

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

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**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<sub>I</sub>) 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<sub>I</sub>) is decreasing as number of PCs in a cluster is growing. It has been explained that THD<sub>I</sub> 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<sub>I</sub> 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<sub>I</sub> 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<sub>I</sub> has not been shown. From presented results, it could be estimated that influence on THD<sub>I</sub> is rather small ( $\pm 5\%$ ). Only in case of low network impedance, this effect becomes more pronounced (up to  $\pm 10\%$ ). It must be noted that the applied experimental setup and mathematical model is assuming relatively small value of smoothing capacitance ( $C=76\mu F$  in [14],  $C=198\mu F$  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<sub>I</sub> are

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).

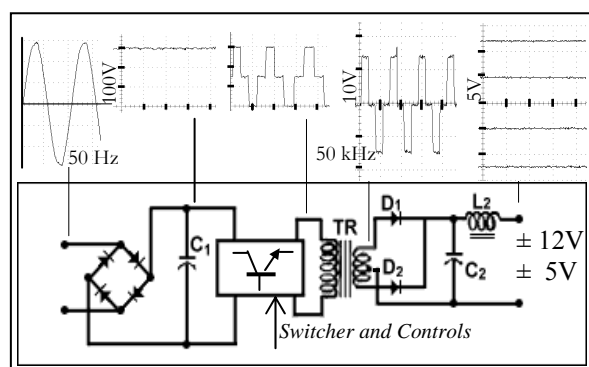


Figure 1. Simplified representation of a PC power supply unit (below) and characteristic wave-shapes (above).

## 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).

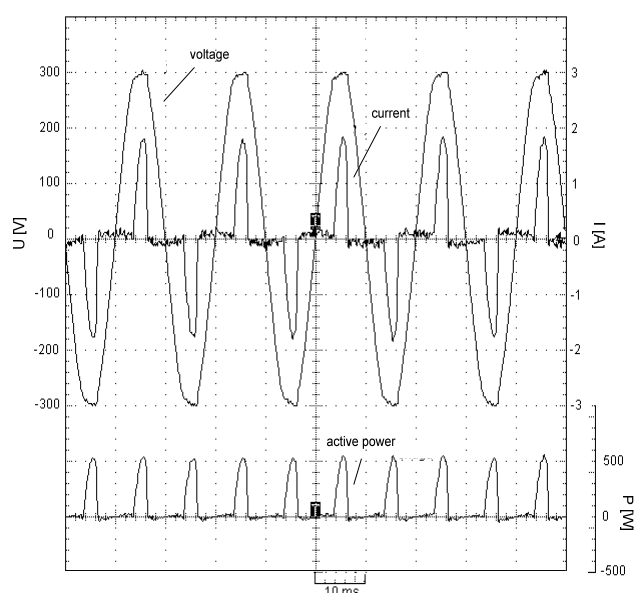


Figure 2. Input voltage and current wave-shapes (above) and instant power consumption (below).

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

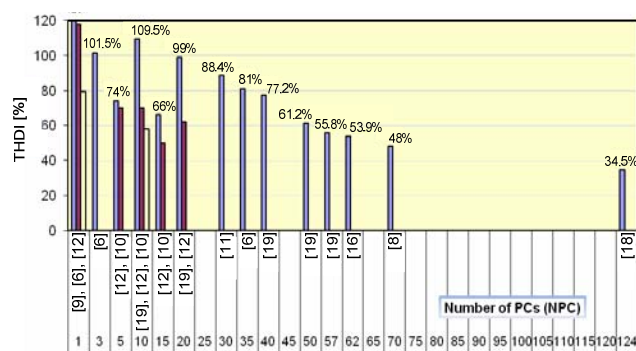
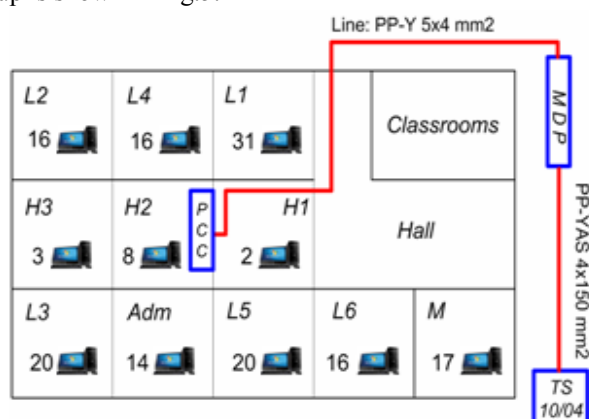


