of measurements on actual plants¹. On the other hand, the choice of a too large window can generate averaged harmonics and a wide range of interharmonics, as shown in Fig. 2 b), where a 1 s time window has been used.

To better evidence the aforementioned problems with an other example, in Figs. 3 a) and b) the amplitudes of the voltage spectral components at the frequencies closest to 50 (fundamental) and 550 Hz (11th harmonic order) have been plotted versus the time window length (in the next these components will be named as \tilde{V}^1 , \tilde{V}^{11})².

Figs. 4 a) and b) show a zoom of Figs. 2 a) and b), respectively, around 1 s.

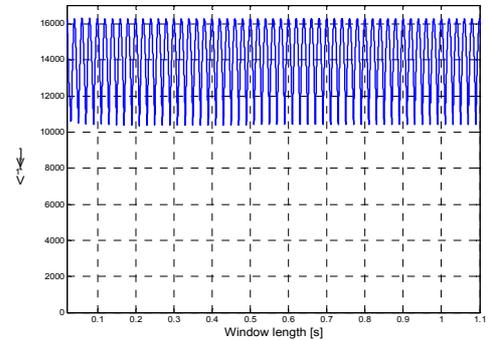


(a)

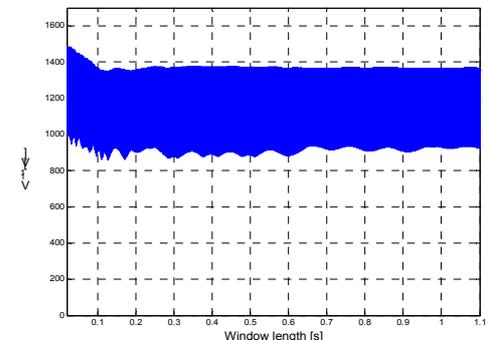


(b)

Fig. 2. FFT spectra: a) 20 ms window; b) 1 s window



(a)



(b)

Fig. 3. Amplitudes of the spectral components \tilde{V}^1 (a) and \tilde{V}^{11} (b) versus time window duration. As it clearly appears from the analysis of Figs. 3 and 4, the maximum values of both \tilde{V}^1 and \tilde{V}^{11}

¹ It is well known that the amount of interactions between different spectral components reduces when increasing the time window.

² It should be noted that when a continuous time window is taken into account, the frequency resolution changes accordingly, with the consequence that, for some time windows, the 50 and 550 Hz components can disappear while spectral components close to them appear.

appear when the synchronisation condition is verified (T_{wn} and $T_{w(n+1)}$ in Figs. 4, being these time durations integer multiple of the fundamental period $T_f = 20$ ms); these amplitude values are decreasing versus time (Figs. 3).

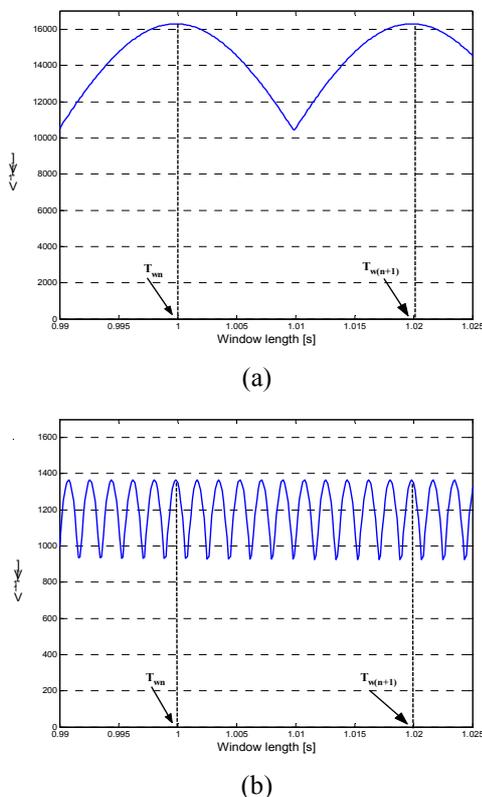


Fig. 4. Zoom of the amplitudes of the spectral components \tilde{V}^1 (a) and \tilde{V}^{11} (b) in Fig. 3

It is interesting to note also that the maximum values seems to repeat with a constant period, as clearly evidenced in Figs 4, so confirming the constant frequency behaviour versus time of the examined components.

