The Impact of the Load Side Parameters on PC Cluster's Harmonics Emission

Vladimir A. KATIĆ[1], Saša V. MUJOVIĆ[2], Vladan M. RADULOVIĆ[2], Jadranka S. RADOVIĆ[2]
[1]University of Novi Sad, Faculty of Technical Sciences, Novi Sad,21000, Serbia
[2]University of Montenegro, Faculty of Electrical Engineering, Podgorica,81000, Montenegro
katav@uns.ac.rs

***Abstract*—Harmonics current emission from personal computers (PCs) is of special interest to power quality researchers, due to their wide spread application and the fact that they are usually concentrated in large groups (clusters). The input current total harmonic distortion (THD_I) dependence on number of connected PCs in a cluster (N_{PC}) is affected by network parameters and load side parameters of each cluster's PC simultaneously. As the impact of grid parameters on the $THD_I=f(N_{PC})$ dependence is analyzed in the author's previous papers, special emphasis is given on the impact of the DC side smoothing capacitor (C) in PCs power supply unit. For engineering application it is convenient to present the $THD_I =f (N_{PC})$ function with simple mathematical expressions which include these effects. In the paper authors are proposing an improved mathematical expression to presents impact of load side (DC capacitance) parameters. To achieve this goal, results of the measurements of harmonic emission from a large computer center with 167 clustered PCs and the computer simulation for even larger number of PCs are used.**

***Index Terms*—PC clusters, Power conversion, Harmonics.**

I. INTRODUCTION

It is well-known that single personal computer (PC) is consuming non-sinusoidal current from the mains and generate harmonics [1]. Similar case is with other electronic or microelectronic devices that are supplied from the public single phase AC grid [2]. Operation of such and alike low power loads are regulated with several standards or recommendations. The most known is IEC 61000-3-2, which limits current harmonic emission from small loads ($I \leq 16A$) [3]. Single units are design to comply with it, both in current wave shape and in current harmonic emission intensity (expressed in mA/W).

However, application of PCs in modern systems very often requires their use in large numbers. Frequently numerous PCs are connected simultaneously to the distribution grid. In that sense they form kind of clusters. There are different clustering techniques applied for distribution network. They are used to group objects into clusters so that objects within one cluster share common characteristics [4]. In that way two types of clusters can be distinguished: one formed in a regular (or designed) manner, like in computer centers, insurance companies, banks, burses, etc., and another formed in random manner, like in residential and collective housing areas, university campuses, places (areas) with free wireless network (wi-fi) access, airports etc. The paper will deal with the first type.

Determination of joint effect of PC cluster on network (line) current harmonic distortion has drawn attention of many researchers [5]-[20]. Results show that level of input current total harmonic distortion (THD_I) is decreasing as number of PCs in a cluster is growing. It has been explained that THD_I dependence on number of PCs (N_{PC}) in a cluster, $THD_I = f(N_{PC})$, is affected by network (grid) parameters, and load side parameters of each cluster's PC (i.e. parameters of its power supply unit).

The impacts of line side (network) parameter have been studied in more details. It has been expressed with different variables, like ratio of short circuit current to fundamental-frequency load current I_{SC}/I_L, [20], short-circuit ratio (R_{SC}) [13] or rectifier invariant x_{LN} [14] - [15], which are actually related to short-circuit power (S_{SC}) or grid stiffness. It has been shown that THD_I of single PC is increasing with S_{SC} increase and opposite [10]. But, in case of PC cluster, the function $THD_I=f(N_{PC})$ is decreasing one [12], [16]. The explanation was found in attenuation and diversity effects of simultaneous operation of PCs and an attenuation factor (AF) and corresponding mathematical model has been proposed [10], [11], [13] - [15], [17]. The attenuation is increasing with number of PCs in a cluster [7], [10], [13], [18], but for larger N_{PC} this increase is not significant, as estimated in [13]. This was further investigated in [16]. The results showed two new, additional effects:

1. For certain number of PCs in a cluster the $THD_I=f(N_{PC})$ line cease to decrease and becomes constant, regardless of further N_{PC} increase, and
2. Overall deviation of $THD_I=f(N_{PC})$ from the most probable practical case in low voltage (0.4kV) networks (S_{SC} = 4000 kVA) is rather small.

Impacts of load side parameters have been presented in [13] - [15] in combination with line side parameters. The DC side smoothing capacitor (C) size was highlighted as a possible contributor to the THD_I level. Its effects have been expressed with invariant x_{CN}. Different cases have been discussed for a single PC operation. It was shown that effect of x_{CN} on individual harmonics depends on harmonic order and line side impedance. But, the effect on THD_I has not been shown. From presented results, it could be estimated that influence on THD_I is rather small (±5%). Only in case of low network impedance, this effect becomes more pronounced (up to ±10%). It must be noted that the applied experimental setup and mathematical model is assuming relatively small value of smoothing capacitance (C=76μF in [14], C=198 μF in [15]) in comparison to actual values in a modern PC power supply unit. For a case of larger number of PCs, it was proposed to find equivalent single PC topology. In such case, the effects of the C to THD_I are

Digital Object Identifier 10.4316/AECE.2011.01017

similar to above mentioned.

The aim of this paper is to go further in research of the effects of DC side capacitance on the THD_I level of a PC cluster. The motivation is that considered cluster size in previous papers was rather small, as the number of PCs was generally 5-20, with very few cases of larger number (above 50). Also, similar new effects, as the ones presented in [16], are expecting to be present in these cases also. Some results have been already presented in [17], showing effects on $THD_I=f(N_{PC})$ curves.

In this paper the authors are looking for more general solution for effects of DC side capacitor size on THD_I in order to develop mathematical expression suitable for practical engineering calculation. To achieve this goal, results of measurements of harmonic emission from a large computer center with 167 clustered PCs and computer simulation for even larger number of PCs, are used [19].