Figure 3. Overview of  $THD_i$  values reported in references, obtained from measurement of harmonic emission of a PCs cluster with different number of PCs.

#### 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.



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	$I_1$ [%]	$I_2$ [%]	$I_3$ [%]
3 <sup>rd</sup>	43.5	28.5	33.2
5 <sup>th</sup>	47.9	24	34.3
7 <sup>th</sup>	34.2	14.3	23.1
9 <sup>th</sup>	20.5	9.4	13.1
11 <sup>th</sup>	10.5	3.7	4.3
13 <sup>th</sup>	9.1	2.7	5.9
15 <sup>th</sup>	10.1	3.8	6.1
17 <sup>th</sup>	6.1	4.2	4.3
19 <sup>th</sup>	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].

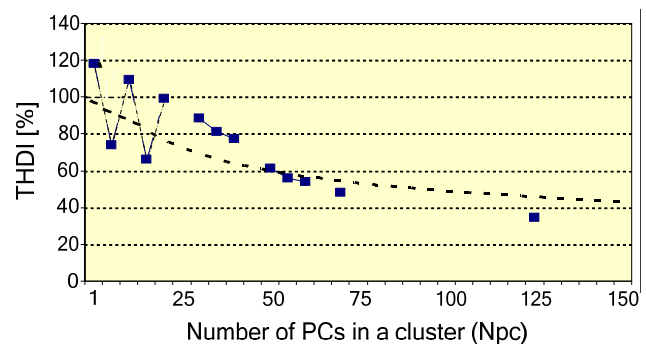


Figure 7. Graph summarizing the  $THDI$  values reported in various references.

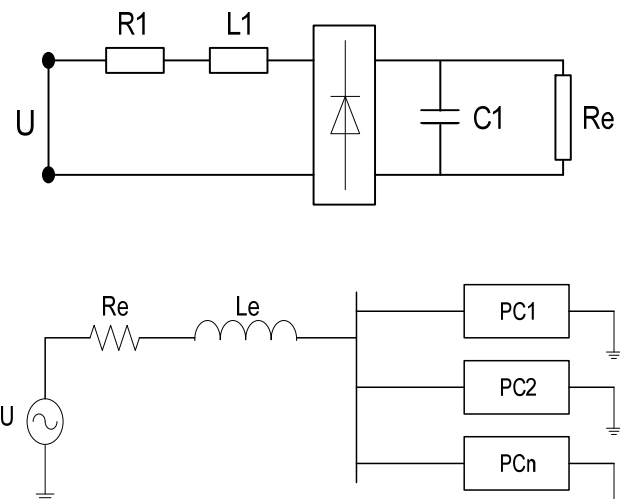


Figure 8. Simple model of a PC (up) and of a PC cluster with  $NPC=n$  (down) used for computer simulation [20].

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  $81 < N_{PC} < 200$ . It 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]:

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

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 ( $1 < N_{PC} < 200$ ). 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].

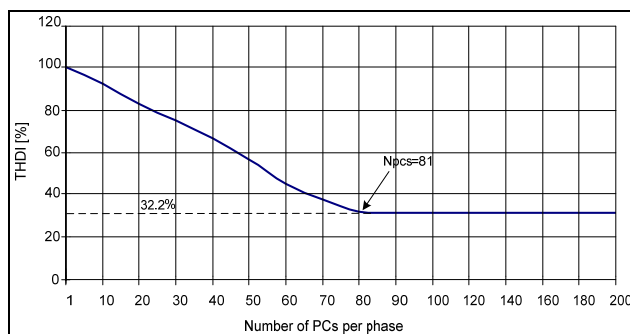


Figure 9. Graphic  $THDI = f(N_{PC})$  dependence presentation ( $C_1 = 235 \mu F$ ).