Similar considerations can be effected with reference to other harmonics.

Having in mind the aforementioned problems, in the next some considerations about the waveform distortion behaviour of the DC arc furnace plant in Fig. 1 will be effected referring to the indications of the IEC Std 61000-4-7, that is by using an FFT with a 10 AC cycle rectangular window and considering the subgrouping procedure.

First of all, the harmonic and interharmonic subgroup amplitudes have been calculated in order to compare the waveform distortion behaviour with different control systems. In fact, as clearly shown in [3], the waveform distortions on the AC side are influenced by the converter control system behaviour; a wrong choice of the control system parameters can determine unreasonable results.

The following cases have been considered:

1. the current control system is composed by a DC current control loop and a PLL, with each converter provided of a separate current control system (Fig. 5);
2. as in 1., but with both AC/DC converters controlled with only one current control system (Fig. 6);
3. as in 1., but with incorrect values for the control system parameters (Fig.7).

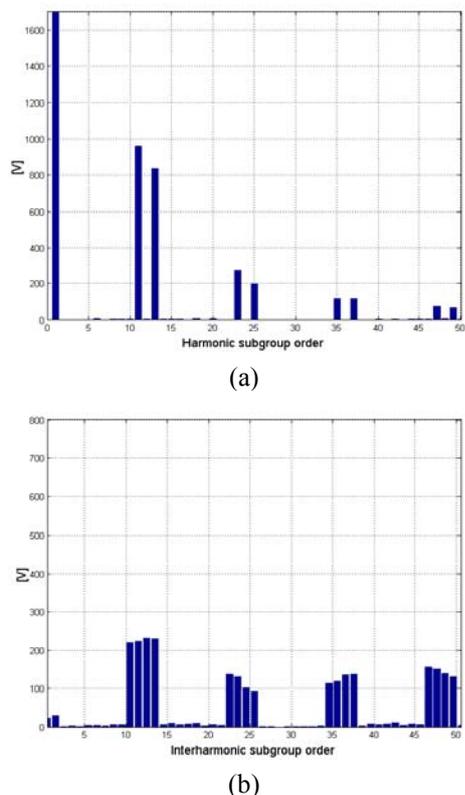
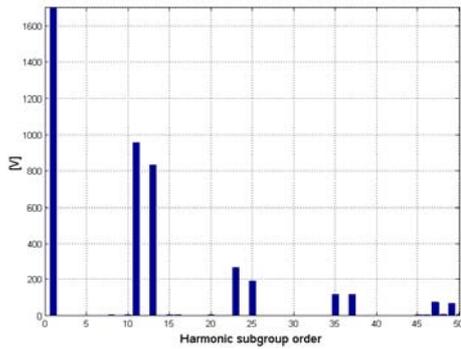


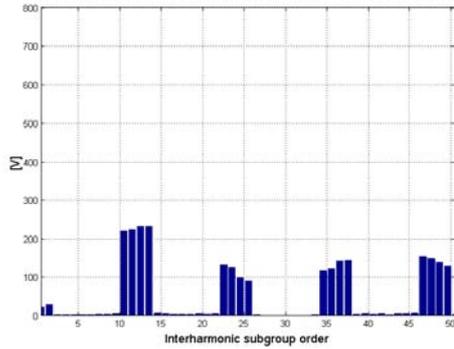
Fig. 5. IEC harmonic (a) and inter-harmonic (b) subgroup amplitudes of the voltage waveform with separate control systems.

