The Influence of the High Power Ratio Non-linear Loads on the Low Voltage System Operation – Case Studies

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Abstract - **This paper presents the results of current and voltage measurements in the real low voltage distribution system with a welding device and gives the interpretation of the results in the harmonic domain. The measuring set-up is shown. The distribution system components: step-down transformer, power factor correction capacitances, linear and power electronic loads are modelled and the system behaviour is analyzed using the harmonic simulation program SuperHarm®. The results of measurements and calculation analysis with special emphasis onto power computation are disussed.**

Keywords: Power System, Harmonics, Power Factor.

I. INTRODUCTION

The problem of harmonics penetration in distribution systems has been significantly growing during the last few years. Due to the still increasing number of distortion introducing power electronic devices in power networks the need of the study of their operation and, especially, of their influence onto another parts of the system is indispensable both from the utility and the consumer point of view.

Such a device originates harmonic current in the power system. Since this current is propagated through the network the secure operation of a system and the standards of supply parameters can not be assured in all cases.

Moreover, the resulting enhance of the voltage waveform distortion turns out with the appearance of harmonic and inter-harmonic frequencies in the network voltage. This can be dangerous to some sensitive equipment (e.g. protection devices, capacitor banks) and some sensitive loads (motors, computers and so on) [1]. It may also end up with a significant reduction of the equipment lifespan, affect the service life and cause other damages ending with a breakdown of insulation. All circumstances mentioned above go hand-in-hand with increased costs – equipment, quality maintenance – and are of big importance to efficiency and productivity.

II. HARMONIC LEVEL AND POWER DEFINITIONS

In view of the extensive use of power electronic equipment connected to utility systems various national and international agencies have introduced limits on harmonic current injection into the system by this equipment as well as limits for the acceptable levels of voltage pollution depending on the type of equipment and its place in a power system [2,3].

There are several measures which are the main definitions for the most common indication of harmonics presence like the Total Harmonic Distortion factor (THD), which can be obtained for either voltage or current, and the Total Demand Distortion factor (TDD) used during calculation of current distortion at the point of common coupling between customer and utility. The limits for the harmonic pollution are defined both for the whole harmonic span (THD) and for each harmonic (HD) and inter-harmonic component in the system.

Beside them there are defined other indices: Telephone Influence Factor (TIF) and K – factor. The first one is used to measure telephone interference, the second to describe the impact of harmonics on losses and is often used in de-rating of equipment, e.g. transformers [4].

The resulting harmonic pollution in the distribution system affects the power properties of such circuits. The power definitions under non-sinusoidal conditions are nowadays strongly discussed [5, 6, 7]. There is still no consensus in the interpretation and definition of non-active powers in circuits with distorted and/or unbalanced voltages and currents. Recently a few papers have been published dealing with powers, mostly how to figure them out in some cases based on simulations and measurements using selected approaches and definitions [8]. Therefore in this paper three different methods of power resolution were chosen for power calculations in the real low voltage distribution system.

The first one – still the most popular in industry – a resolution in the frequency domain, introduced in 1927 by Budeanu. The second one, based on the time domain theory, the definition of the power components initiated by Fryze in 1932 and developed later by Czarnecki, and, the last one, the approach of the IEEE Working Group.

Frequency domain – Budeanu Theory

Budeanu has presented in his works the basic equations of power in linear electric circuits supplied by sinusoidal voltages with periodical, non-sinusoidal currents. The non-active (reactive) power Q spanned over the *n*-harmonic frequencies was defined by Budeanu:

$$Q = \sum_{n} U_n \cdot I_n \cdot \sin\varphi_n \,, \tag{1}$$

He has also proposed a new term: the *distortion power* D which should reflect the level of distortion introduced to the circuit by non-sinusoidal current or voltage. It can be calculated knowing apparent, active and reactive powers, as:

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

The equations defined by Budeanu have found wide acceptance of engineers and are still the most popular in spite of erroneous results in cases where the distortion level of voltages and currents are high. The misleading results of power calculations using Budeanu were shown by Czarnecki and Pretorius et al. in [8] and are also discussed in this paper.