II. Single PC as a Harmonic Source

Power supply unit of a modern PC consists of input AC/DC converter with capacitive filtering on DC side. Simplified electrical scheme is shown in Fig. 1. Current on AC side is determined with capacitor charging/discharging and therefore is impulse in nature (Fig. 2). Such a wave-shape is far from sinusoidal, so harmonic distortion is high. Table 1 shows the main characteristics of a PC operation in different processing modes: Input current (I), active power (P), reactive power (Q), distortion power (D), power factor (PF) and THD_I. It can be seen that total harmonic distortion of input current (THD_I) is between 110% and 120% in all cases, except during the laser printing, when due to heater operation (resistive type of load) THD_I is decreased. This different values of THD_I resulting from different processing modes of the PC, explains variety of the reported THD_I in references: 79.3% [12], 100-120% [9], 100% [10], 110% [5], 119% [19], 118-122% [6], 140% [1].

Similar case is with instant power consumption, which is series of impulses. As a result, there is a voltage drop on input impedance and voltage wave-shape is distorted- top of the sinusoid is flattened (flat-top) (Fig.2).

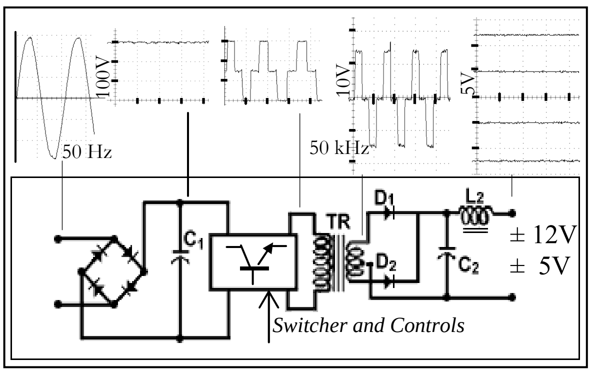

Figure 1. Simplified representation of a PC power supply unit (below) and characteristic wave-shapes (above).

III. THD_I of a PC Cluster

When a group of PCs are considered, the value of the THD_I depends on a cluster size (number of PCs in a group - N_{PC}). For a group of 3 PCs a level of THD_I=101.5% has been reported in [6]. For a group of 5 PCs two values are given: 70% in [10] and 74% in [12]. For a group of 10 PCs, three different values can be found: 58% in [10], 70.1% in [12] and 109.5% in [19]. For more PCs in a group, these THD_I values are reported as: for 15 PCs, 50% [10] and 66% [12]; for 20 PCs, 62% [12] and 99% [19]; for 30 PCs, 88.4% [11]; for 35 PCs, 81.0% [6], for 40 PCs, 77.2% [19]; for 50 PCs, 66.3% [19]; for 56 PCs, 61.3% [19]; for 70 PCs, 48% [8]; and for 124 PCs, 34.5% [18]. Fig. 3 graphically represents all these results.

It can be seen that the THD_I values differs in various publications with the same number of connected PCs, which is the similar case as the one noticed for the single PC. The explanation can be found in different grid stiffness, as mentioned in the Introduction chapter.

Another observation is that THD_I level is decreasing with increase of number of PCs in a cluster. This is in compliance with conclusion of several papers regarding attenuation and diversity effects, which have been mentioned in the Introduction chapter, also. Furthermore, there are very few papers considering THD_I values for the case of a greater number of connected PCs (e.g. more than 50 PCs per phase).

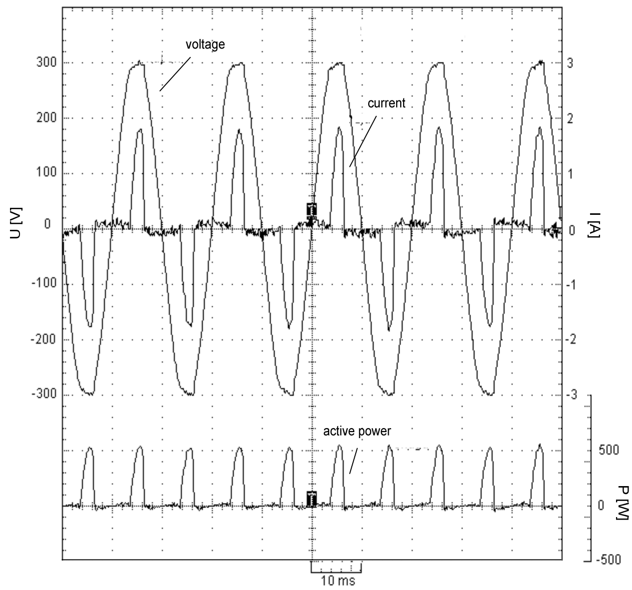

Figure 2. Input voltage and current wave-shapes (above) and instant power consumption (below).

TABLE I. THD_I VALUES DURING DIFFERENT PC PROCESSING MODES

Operation	I [A]	P [W]	Q [VAr]	D [VAd]	PF	THD_I [%]
Stand-by	0.75	103.90	-0.96	127.53	0.63	117.83
Copying	0.78	110.60	-0.12	130.96	0.64	113.21
Printing (laser)	2.46	451.70	-3.54	271.15	0.85	43.76
Printing (matrix)	1.10	176.00	12.60	175.61	0.70	94.49
Matlab operation	0.81	110.50	-2.11	133.53	0.64	112.10
Internet operation	0.80	115.80	-0.21	133.75	0.65	110.73

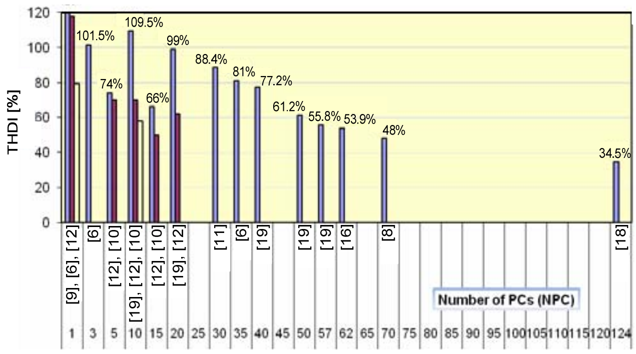

Figure 3. Overview of THD_I values reported in references, obtained from measurement of harmonic emission of a PCs cluster with different number of PCs.

IV. Measurement Results

As a very good case of PCs clustering, the Computer centre located at the Faculty of Technical Sciences of the University of Novi Sad was chosen for measurement of harmonic emission. The measurement has been performed in two sessions: the first one in October 2008 and the second one in December 2009. The Computer center laboratories, with number of PCs in each and position of measurement point are presented in Fig.4, while the measurement site setup is shown in Fig.5.