## VI. EFFECT OF LOAD SIDE PARAMETER ON $THDI$

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  $THDI = f(N_{PC})$  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  $S_{SC} = 4000 \text{ kVA}$ , 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  $THDI$  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  $THDI$  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  $THDI$  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  $470 \mu F$ ,  $680 \mu F$ ,  $820 \mu F$  or  $1000 \mu F$  size, depending on nominal power and manufacturer.

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

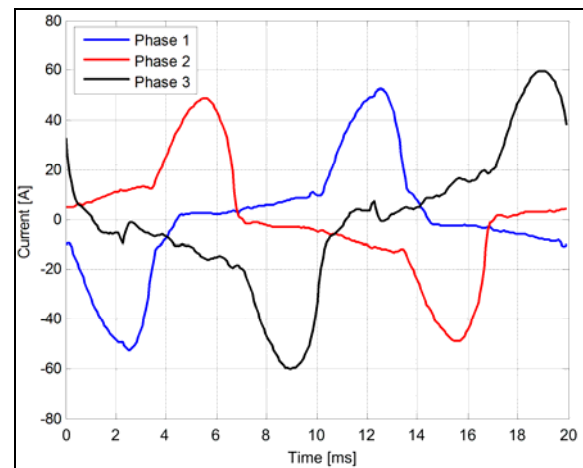


Figure 10. Line current waveforms at the grid supplying mainly standard PCs obtained during the 2<sup>nd</sup> of measurement in Computer centre.

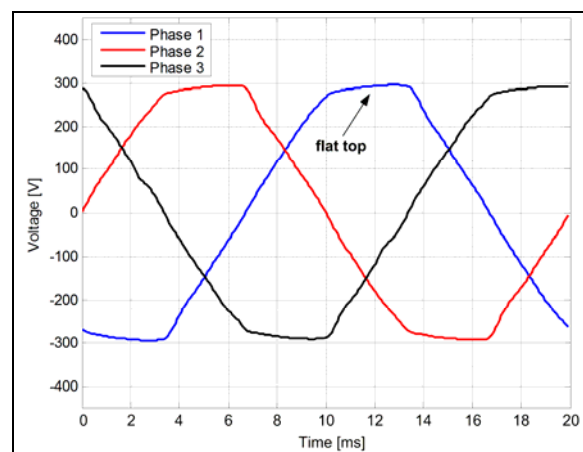


Figure 11. Voltage distortion ("flat top") due to high current pulses in case of PC clusters.

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  $THDI$  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  $THDI$  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  $C_1 = 340 \mu F$ ,  $C_1 = 410 \mu F$  and  $C_1 = 500 \mu F$ , respectively.

Considering these figures and Fig. 9, it can be seen that for a large number of PCs in a cluster the  $THDI$  has steady values between  $THDI = 32.2\%$  and  $THDI = 35.5\%$  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  $N_{PCS}$ .

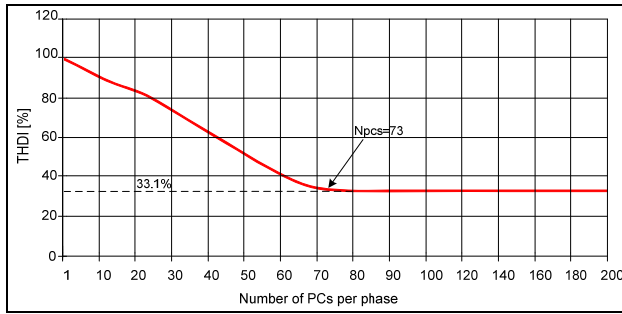


Figure 12. Graphic  $THD_I = f(N_{PC})$  for  $C_1=340 \mu F$ .