Time domain – Czarnecki Theory

The concept of the momentary current decomposition into two orthogonal components: active and reactive current was introduced by Fryze and has found its extension in the work of Czarnecki. His theory bases on the decomposition of currents into many orthogonal components. Non-active powers are then defined as the product of the rms value of voltage by the rms value of current components. This current decomposition bases on the partitioning of the set of N harmonic orders into two subsets N_A and N_B, namely:

$$\begin{aligned} &\text{if } P_n \geq 0 \text{ then } n \in N_A \\ &\text{if } P_n < 0 \text{ then } n \in N_B \end{aligned}, \qquad (3)$$

where P_n is the active power transmitted from the source to the load at the *n*-order harmonic frequency amounts to:

$$P_n = Re\{\boldsymbol{S_n}\} = Re\left\{\boldsymbol{U_n}^T \cdot \boldsymbol{I_n}^*\right\}, \qquad (4)$$

in which the vectors of voltages and currents are calculated as the complex root mean square values for each harmonic frequency. In three-phase circuits these quantities can be obtained for line-to-ground voltages and line currents:

$$\boldsymbol{U_n} = [U_{Rn}, U_{Sn}, U_{Tn}]^T,\ \boldsymbol{I_n} = [I_{Rn}, I_{Sn}, I_{Tn}]^T\ . \quad (5)$$

An explanation for this decomposition lies in the direction of the energy flow. When the load is passive, linear and time-invariant then each of the harmonic active power P_n can not be negative. However, if any of these conditions is not fulfilled, the harmonic currents may be generated in the load, so that the energy at that frequency may be transmitted back to the source (P_n<0). This decomposition also enables to decompose the current observed at the bus into two mutually orthogonal components [9] and their rms values fulfil the relationship:

$$\|\boldsymbol{i}\|^2 = \|\boldsymbol{i_A}\|^2 + \|\boldsymbol{i_B}\|^2\ . \qquad (6)$$

Similar relationship for the voltages yields to the statement describing the apparent power S, which was first defined by Buchholz and then extended by Czarnecki:

$$S^2 = \|\boldsymbol{u}\|^2 \cdot \|\boldsymbol{i}\|^2 = S_A{}^2 + S_B{}^2 + S_F{}^2\ . \qquad (7)$$

The last quantity in (7) occurs also in single-phase circuits under distorted conditions and is called *forced apparent power*. It can be observed that the presence of bi-directional transmission of active power reduces the transmitted useful power P while increasing the apparent power S due to an increase in the voltage and current rms values. Continuing the decomposition of the current $\mathbf{i}_A$, Czarnecki has split it into the next four orthogonal components bounded to the separate power phenomena in such circuits [9]. The details can be found in several papers of Czarnecki.

IEEE Power Definitions

The concept presented in [10] which is also similar in [11] bases on the main assumption that the object of transmission is to deliver as much of the power as possible through 50/60Hz positive sequence component to the consumer. Therefore it makes sense to separate the fundamental and the harmonic components from each other:

$$U^2 = U_1^2 + U_H^2\,;\, I^2 = I_1^2 + I_H^2\,, \qquad (8)$$

with:

$$U_H^2 = \sum_{n \neq 1} U_n^2 \text{ and } I_H^2 = \sum_{n \neq 1} I_n^2 \qquad (9)$$

respectively. The apparent power S:

$$S^2 = (U \cdot I)^2 = S_1^2 + S_N^2 \qquad (10)$$

is divided into two main components, where S_1 is the *fundamental apparent power* which is in turn resolved into the *fundamental active power* P_1 and *fundamental reactive power* Q_1 according to well-known equations used under pure 50/60Hz sinusoidal conditions. The second component in (10) is named *non-fundamental apparent power* S_N and consists of three components:

$$S_N^2 = (U_1 \cdot I_H)^2 + (U_H \cdot I_1)^2 + (U_H \cdot I_H)^2\ . \quad (11)$$

Because of the fact that the first component is the product of fundamental rms voltage by harmonic current, it is named *current distortion power* and usually this is a dominant term in (11). The second term, thinking in similar way, is named *voltage distortion power* and it is a reflection of the voltage distortion at the bus. The third term is called *harmonic apparent power* S_H. More details for the three phase quantities with discussions can be found in [10].