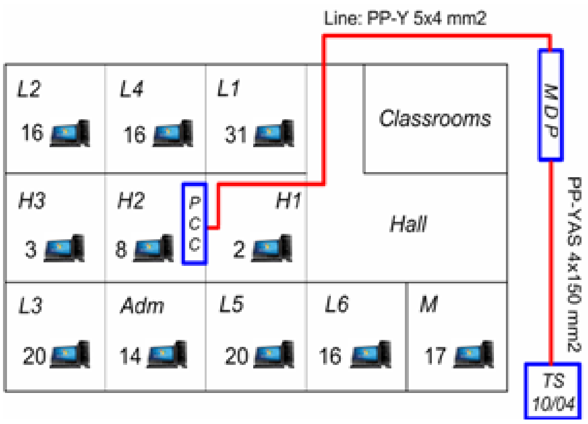

Figure 4. Computer centre laboratories with number of PCs in each lab and position of the measurement point (PCC).

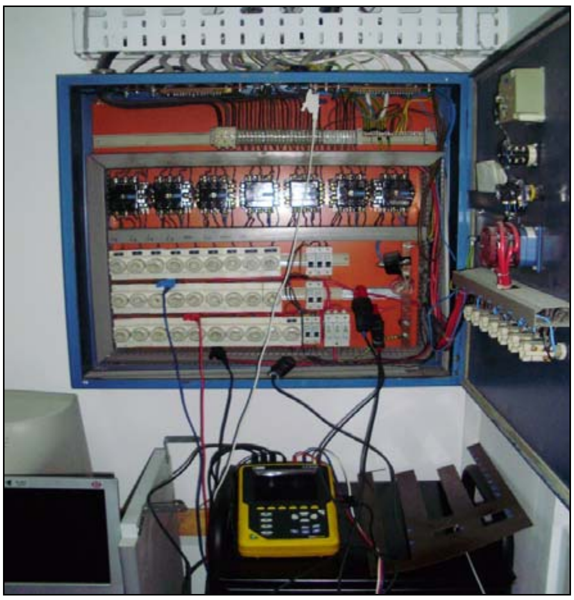

Figure 5. Measurement site setup for the Computer center harmonics measurement.

Measured quantities were line currents, neutral conductor current and grid voltages at the point of common coupling (PCC). The short-circuit current (I_{SC}) at the PCC of the Computer centre was I_{SC}=6kA. Measurement was conducted throughout 7 days, while measuring samples were taken at intervals of 10 minutes in reference to IEC 61000-4-7 Standard [21]. Detailed description of the measurement procedure and results is given in [19]. In this paper, results of harmonic emission will be presented in short.

In time of the first session, the Computer Centre had 163 PCs connected to all three phases of the public supply low voltage network. The most of the PCs were of standard type, while a dozen were PC servers. Rated power of a single PC was 150 W and of a PC server 450 W. The second session has been conducted in the same manner as the previous one. Only difference was the number of PCs, which has been increased to 177. A sample of the recorded waveforms, three line currents and a neutral conductor one is presented in Fig.6.

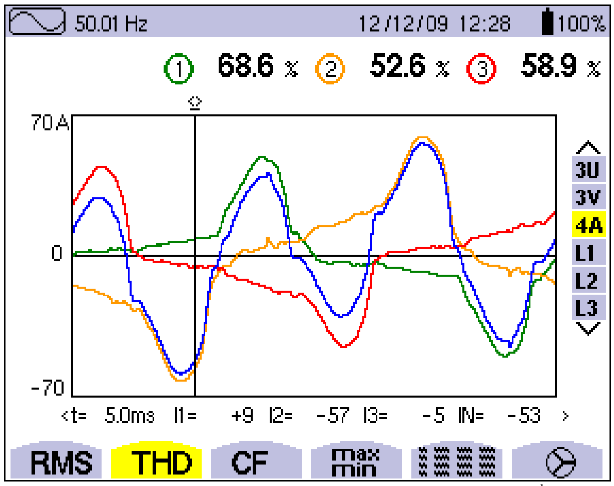

Figure 6. PC cluster line current waveforms obtained during the 2nd session.

Some measurement results of the first session are presented in the Table II. The 2nd column shows harmonics and THD_I of a single PC, while the 3rd, the 4th and the 5th the same quantities of 57 PCs (line 1), 50 PCs (48 PCs and 2 PC servers, line 2) and 56 PCs (48 PCs and 8 PC servers, line 3) obtained by measurement at the PCC. The maximum value of the THD_I for one PC was 119.7%, while for a PC cluster (56 PCs, line 3) was 61.3%.

TABLE II. MEASURED HARMONICS AND THD_I VALUES FOR GROUP OF PCS IN THE COMPUTER CENTRE-SESSION 2008

Line		**1**	**2**	**3**
Number of PCs		**57**	**48+2s**	**48+8s**
Harmonics	**I_{1PC} [%]**	**I_1 [%]**	**I_2 [%]**	**I_3 [%]**
3rd	87.2	49.4	49.8	51.9
5th	66.2	25.2	31.1	29.7
7th	40.5	7.2	12.0	9.2
9th	17.9	4.5	4.8	3.7
11th	3.0	4.6	5.7	4.1
13th	8.2	3.0	4.5	4.5
15th	9.3	1.6	2.5	2.9
17th	5.9	2.3	3.2	2.5
19th	1.7	1.7	2.0	2.3
21st	2.0	1.4	1.4	1.8
THD_I [%]	119.7	55.8	61.2	61.3

Selected results from the second session are presented in the Table III. The values of line current individual and total harmonic distortion at the PCC are given. The maximum values of the THD_I for a group of PCs for each line were: 80.0% (line1), 53.3 (line 2) and 58.1% (line 3).

TABLE III. MEASURED HARMONICS AND THD_I VALUES FOR GROUP OF PCS IN THE COMPUTER CENTRE-SESSION 2009

Line	1	2	3
Harmonics	I_1 [%]	I_2 [%]	I_3 [%]
3rd	43.5	28.5	33.2
5th	47.9	24	34.3
7th	34.2	14.3	23.1
9th	20.5	9.4	13.1
11th	10.5	3.7	4.3
13th	9.1	2.7	5.9
15th	10.1	3.8	6.1
17th	6.1	4.2	4.3
19th	5.8	1.3	1.7
THD_I [%]	80	53.3	58.1

Beside PCs, harmonic emission is coming from uninterruptible power supplies (UPS) units of the server computers, connected on lines 2 and 3, as well as supplied fluorescent lamps connected to line 1 (total active power of 1.6 kW). The presence of fluorescent lamps has effect in current harmonics reduction [11], so the THD_I value of the line 1 is lower compared to THD_I values of the lines 2 and 3.