From the analysis of Figs 5 and 6 it clearly appears that the two different control systems are characterized by very slight differences. As it will be shown in the next, this behaviour holds also in presence of unbalances in the voltage waveforms.

From the analysis of Figs 5 and 7 it clearly appears that the setting of the control system parameters is crucial also with reference to the waveform distortion assessment of the dc arc furnaces. These results fully comply with the conclusions of the paper [3]; also with a different representation of the DC arc (in this paper Chua Model based on chaos theory), an incorrect setting of the control system parameters gives unreliable results in the calculation not only of the harmonic subgroups but also of the interharmonic subgroups.

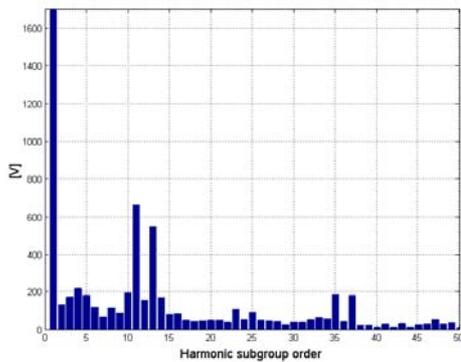


(a)

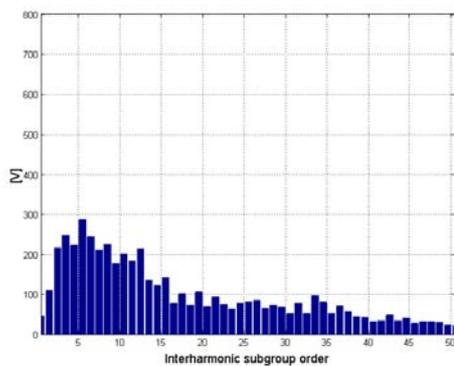


(b)

Fig. 6. IEC harmonic (a) and inter-harmonic (b) subgroup amplitudes of the voltage waveform with one control system.



(a)

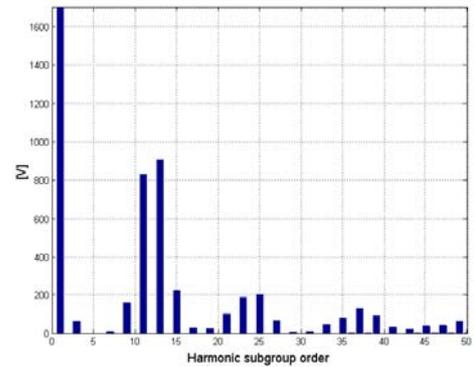


(b)

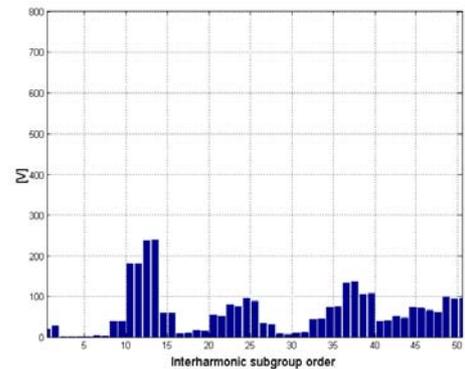
Fig. 7. IEC harmonic (a) and inter-harmonic (b) subgroup amplitudes of the voltage waveform with incorrect control system parameters.

As a further example of waveform distortion assessment, Figs. 8 show the harmonic and interharmonic subgroup amplitudes in presence of a voltage unbalance factor equal to 2%. Only the results obtained with the control system of Fig. 5 has been considered since no significant differences have been detected with the control system of Fig. 6.

The analysis of the Fig. 8 clearly shows that the presence of the voltage unbalances generates new significant harmonic and interharmonic subgroups.



(a)



(b)

Fig. 8 - IEC harmonic (a) and inter-harmonic (b) subgroup amplitudes of a phase-voltage waveform with 2% of voltage unbalance.