In this paper the three concepts are compared for power calculations at the clamps of the single-phase welder and at the main bus of the low voltage distribution system.

III. MEASUREMENTS IN THE DISTRIBUTION SYSTEM

The measurements were made in the real low voltage distribution system (Fig.1) consisting of – among other – two step-down transformers, power factor correction capacitances and loads with a background level of voltage distortion about 3% THD.

In the case when welding devices are working in the distribution system the conditions of its operation are hindered. High current pulses – pulse rise about 0.5A/µs with peak value about 700A – demanded by the devices result with stronger voltage distortion and increase the possibility of disturbances in the distribution system operation.

In the described low voltage system a single-phase welding machine was installed at the laboratory cubicle L01. The voltage and the current at its clamps were measured simultaneously. Moreover, two other voltages were measured at the same time but at other locations in the system. The location of three measurement points, namely: *UNIV*, *LABOR* and *CLAMPS* are shown in Fig.1:

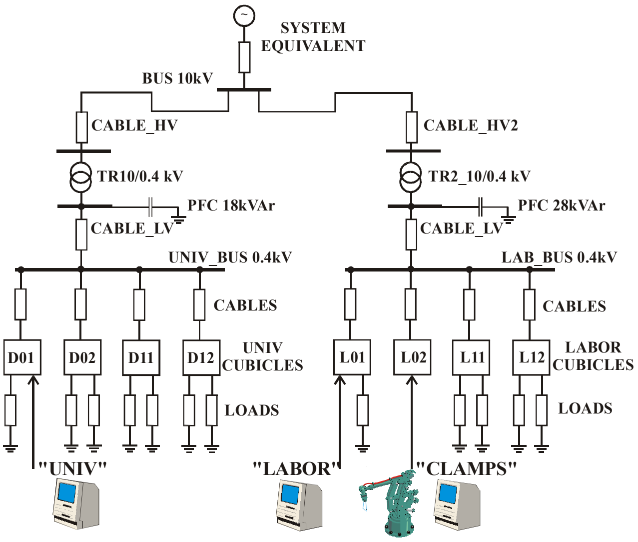

Fig. 1. Low voltage distribution system with measurement points.

The task was to obtain the kind of distortion introduced by a welding machine during its normal operation to the distribution system. So the machine's welding power was changed from 5% to 80% of its maximal value and for every position all quantities – supply current and three voltages – were measured simultaneously. The shapes of the supply current at the machine's clamps are presented in Fig.A1 in the Appendix.

All measurements were in process according to conditions specified in [3]. The measuring device – Oscilloscope LeCroy AL584 – was provided with the signals from three voltage differential probes Tektronix P5200 and one current probe Tektronix A621. The binary data recorded over 5 periods (100ms) were converted into ASCII files which then were used to calculate the total harmonic distortion factors of the current (THDi) and of the voltages (THDu) at each measuring point using Matlab's FFT algorithm. The THDs are presented in Fig.2.

It is interesting to see that the maximum distortion introduced by this machine into supply voltage (Fig.2) lies near the point of 50% of the machine's nominal welding power. The level of harmonic distortion both for the current and for the three observed voltages with their harmonic contents (for several voltage and current harmonics only) can be exactly observed in figures Fig.A2 to Fig.A5 in the Appendix.

The 5th harmonic appears as a main component in the supply voltage forming its background distortion factor (values for 0 S_{Lnom} in Fig.A3 to A5). When the machine starts working – for relatively small powers – the level of distortion decreases. The harmonic cancellation effect due to the phase difference gives the explanation for this case, because in the described system there are many decentralized sources of harmonic pollution.

When the power of the welder becomes dominant in the system, the distortion level is increasing according to the machine's power in spite of decreasing distortion of the current demanding by it. This can be explained looking at the current shape (Fig.A1). Steep pulses cause short voltage collapses. However, when the welding machine requires relatively big power the current turns out to be a sinusoidal-like waveform and the distortion level again decreases.