In the second session, the case was opposite. Line 1 had the highest distortion, indicating that the effect of fluorescent lamps was not included and that there was change in number of PCs (lower number of operating PCs in a time of measurement). On the other hand, the line 2 and 3, had lower distortion, showing (confirming) that number of PCs have been increased.

V. Mathematical Model for THD_I Calculation

For better estimation of THD_I values coming from a large group of PCs a reliable mathematical model is needed. The mathematical expression representing THD_I values for a large number of PCs presented in [12] is given with:

$$THD_I(\%) = -0.81 \cdot N_{PC} + 80.11. \quad (1)$$

However, it proved to be unsuitable in case of N_{PC} larger than 80. For example, for N_{PC} equal 80, the expression gives THD_I=15.13%, while for larger number, for example N_{PC}=100, it results in THD_I=0.89%, which is not correct, obviously. Therefore, an improved model was needed.

To develop such a model the authors have summarized results from Fig. 3 showing the THD_I values in case of different PC cluster sizes. Fig. 7 shows the final result of this summation. It is obvious that THD_I is decreasing with increasing of the number of PCs in a cluster.

However, the problem was that there was only one measurement, which gives the THD_I values for larger number of PCs [18], beside the ones the authors have conducted. To solve this problem, a computer model was developed and verified with previously presented measurement results on a large PC cluster [19]. The model was based on simple presentation of a PC power supply unit shown in Fig. 8 (up) and on usual parallel connection of n PCs in a PC cluster (Fig. 8, down) [20].

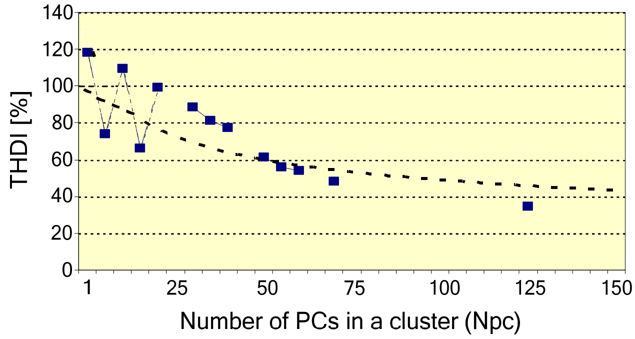

Figure 7. Graph summarizing the THDI values reported in various references.

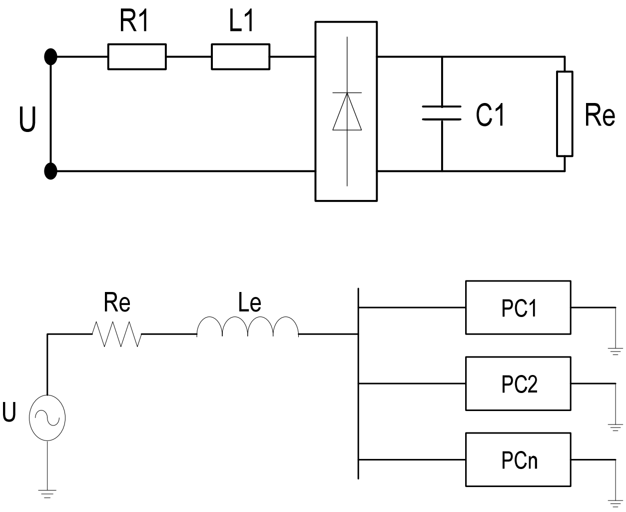

Figure 8. Simple model of a PC (up) and of a PC cluster with NPC=n (down) used for computer simulation [20].

Results of computer simulation for increased number of PCs (above 81), combined with results from [18], showed that the function THD_I= f(N_{PC}) is not continuous, but that it has, actually, two segments – linear (decreasing) for 1<N_{PC}<81 and almost constant for 81<N_{PC}<200. Is looks like there is kind of saturation in THD_I values, when number of PCs is increasing above 81. This number is denoted as N_{PCS}, while the effect was considered in more details in [16].

Taking into consideration numerous THD_I numerical values present in previously cited references, mathematical model given in [12] and results of performed computer simulation, an averaged THD_I value for number of PCs in the group can be calculated. In this sense, an improved analytical expression for the THD_I = f(N_{PC}) has been proposed in [16]:

$$THD_I(\%) = \begin{cases} -0.85 \cdot N_{PC} + 101, \; for \; N_{PC} < N_{PCS} \\ 32.2, \; for \; N_{PC} \geq N_{PCS} \end{cases}. \quad (2)$$

where N_{PCS}=81.

A graphical representation of the model (2) is presented in Fig. 9. It can be seen that THD_I = f(N_{PC}) line changed from decreasing to steady value (saturation) around N_{PCS}=81. For greater number of PCs in a cluster the level of THD_I is THD_I = 32.2%.

Although the proposed model (2) may be applied for assessment of the current distortion caused by simultaneous operation of an arbitrary number of connected PCs, the authors suggest that this model should be applied for clusters of up to 200 PCs per phase (1<NPC<200). This recommendation is a consequence of lack of measurement results and THDI values for cases of very large PC clusters (>200 PCs per phase) and the inability of verifying the accuracy of the proposed model for mentioned case.

It should be noted that the developed model is applicable for the cases when the unbalance factor and supply voltage distortion are within the limit defined by EN 50160 Standard [22].

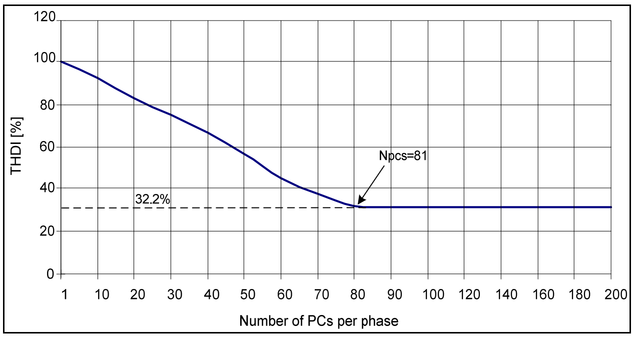

Figure 9. Graphic $THD_I = f(N_{PC})$ dependence presentation (C_1=235 μF).