It follows that when the DC arc furnaces are fed by a network bus where unbalances can be forecasted, high attention must be paid in waveform distortion evaluation due the strong influence the unbalances have.

All the results previously shown have been obtained with the use of the FFT. In the relevant literature, other methods have been proposed to capture the time-changes of the spectral components in case of aperiodic signals, as an alternative to FFT. For instance, the Wavelet transform can be also used for this purpose, due to its powerful features of time frequency analysis of nonstationary signals. Recently, in [8] the Prony method was tested for the calculation of several waveform distortion indices in presence of non-

stationary signals in power systems; this method is a signal processing technique that approximates a sampled waveform as a linear combination of complex conjugate exponentials. It appears particularly useful when we deal with spectral components with not only amplitude but also frequency variations versus time. This method does not suffer of the synchronization problems of the FFT.

The Prony method can be also useful in assessing the effects of compensation strategies on waveform distortions [8]. For instance, it can be used to calculate the time-variations of the spectral components (fundamental, harmonics and interharmonics) when passive filters are provided in order to reduce the distortions. As well known, the passive filters are one of the most usual compensation strategy used in the AC/DC arc furnace plants.

Figs. 9 and 10 show the time variations of the fundamental and 11th harmonic without and with passive filters. The passive filters have been chosen on the basis of the Recommendations given by the IEEE Task Force on Interharmonics [9]. In particular, it was provided two notch filters tuned at 600 Hz and at 1150 Hz; moreover, the unavoidable parallel resonance produced by the notch filter was significantly reduced by a third order high pass filter tuned at 250 Hz [10].

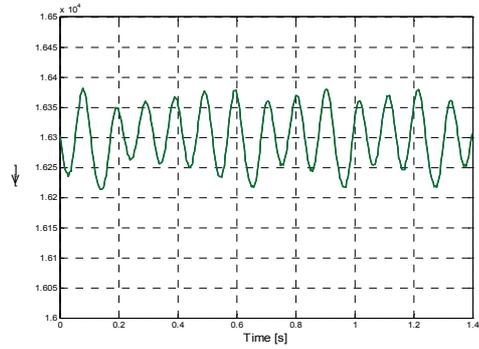
Similar plots can be obtained for the other spectral components.

The analysis of Figs 9 and 10 clearly reveals that the passive filters guarantee a good compensation action at harmonic frequencies. Moreover, the control systems act better so that the fluctuations of the spectral components versus time (including the fundamental) reduce.

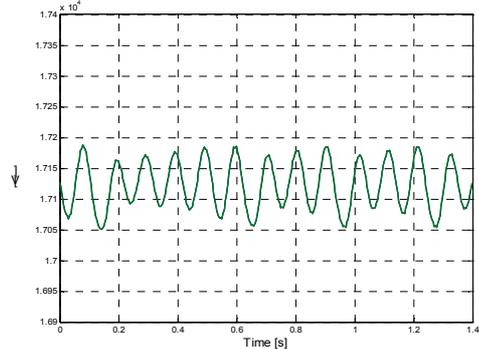
To confirm this consideration, Figs. 11 show the time variations of the converter delay angle, once again without (a) and with passive filters (b).

The difference between the maximum and minimum values of the converter delay angle is equal to 7.9° (5.6°) without (with) passive filters.

As another example of modern spectral analysis methods, it can be considered the ESPRIT method (abbreviation of Estimation of Signal Parameters via Rotational Invariance techniques); it was used in [8] for calculation of various parameters of currents and voltages in the supply system of the above-described DC arc furnace. In the next an improved version, namely the TLS-ESPRIT algorithm [8] (TLS, Total Least Squares algorithm) will be applied.