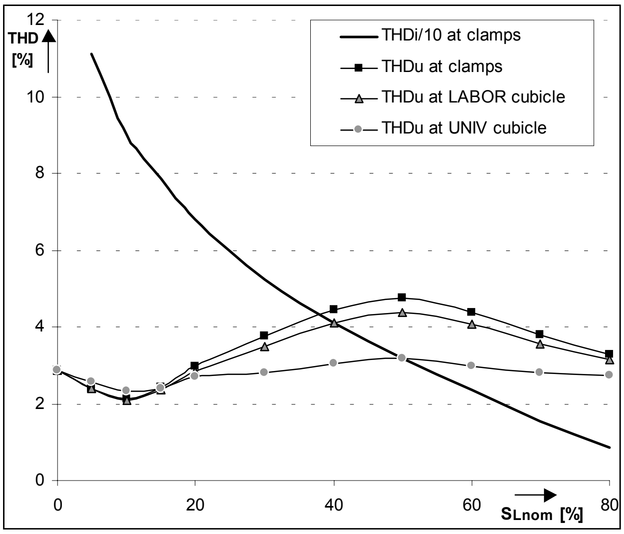

Fig. 2. Total harmonic distortion factors calculated for measured quantities versus the power of the device.

There is also another conclusion which can be obtained from Fig.1 and Fig.A2 to Fig.A5: The distortion introduced by this machine in the supply voltage is propagated through the network and appears also in both other measured voltages. The changes of the THDu level curves for the three voltages have nearly the same shape.

Besides the distortion calculations also power quantities were computed utilizing the three described power theories. As far as the differences between power calculations are concerned no big dissimilarities have been found taking into account the active and apparent power calculations. Some disagreements in the results appear during reactive power figuring (Fig.3).

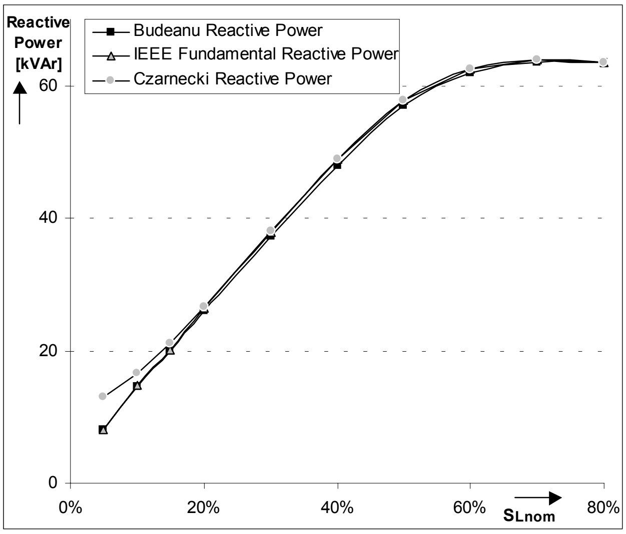

Fig. 3. The reactive powers calculated for the single welding machine as a function of its apparent power.

Additionally, power factors according to the IEEE definitions have been calculated and are presented in Fig.4.

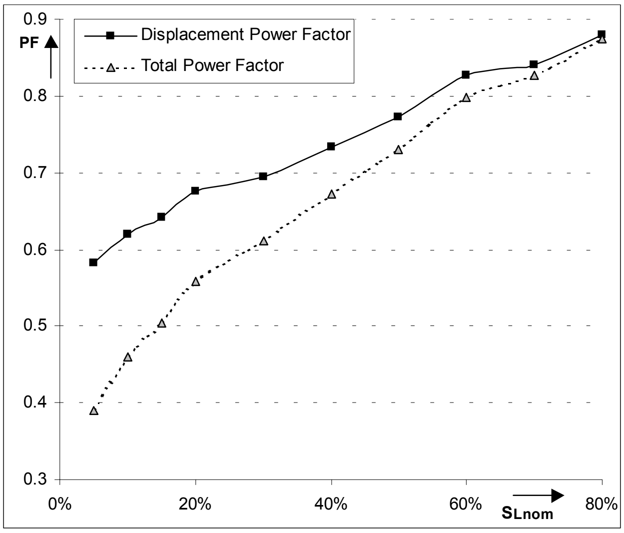

Fig. 4. Displacement and total power factors of the machine as a function of its power.