VI. Effect of Load Side Parameter on THD_I

The analytical expression, represented with (2), is sensitive on line side and load side parameters. Previous works on effects of these parameters have been mentioned in the Introduction chapter.

Effects of the S_{SC}, as a line side parameter, on $THD_I = f(N_{PC})$ given with expression (2), has been discussed by the authors in [16]. A range of S_{SC} values has been tested and additional expression, which incorporates parameter S_{SC}, has been proposed. The model (2) is developed for S_{SC} of the grid S_{SC}=4000kVA, which is the most common value in the practice. But, for engineering practice, it may be used for a range of values of the S_{SC}, as deviations are not significant [16].

Load side parameter, DC side smoothing capacitor (C_1 in simplified power supply representation - Fig.1), has influence on expression (2), also. Two effects have been noticed, again:

1. Saturation effect, i.e. effect on THD_I for $N_{PC}>N_{PCS}$ and
2. Impact on knee value of number of PCs - N_{PCS} .

The saturation effect or the steady value of THD_I for N_{PC}>81 (line in Fig. 9), needs to be further elaborated. The N_{PC} affects the shape of the PCs group current pulse as follows: for a single PC the current pulse is narrow and concentrated around T/4 and 3T/4, where $\omega T=2\pi$ (Fig.2). As N_{PC} increases, the pulse wave-shape becomes wider and taller. The measurement described in the part IV gave the current wave-shapes presented at the Figs. 6 and 10. Obviously THD_I is decreasing, as current pulses are becoming wider, closer to sinusoidal. Also, with increase of the N_{PC}, the same happens with voltage distortion ("flat top"). Fig. 11 shows this effect.

It is clear that this process is due to charging (discharging) of the DC side capacitor in the power supply unit of a PC. Nowadays, these units are standardized. The most common are ATX and ATX-2 types, while previous AT units may be still in use in some PCs. For 230V mains voltage, DC side capacitor is consisting of two units connected in series of 470μF, 680μF, 820μF or 1000μF size, depending on nominal power and manufacturer.

Standard PC power supply unit of 200W (peak) usually has 2 capacitors of 470μF in series, i.e. the value of equivalent capacitance represented by C_1 in Fig. 1 is C_1=235μF. The current wave shape represented in Fig. 6 and 10 and the THD_I expression given with (2) are mainly due to such types of PCs.

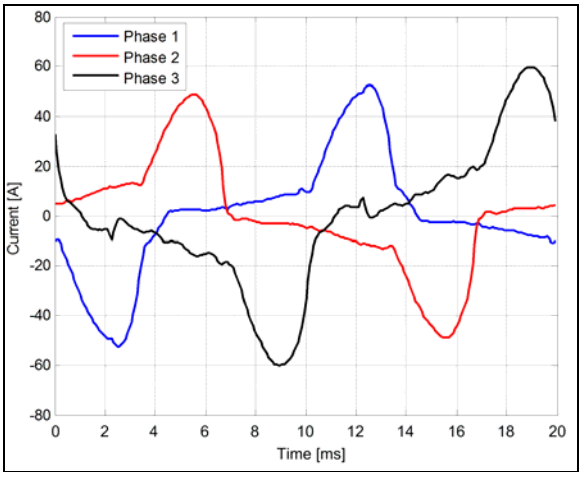

Figure 10. Line current waveforms at the grid supplying mainly standard PCs obtained during the 2nd of measurement in Computer centre.

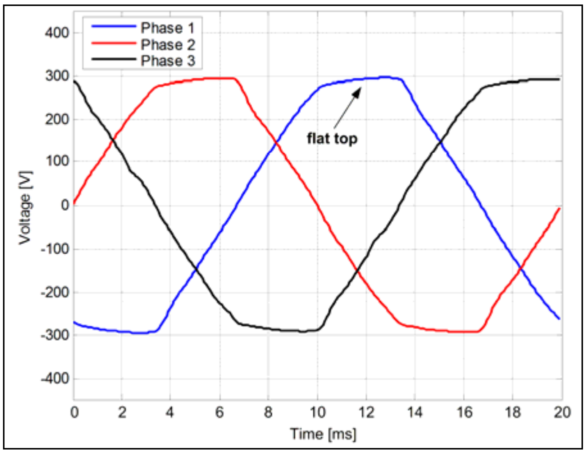

Figure 11. Voltage distortion ("flat top") due to high current pulses in case of PC clusters.

However, if we consider different type of power supply unit, less or more powerful, than different value of capacitance will be used in input stage of the power supply unit. For example, for a PC with higher power supply unit power and a higher capacitance value is needed. The computer simulations, using developed model, shows that in such a case, input current pulse becomes more distorted, i.e. the values of THD_I for $N_{PC}>N_{PCS}$ are getting higher. Also, while increasing the number of PCs, the saturation point N_{PCS} is moving toward lower N_{PC} values.

Figures 12-14 represent results of THD_I values for different number of PCs in a cluster, obtained by performed simulations, with the assumption that input capacitor in the power supply unit has a size of C_1 = 340 μF, C_1 = 410 μF and C_1 = 500 μF, respectively.

Considering these figures and Fig. 9, it can be seen that for a large number of PCs in a cluster the THD_I has steady values between THD_I=32.2% and THD_I=35.5% depending on the DC side capacitor size. In case of lower number of PCs in a cluster, the THD_I value follows linear decreasing line starting from around THD_I=100% for a single PC. The effect of capacitor on this line is low.

The point (number of PCs in a cluster, N_{PCS}), where the THD_I line is changing its flow from linear to steady, depends on capacitor size and has value between N_{PCS} =62 (for high C_1 value, Fig. 14) to N_{PCS} =81 (for low C_1 value, Fig. 9).

It can be concluded that due to charging/discharging of a power supply unit DC side capacitors, its size will have effect on the value of the THD_I and N_{PCS}.