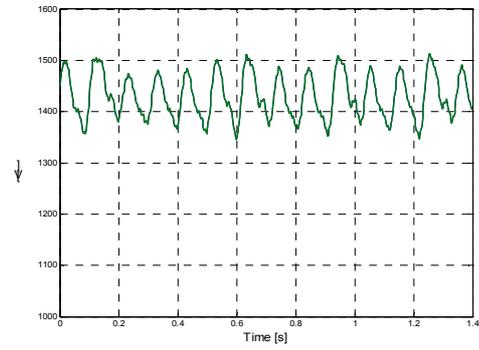


(a)

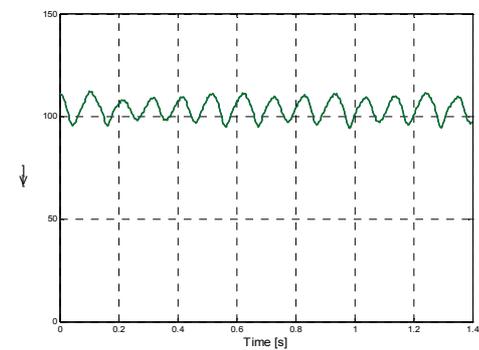


(b)

Fig. 9. Voltage fundamental versus time obtained with Prony method: (a) without passive filters; (b) with passive filters

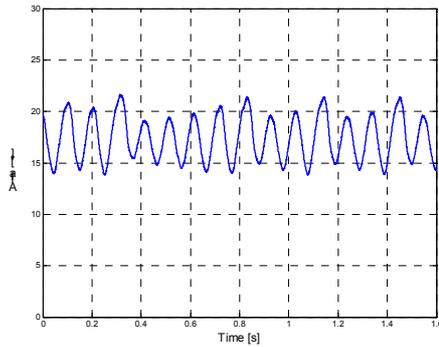


(a)

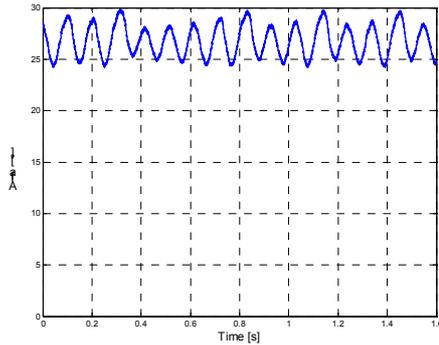


(b)

Fig. 10. 11th voltage harmonic versus time obtained with Prony method: (a) without passive filters; (b) with passive filters



(a)



(b)

Fig. 11. Converter delay angle versus time: (a) without passive filters; (b) with passive filters

It should be noted that, even if ESPRIT and Prony methods are based on different assumptions and algorithms, the results of analysis of strongly distorted signals show very good similarity when using both methods. Another advantage of ESPRIT algorithm lies in its high accuracy and low computational complexity.

Firstly, the problem of the choice of the window length was addressed. In Fig. 12 the amplitude of the voltage spectral component at the frequency closest to 50 Hz (fundamental) has been plotted versus the time window length.

The analysis of Fig. 12 clearly shows that for small window lengths appears a significant bias in amplitude estimation, which can be easily corrected by a factor depending on the window length. The synchronisation problem, inherent to FFT, completely disappears.

The TLS-ESPRIT algorithm has been applied also for the evaluation of the time variations of the fundamental component \tilde{V}^1 , without and with passive filters (Figs. 13).

Although Prony and ESPRIT methods are based on different assumptions and algorithms, they show similar results, as it clearly appears from the analysis of Figs. 9 and 13.