Concluding the power quantities calculations it should be noted that, especially at small powers of the welding machine, the discrepancy between the Czarnecki approach and both others is noticeable. It should be underlined that those results are caused by the single welder. At very small welding powers the distortion for the current was very high while the supply voltage was generally polluted by other, not known, devices working in the system. This has resulted in such a co-incidence that the summation of every harmonic component in reactive power according to Budeanu brought the same result as the value for the fundamental one. The theory of Czarnecki brings more information about this situation.

The bad conditions of distribution system operation in this case can be assumed looking at Fig.4 where the total power factor is distinctly lower as the power factor calculated using quantities for fundamental components. This signalizes strong distortion. Some other power quantities flowing out from the theory proposed by Czarnecki are shown at Fig.A6 in the Appendix.

For the significant powers of the welder all three theories bring comparable results due to the low level of distortion introduced by the machine into the distribution system in comparison with its short-circuit power. A problem can appear when more such devices will operate in a distribution system. This case became a motivation for the simulations described in the next chapter.

IV. THE SYSTEM MODEL FOR HARMONIC ANALYSIS

The most common technique used for harmonic analysis is the frequency scan in which the frequency response at particular node or bus is calculated [4]. Typically a one per unit sinusoidal current is injected into the bus of interest and the voltage response is calculated using discrete frequency steps throughout the range of interest, according to the equation:

$$\boldsymbol{Y}_{\mathrm{n}} \cdot \boldsymbol{U}_{\mathrm{n}} = \boldsymbol{I}_{\mathrm{n}} \ , \qquad (12)$$

where $\mathbf{I_n}$ is the known current complex vector and $\mathbf{U_n}$ is the nodal voltage complex vector to be solved, $\mathbf{Y_n}$ is the complex admittance matrix.

When more data are available the frequency scan can be extended to determine an additional harmonic distortion information. The one per unit harmonic current is then replaced by a specific harmonic current according to the data obtained either from measurement or from literature [12]. This approach has been expanded to cases with multiple sources of harmonics in the harmonic analysis program – SuperHarm® developed by Electrotek Concepts, USA, Tennessee [13]. The results are harmonic voltages created by harmonic-producing equipment.

In other words: the most common way of harmonic analysis is performed using steady state, linear circuit solution techniques. Harmonic sources which are non-linear elements are generally considered to be injection sources into the network models.

Models available in SuperHarm were used during simulations described in this paper to represent the simplified model of the system from Fig.1. The electrical data of the system components were taken from available device and equipment descriptions; the length of the cables were acquired approximately. All capacitances and the inductive coupling between phases in all cables were neglected. The source system was modelled as a purely sinusoidal source with an impedance derived from the short-circuit data.

The waveforms of the injected current for the dominant non-linear load were taken from the measurements described in chapter III. The appropriate power density and harmonic contents were calculated using Matlab’s FFT procedure, then the harmonic data were converted and saved in the SuperHarm® library file. This succeeding was used in the simulations on conditions that during the power regulation (in the program) the shape of the current curve is constant. This regulation had in sight to increase the number of simultaneously working devices. Moreover, at first it was assumed there is no phase difference between these devices and they all are working with equal power, so that the case of multiple-device operation was limited to this selected situation.

For the case described below a measured current waveform for the 30% of the single machine’s apparent power was chosen (the second largest curve on the Fig.A1 in Appendix). The resulting data were used to calculate power quantities according to the three power theories described above. It is to underline that at this position the welding machine has its displacement power factor equal to 0.7 and the total power factor lies about 0.1 lower (Fig.4).

In the simulations it was assumed that there are three single-phase machines working under conditions related above and connected to the three-phase system as in Fig.1. Afterward, the number of machines was increased and for every simulation step the analysis in SuperHarm® was carried out to obtain the current and voltage harmonic contents over the system. In Fig.5 the calculations of reactive power realized at the Lab_bus_0.4kV are presented.