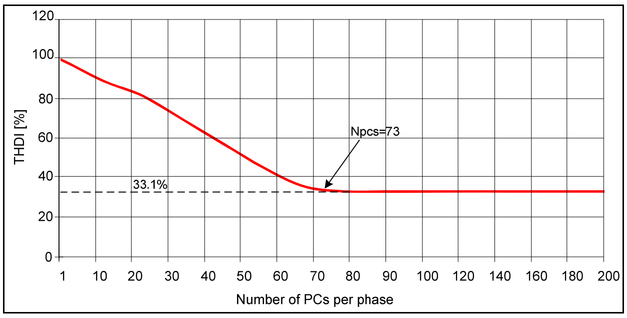

Figure 12. Graphic THD_I= f(N_{PC}) for C1=340 µF.

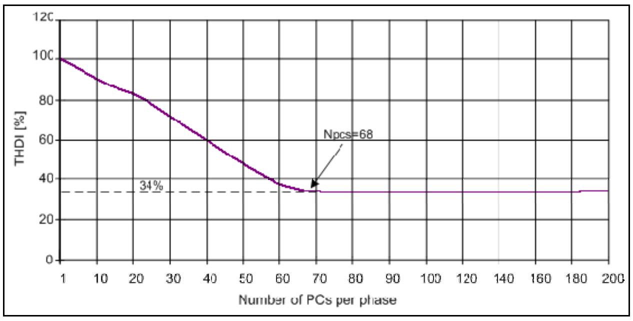

Figure 13. Graphic THD_I= f(N_{PC}) for C1=410 µF.

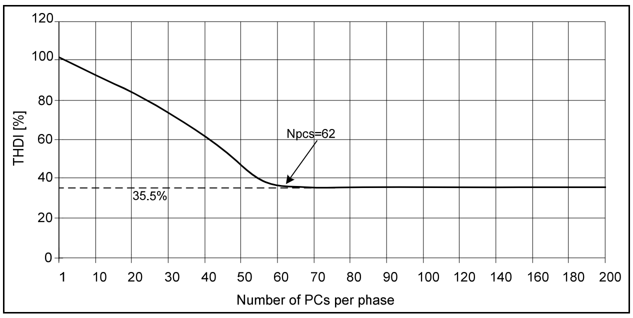

Figure 14. Graphic THD_I= f(N_{PC}) for C1=500 µF.

VII. Improved Mathematical Model

Analyzing computer simulation results and observed characteristics of THD_I=f (N_{PC}) function presented in Figs. 9 and 12-14, it is obvious that THD_I=f (N_{PC}) function, expressed by (2), should be improved. Both the curve and the saturation point N_{PCS} are sensitive on DC link capacitor size (C_1) and therefore it should be added as an additional parameter. Taking all these into account, a modification of the expression (2) leads to following THD_I=f (N_{PC}, C) function:

$$THD_I(\%)=\begin{cases}(19-N_{PC})\cdot C^{'}-0.67\cdot N_{PC}+100,\ N_{PC}<N_{PCS}\\ 15\cdot C^{'}+28,\ N_{PC}\geq N_{PCS}\end{cases},(3)$$

$$N_{PCS}=-70\cdot C^{'}+97, \quad (4)$$

where C' is normalized DC link capacitance C'= C_1/C_b, C_b = 10^3µF.

Results for N_{PCS} and THD_I obtained by using the proposed model represented by equations (3) and (4), are given in Table IV. Comparison of these with simulation results presented on Figs. 9, 12-14, a high level of matching can be observed (difference between these results is less than 10^{-6}).

TABLE IV. DEPENDENCE OF N_{PCS} AND THD_I VALUE ON CAPACITOR SIZE (VALUES OBTAINED BY THE MODELS)

C_1 [µF]	N_{PCS} (4)	THD_I [%] (3)
235	81	32.2
340	73	33.1
410	68	34
500	62	35.5

Above expressions (3) and (4) are developed assuming that a PC cluster is composed of large number (N_{PC}) of equal PC units. In a practical PC cluster, it is realistic to expect some diversity, i.e. that all PCs are not of the same type. It means that there are different power supply units (PSU) responsible for emitting harmonics to the grid. Still, as PC power supply units are standardized, there are not many options. Therefore, several cases of two different types of mixed PSU in a PC cluster have been considered. These units are characterized with DC side capacitance of 235µF and 500 µF. Results are shown in Table V and on Figs.15-17. It can be seen that in case of mixed PSU in a PC cluster, the THD_I values and N_{PCS} are between (inside) the lines which represents a PC cluster with single type of PSU.

TABLE V. DEPENDENCE OF N_{PCS} AND THD_I ON PSU SHARE IN A PC CLUSTER

	Percentage of PSU with C_1 equals 235µF and 500 µF	N_{PCS}	THD_I [%]
1. (Fig.14)	0% / 100%	62	35.5
2. (Fig.15)	20% / 80%	63	34.7
3. (Fig.16)	50% / 50%	71	34.1
4. (Fig.17)	80% / 20%	75	33.4
5. (Fig.9)	100% / 0%	81	32.2

Referring to previous conclusion, the THD_I=f (N_{PC}) curves for all cases of PSU units are drawn in one diagram (Fig.18). Fig.18 shows that all curves are more or less grouped together. The largest deviation is in range of N_{PC}=30-70. Results presented in Fig.16 show that THD_I=f (N_{PC}) curve representing PSU share in a PC cluster in relation of 50% of PCs with C_1=235 µF and 50% of PCs with C_1=500 µF (red, solid line) is at the mid distance from cases of 100% C_1=235 µF and 100% C_1=500 µF for number of PC in a cluster N_{PC} >30. This curve is denoted THD_I=f (N_{PC}, 50-50%). It is obvious that this curve is the best representative for the overall THD_I=f (N_{PC}, C) dependence. Therefore, the model represented with (3) and (4) should be fine tuned. The proposed improved mathematical model is now given with:

$$THD_I(\%)=\begin{cases}(21.1-N_{PC})\cdot C^{'}-0.67\cdot N_{PC}+100,\ N_{PC}<N_{PCS}\\ 16\cdot C^{'}+28,\ N_{PC}\geq N_{PCS}\end{cases},\ (5)$$