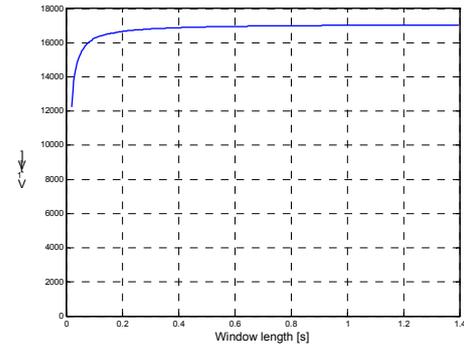
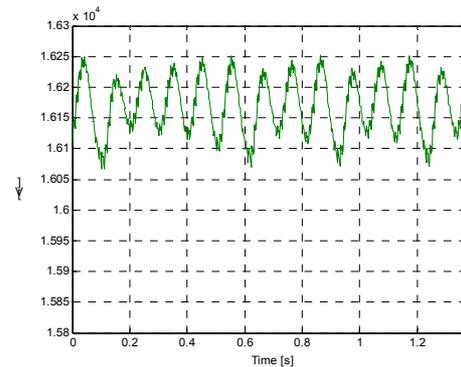
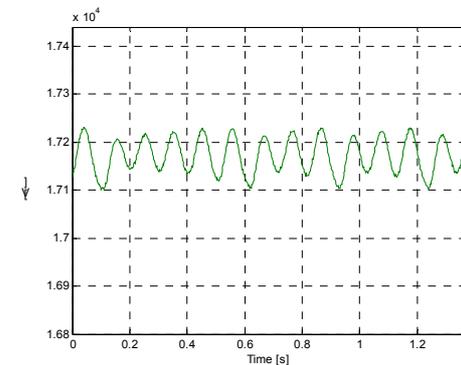


Fig. 12. Amplitude of the spectral components \tilde{V}^1 versus time window duration calculated by ESPRIT method.



(a)



(b)

Fig. 13. Voltage fundamental versus time obtained with TLS-ESPRIT method: (a) without passive filters; (b) with passive filters

5. CONCLUSIONS

The problem of the waveform distortion assessment in a DC arc furnace has been taken into account.

This load is particularly critical because the presence of the AC/DC static converters and the random motion of the electric arc are responsible for dangerous perturbations, even if the converters are current controlled in order to limit current fluctuations in the electrodes.

Several methods for the spectral components analysis have been applied, in order to evidence

their time-varying nature. These methods are DFT-based methods and high resolution methods, such as Prony and TLS-ESPRIT.

The main conclusions of the paper are that:

- an incorrect setting of the AC/DC converter control system parameters gives unreliable results in the calculation not only of the harmonic subgroups but also of the interharmonic subgroups;
- when the DC arc furnaces are fed by a network bus where unbalances can be forecasted, high attention must be paid in waveform distortion evaluation due to the strong influence the unbalances have;
- particular attention must be paid in the choice of the window length of analysis in the DFT-based methods, due to the well known synchronization problems;
- ESPRIT and Prony methods do not suffer of synchronization problems, but can require not negligible computational efforts.

6. REFERENCES

- [1]. Task Force on Harmonics Modeling and Simulation, IEEE PES Harmonic Working Group: *Characteristics and Modeling of Harmonic Sources – Power Electronic Devices*. IEEE Trans. on Power Delivery, Vol. 16, No 4, October 2004, pp. 791-800.
- [2]. M. Bauta, M. Grotzbach: *Noncharacteristic Line Harmonics of AC/DC Converters with High DC Current Ripple*. IEEE Trans. on Power Delivery, Vol. 15, No 3, July 2000, pp. 1060-1066.
- [3]. D. Stade, H. Schau, St. Prinz: *Influence of Current Control Loops of DC Arc Furnaces on Voltage Fluctuations and Harmonics in the HV Power Supply System*. 9th International Conference on Harmonics and Quality of Power (ICHQP) 2000, Vol. 3, Orlando (USA), 1-3 October 2000.
- [4]. G. Carpinelli, F. Iacovone, A. Russo, P. Varilone: *Chaos-based Modeling of DC Arc Furnaces for Power Quality Issues*. IEEE Trans. on Power Delivery, Vol. 19, No. October 2004, pp. 1969-1876.
- [5]. Z. Leonowicz, T. Lobos, J. Rezmer: *Advanced Spectrum Estimation Methods for Signal Analysis in Power Electronics*. IEEE Trans. on Industrial Electronics, Vol. 50, No. 3, 2000, pp 514-519.
- [6]. T. Lobos, Z. Leonowicz and J Rezmer: *Harmonics and Interharmonics Estimation Using Advanced Signal Processing Methods*. 9th International Conference on Harmonics

and Quality of Power (ICHQP) 2000, Vol. 3, Orlando (USA), 1-3 October 2000.