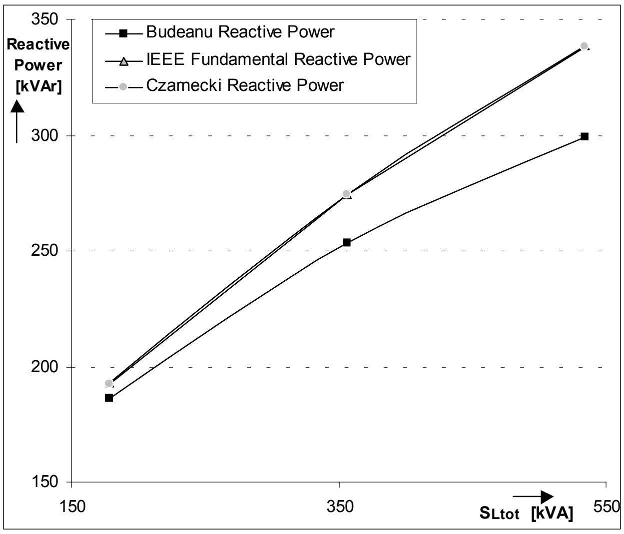

Fig. 5. The reactive powers calculated using simulation results.

It can be seen that for the relatively big amount of devices which introduce a huge portion of harmonic distortion into the system the calculations of the Budeanu's reactive power fail. So the usage of the terms defined by Budeanu, e.g. *distortion power* is misleading and should be forsaken for the cases with strong distortion in the power system.

V. SUMMARY

This paper presents the results of some case studies in which the findings of measurements and simulations in the real low voltage distribution system with welding devices connected to it are discussed. Concerning the results of measurements an important non-linear characteristic of the injected harmonic current by the single-phase welder is described upon the machine's welding power. The distribution system components are also modelled and in the case with multiple-device operation the system behaviour is analyzed using the harmonic simulation program SuperHarm®. The analysis of measurements and calculations is made focusing onto power definitions in such circuits and it shows some inaccuracies during the computation of reactive powers.

At this stage of the modelling process it was not possible to assemble large and aggregate structure of the whole load in the described system to reflect the real situation exactly. Simulations made in the modelled system were concentrated on the prediction of the system behaviour on conditions when several similar welding machines are working in a plant or factory. This multiple- device operation was focused on the selected situation when all welders are working with the same power. It should be noted that in a factory there are many of such devices and their working cycles can be reflected by a stochastic process.

In such cases the proper adjusting of the system short-circuit power is proposed as a safe procedure for the significant reduction of the harmonic influence onto the system components and onto the welders themselves. The proper dimensioning of harmonic filters appears in such situations as a complex task.

This study is made to introduce the problem of the presence of high power ratio loads with pulsed power in a distribution system. Further work will concentrate on the measurements in the network, verification of the calculated values and determination of accurate models of the system elements for the investigation of the mechanisms of harmonic propagation in distribution systems.

VI. REFERENCES

[1] R.C. Dugan, M.F. McGranaghan, H.W. Beaty, *Electrical Power Systems Quality*, McGraw-Hill, New York, 1996

[2] IEEE 519-1992 Standard.

[3] EN 61000 – European Norm.

[4] IEEE PES *Tutorial on Harmonics Modeling and Simulation*, 98TP125-0, Piscataway, NJ, 1998.

[5] L.S. Czarnecki, "Scattered and Reactive Current, Voltage, and Power in Circuits with Nonsinusoidal Waveforms and Their Compensation", *IEEE Transactions on Instrumentation and Measurement*, vol. 40, No. 3, June 1991, pp. 563-567.

[6] A. Ferrero, G. Superti-Furga, "A New Approach to the Definition of Power Components in Three-Phase Systems Under Nonsinusoidal Conditions", *IEEE Transactions on Instrumentation and Measurement*, vol. 40, No. 3, June 1991, pp. 568-577.

[7] A.E. Emanuel, "Apparent and reactive powers in three-phase systems: In search of a physical meaning and a better resolution", *ETEP*, vol. 3, No. 1, 1993, pp. 7-14.

[8] J.H.C. Pretorius, J.D. Van Wyk, P.H. Swart, "An Evaluation of Some Alternative Methods of Power Resolution in a Large Industrial Plant", *ICHQP* Athens, Greece, Oct. 14-16, 1998, pp. 99-106.