$$N_{PCS} = -70 \cdot C' + 97. \tag{6}$$

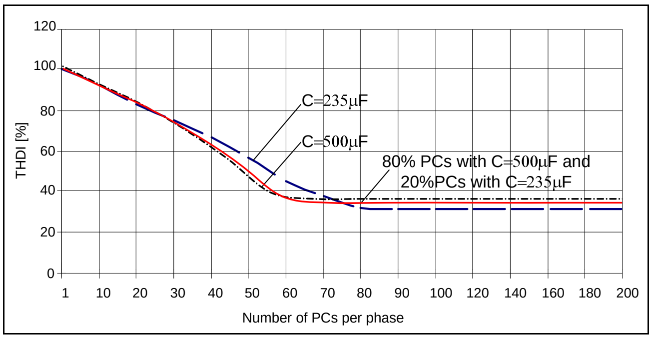

Figure 15. THDI =f (NPC) curve for PSU share in a cluster: 20% of PCs with C1=235 µF and 80% of PCs with C1=500 µF (Red, solid line). Dotted lines represent single type of PSU in a cluster.

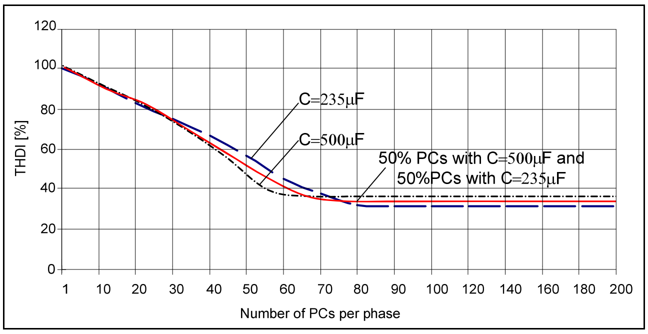

Figure 16. $THD_I = f(N_{PC})$ curve for PSU share in a cluster: 50% of PCs with C_1=235 µF and 50% of PCs with C_1=500 µF (Red, solid line). Dotted lines represent single type of PSU in a cluster.

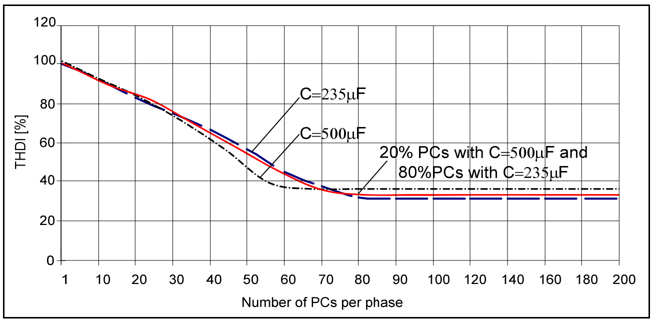

Figure 17. $THD_I = f(N_{PC})$ curve for PSU share in a cluster: 80% of PCs with C_1=235 µF and 20% of PCs with C_1=500 µF (Red, solid line). Dotted lines represent single type of PSU in a cluster.

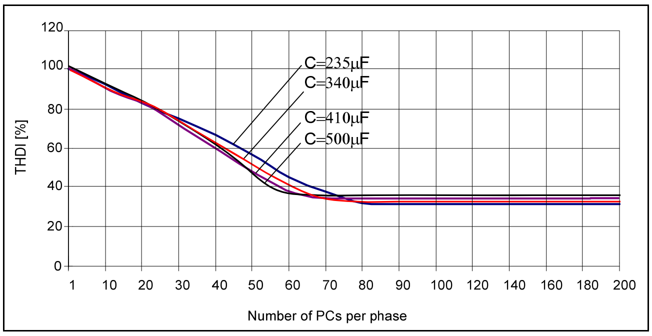

Figure 18. $THD_I = f(N_{PC})$ curves for PSU with C_1=235µF (blue), C_1=340µF (red), C_1=410µF (violet) and C_1=500 µF (black).

VIII. Discussion

The new model represented with equations (5) and (6) is developed to ease calculation of THD_I values for engineers in the field. The initial assumption were that line side parameters are represented by S_{SC}, where its value was S_{SC}=4000 kVA (which is the most common case in 400/230V distribution network) and that load side parameters are represented by a PSU DC side capacitance, where its value was a mix of C_1 = 235 µF and C_1 = 500 µF.

The first assumption has been discussed in [16], as mentioned earlier, and it was concluded that deviation of the THD_I values for a range of S_{SC} = 2000 – 6000 kVA are rather small (less than ±10% in a complete range).

The second assumption should be considered in this paper. Due to above feature, the curve $THD_I = f(N_{PC}$, 50-50%) is taken as referent one for calculation of deviation of $THD_I = f(N_{PC})$ curves from this one in case of other DC side capacitance values. The Fig.19 shows results represented with relative error for certain values of N_{PC} (Fig.19-up) and with root mean square error (RMSE) values for the whole range with the base line $THD_I = f(N_{PC}$, 50-50%) (Fig.19-down). It can be seen that relative error in almost all cases is below ±5%, while RMSE is significantly less then ±5%.

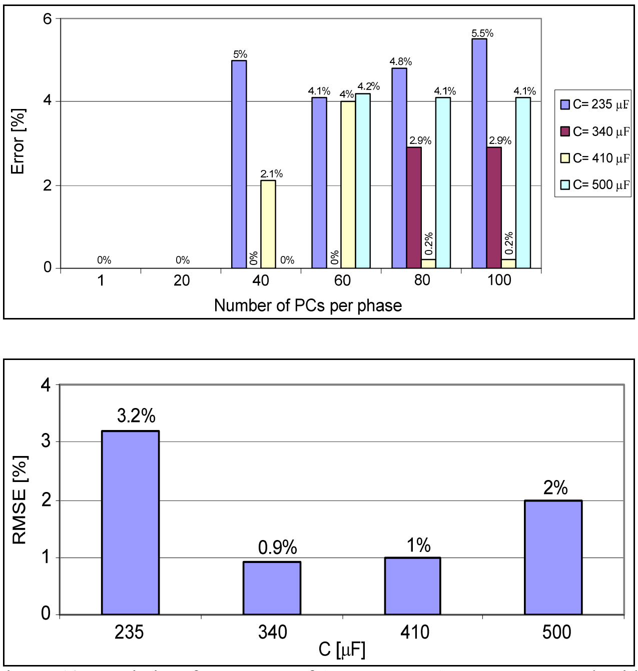

Figure 19. Deviation from *$THD_I = f(N_{PC}$, 50-50%)* curve expressed with relative error (up) and with root mean square error (down).