- [7]. S. H. Jaramillo, G. T. Heydt, E. O'Neill-Carrillo: *Power quality indices for aperiodic voltages and currents*. IEEE Trans. Power Delivery, Vol. 15, Apr. 2000, pp. 784-790.
- [8]. A. Bracale, G. Carpinelli, T. Lobos., Z. Leonowicz, J. Rezmer: *Evaluation of Compensation Devices of DC Arc Furnaces Using Advanced Spectrum Estimation Methods*. Accepted for presentation at PSCC'2005, Liege (Belgium), 22-26 August 2005.
- [9]. IEEE Interharmonics Task Force, CIGRE' 36.05/CIRE2 2 CC02 Voltage Quality Working Group: *Interharmonic in Power Systems*. January 1997.
- [10]. Carpinelli, A. Russo: *Comparison of Some Active Devices for the Compensation of DC Arc Furnaces*. IEEE Bologna PowerTech Conf., 2003, Bologna (Italy).

7. BIOGRAPHIES

Prof. Tadeusz Lobos

received the M.Sc., Ph.D. and Habilitate Doctorate (Dr.Sc.) degrees, all in electrical engineering, from the Wroclaw University of Technology, Poland, in 1960, 1967, and 1975, respectively. He has been with the Department of Electrical Engineering, Wroclaw University of Technology, since 1960, where he became a Full Professor in 1989. From 1982 to 1986, he worked at the University of Erlangen-Nuremberg, Germany. His current research interests are in the areas of transients in power systems, control and protection, and especially application of neural networks and signal processing methods in power systems. The Alexander von Humboldt Foundation, Germany awarded Dr. Lobos a Research Fellowship in 1976 and he spent this fellowship at the Technical University of Darmstadt. He received the Humboldt Research Award, Germany in 1998.

Zbigniew Leonowicz

received the M.Sc. degree in electrical engineering from the Wroclaw University of Technology, Poland in 1997. He has been with the Department of Electrical Engineering since 1997. His current research interests include modern digital signal processing methods.

Dr Jacek Rezmer

received M.Sc. and Ph.D. degrees from the Wroclaw University of Technology, Poland, both in Electrical Engineering, in 1987 and 1995 respectively. His primary professional interests lie in the new signal processing methods for electric power system analysis.

Z. Leonowicz, T. Lobos and J. Rezmer are with the Department of Electrical Engineering, Wrocław University of Technology, Wrocław, Poland,
email: tadeusz.lobos@pwr.wroc.pl

Prof. Guido Carpinelli

was born in Naples, Italy, in 1953. He received his degree in Electrical Engineering from the University of Naples (Italy) in 1978. He is currently professor in Energy Electrical Systems at University of Naples “Federico II” (Italy). He is member of IEEE, component of the IEEE Task Force on “Probabilistic Aspects of Power System Harmonics”, member of the joint CIGRE’-CIRED Working Group C4-07 on “Power Quality Indices and Objectives” and component of the PMAPS International Society. His research interest concerns Power Quality and Electrical Power System Analysis.

Dr. Antonio Bracale

received his degree in Telecommunication Engineering from the University of Naples “Federico II” (Italy) in 2002. He is currently PhD student at Second University of Naples (Italy). His research interest concerns Power Quality.

A. Bracale and G. Carpinelli are with the Dipartimento di Ingegneria Elettrica, Università degli Studi di Napoli “Federico II”, Via Claudio 21, 89100 Napoli – ITALY
email: guido.carpinelli@unina.it