[9] L.S. Czarnecki, "Power related phenomena in three-phase unbalanced systems", *IEEE Transactions on Power Delivery*, vol. 10, No. 3, July 1995, pp. 1168-1176.

[10] IEEE Working Group on Nonsinusoidal Situations, "Practical Definitions for Powers in System with Nonsinusoidal Waveforms and Unbalanced Loads: A Discussion", *IEEE Transactions on Power Delivery*, vol. 11, No. 1, January 1996, pp. 79-101.

[11] DIN 40110, "Wechselstromgrößen, Zweileiter und Mehrleiter – Stromkreise", Beuth - Verlag, Berlin 1994, 1996

[12] A. Bachry, Z. Styczynski, T. Lobos "The Analysis of Low Voltage Distribution Power System Under Non-sinusoidal Conditions – Case Study", *4th International Conference on Power Networks PNET 2000,* Wroclaw, Poland, vol. II, June 2000, pp. 583-591.

[13] SuperHarm – harmonic simulation program, User's Guide, Electrotek Concepts, Tennessee, 1999.

VII. APPENDIX

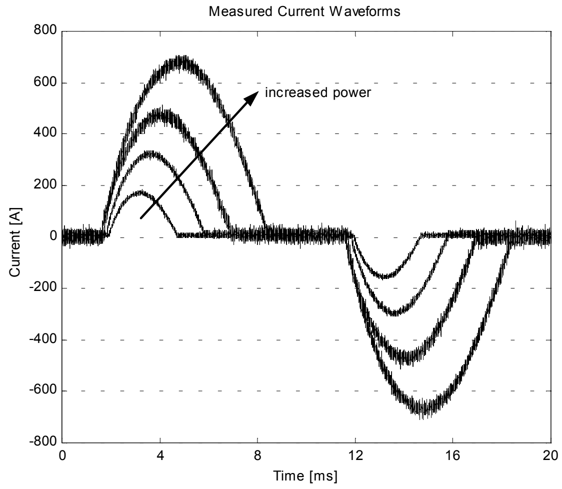

Fig. A1. Measured current shapes of the welding device.

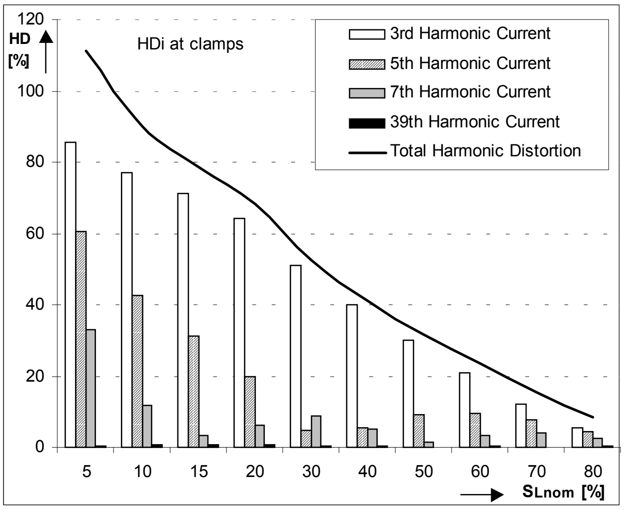

Fig. A2. The level of harmonic distortion for the current with its harmonic contents.

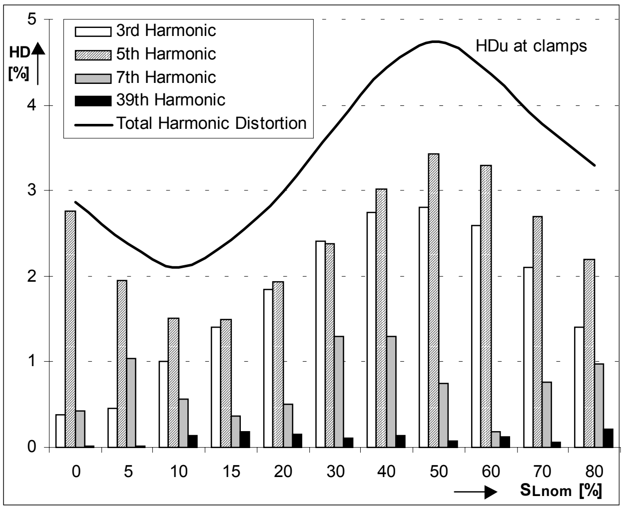

Fig. A3. The level of harmonic distortion for the voltage at clamps with harmonic contents.