IX. Conclusion

The load side parameters, i.e. the size of DC side capacitor in PSU of a PC have impacts on input current harmonic distortion in cases of PC cluster with large number of PCs. The proposed mathematical model in form of two expressions takes into account the effects of DC side capacitance values on $THD_I = f(N_{PC})$ curve. The model is simple, easy to use and convenient for all cases of PSUs in modern PCs. It has been proved that expected error in application of the model is less then ±5%, which is acceptable in practical engineering calculation.

References

[1] A.E. Emanuel, J. Janezak, D.J. Pileggi, E.M. Gulachenski, C.E. Root, M. Breen, and T.J. Gentile, “Voltage Distortion in Distribution Feeders with Nonlinear Loads”, *IEEE Transaction on Power Delivery*, Vol.9, No. 1, Jan. 1994, pp. 79-87.

[2] A. Capasso, R. Lamedica, and A. Prudenzi, "Estimation of Net Harmonic Currents Due to Dispersed Non-linear Loads within Residential Areas", *International Conference on Harmonics and*

[3] *Quality of Power - ICHQP*, Vol.2, Athens, Greece, 14-18 October 1998, pp. 700-705.

[4] IEC 61000-3-2 Standard, "Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤16 A per phase)", *International Electrotechnical Commission*, Geneva, 2002.

[5] E.C. Bobric, G. Cartina, G. Grigoras, "Clustering Techniques in Load Profile Analysis for Distribution Stations", *Advances in Electrical and Computer Engineering,* Vol.9, No.1, 2009, pp.63-66.

[6] D.O. Koval, and C. Carter, "Power Quality Characteristics of Computer Loads" *IEEE Transaction on Industry Application*, Vol. 33, May/June 1997, pp. 613-621.

[7] V.A. Katić, B. Dumnić, S. Mujović, and J. Radović, "Effects of Low Power Electronics & Computer Equipment on Power Quality at Distribution Grid – Measurements and Forecast", *IEEE Int. Conference on Industrial Technology–ICIT'04*, Hammamet (Tunis), December 2004, Vol.2, pp.585-589.

[8] E.E. Ahmed, and W. Xu, "Analyzing Systems With Distributed Harmonic Sources Including the Attenuation and Diversity Effects", *IEEE Tran. on Power Delivery*, Vol.20, No.4, Oct.2005, pp.2602-2612.

[9] M.-Y. Chan, K. Lee, and M. Fung, "A Case Study Survey of Harmonic Currents Generated from a Computer Centre in an Office Building", *Architectural Science Review*, Vol. 50.3., 2007, pp. 274-280.

[10] M.T. Au, and J.V. Milanović, "Development of Stochastic Aggregate Harmonic Load Model Based on Field Measurements", *IEEE Transaction on Power Delivery*, Vol. 22, No. 1, Jan. 2007, pp.323–330.

[11] A. Mansoor, W.M. Grady, A.H. Chowdury, and M.J. Samotyj, "An Investigation of Harmonics Attenuation and Diversity Among Distributed Single-phase Power Electronic Loads", *IEEE Transaction on Power Delivery*, Vol. 10, No. 4, October 1995, pp. 467-473.

[12] E. F. El-Saadany, and M. M. A. Salama, "Reduction of the net harmonic current produced by single-phase non-linear loads due to attenuation and diversity effects", *Electrical Power & Energy Systems*, Vol. 20, No. 4, 1998, pp. 259-268.

[13] R. A. J. Khan, and M. Akmal, "Mathematical Modeling of Current Harmonics Caused by Personal Computers", *In Proceedings of the World Academy of Science Engineering and Technology - WASET*, Vol.29, May 2008., pp. 325-329.

[14] S. Herraiz, L. Sainz, J. Pedra, "Behavior of Single-Phase Full-Wave Rectifier", *European Transaction on Electric Power – ETEP*, Vol.13 No.3, 2003, pp.185-192.

[15] L.Sainz, J.Pedra, J.J.Mesas, "Single-Phase full-wave rectifier study with experimental measurements", *Electric Power System Research*, Vol.77, No.3-4, 2007, pp. 339-351.

[16] L.Sainz, J.J.Mesas, A.Ferrer, "Characterization of non-linear load behaviour", *Electric Power System Research*, Vol.78, No.10, 2008, pp. 1773-1783.

[17] S. Mujović, V.A. Katić and J. Radović, "Improved Analytical Expression for Calculating Total Harmonic Distortion of PC Clusters", *Electric Power System Research*, 2011, Accepted for publication.

[18] V.A. Katić, S. Mujović and J. Radović, "Effects of PC Clusters on Network Harmonics Distortion", *12th International Conference on Optimization of Electrical and Electronic Equipment – OPTIM 2010*, Brasov, Romania, 20-22 May, 2010, pp. 226-231.

[19] P.J. Moore, I.E. Portugues, "The Influence of Personal Computer Processing Modes on Line Current Harmonics", *IEEE Transaction on Power Delivery*, Vol.18, No.4, 2003, pp. 1363-1368.

[20] S. Mujović, V.A. Katić, Z. Čorba, and J. Radović, "Measurement and Analysis of Computer Centre Effects on the Level of Network Harmonics", *Elektroprivreda*, Vol.61, No.4, 2009. (In Serbian)

[21] A. Mansoor, W.M. Grady, P.T. Staats, R.S. Thallam, M.T. Doyle, M.J. Samotyj, "Predicting the Net Harmonic Currents Produced by Large Numbers of Distributed Single-Phase Computer Loads", *IEEE Transaction on Power Delivery*, Vol. 10, No. 4, 1995, pp. 2001-2006.

[22] IEC Standard 61000-4-7, "General Guide on Harmonics and Inter-harmonics Measurements and Instrumentation for Power Supply Systems and Connected Equipment", *International Electrotechnical Commission*, Geneva, 2002.

[23] EN50160 Standard, Voltage Characteristics of Electricity Supplied by Public Distribution Systems, CENELEC, EU, 1994.