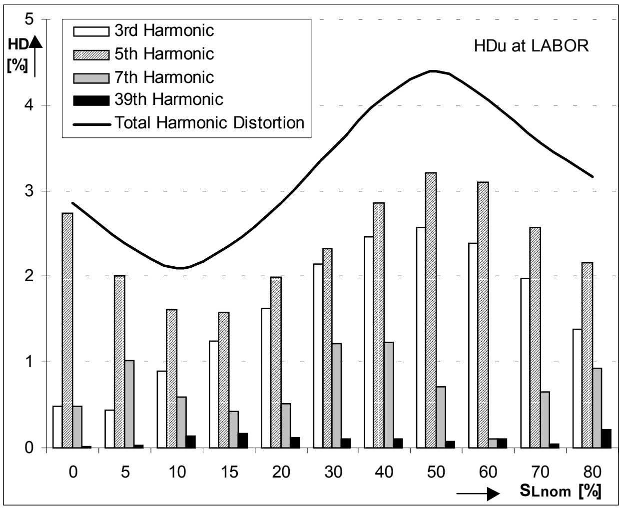

Fig. A4. The level of harmonic distortion for the voltage at *Labor* bus with harmonic contents.

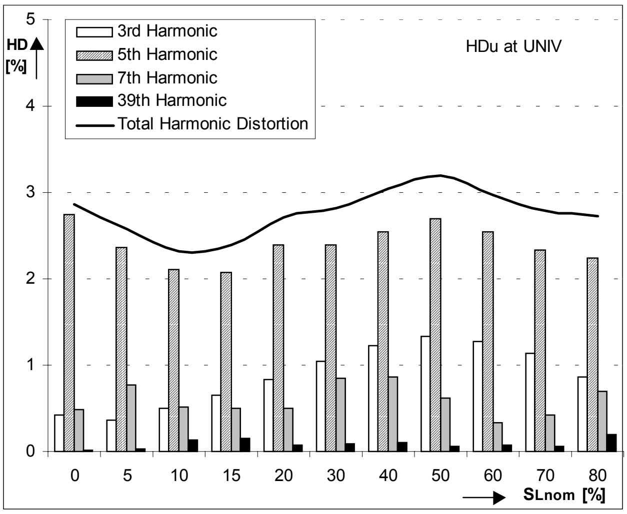

Fig. A5. The level of harmonic distortion for the voltage at *Univ* bus with harmonic contents.

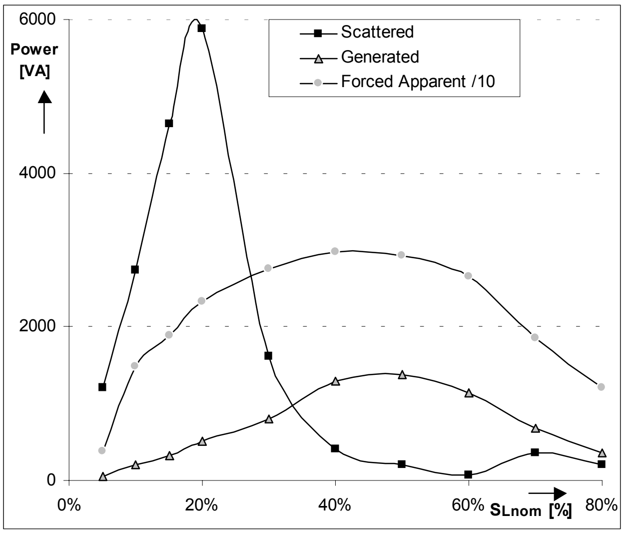

Fig. A6. Power quantities according to Czarnecki's power theory calculated for the welding machine