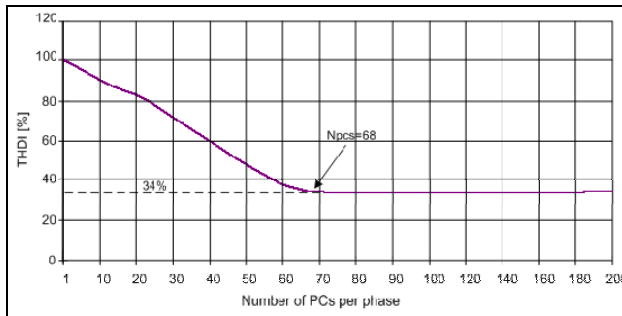


Figure 13. Graphic  $THD_I = f(N_{PC})$  for  $C_1=410 \mu F$ .

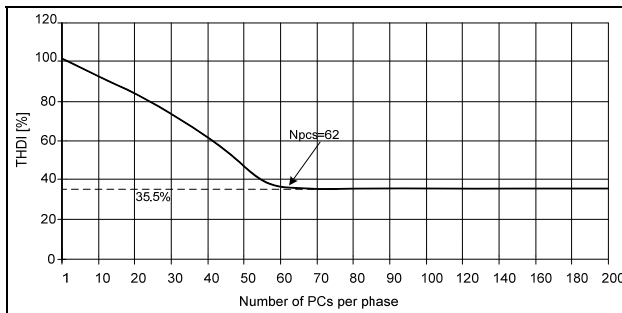


Figure 14. Graphic  $THD_I = f(N_{PC})$  for  $C_1=500 \mu F$ .

## 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:

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

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

where  $C'$  is normalized DC link capacitance  $C' = C_1/C_b$ ,  $C_b = 10^3 \mu F$ .

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)

$C_1 [\mu F]$	$N_{PCS}$ (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  $235 \mu F$  and  $500 \mu F$ . 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 $235 \mu F$ and $500 \mu F$	$N_{PCS}$	$THD_I$ [%]
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  $C_1=235 \mu F$  and 50% of PCs with  $C_1=500 \mu F$  (red, solid line) is at the mid distance from cases of 100%  $C_1=235 \mu F$  and 100%  $C_1=500 \mu F$  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:

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

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

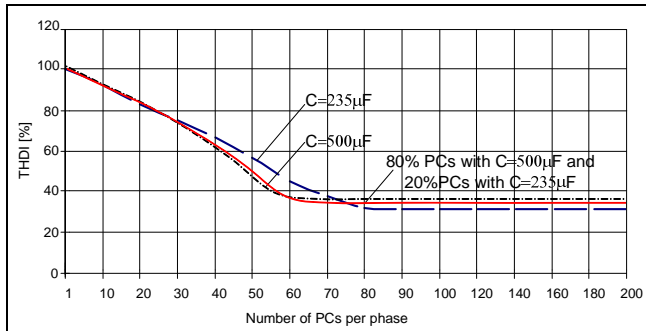


Figure 15.  $THDI=f(NPC)$  curve for PSU share in a cluster: 20% of PCs with  $C_1=235 \mu F$  and 80% of PCs with  $C_1=500 \mu F$  (Red, solid line). Dotted lines represent single type of PSU in a cluster.

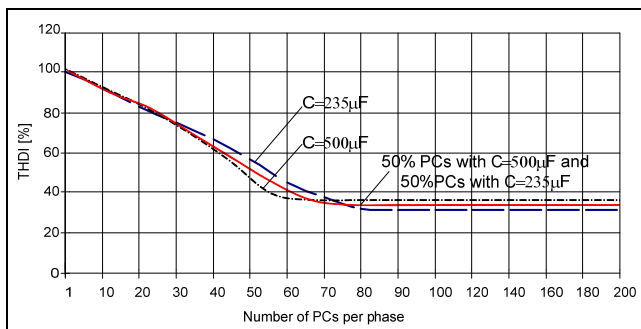


Figure 16.  $THDI=f(NPC)$  curve for PSU share in a cluster: 50% of PCs with  $C_1=235 \mu F$  and 50% of PCs with  $C_1=500 \mu F$  (Red, solid line). Dotted lines represent single type of PSU in a cluster.

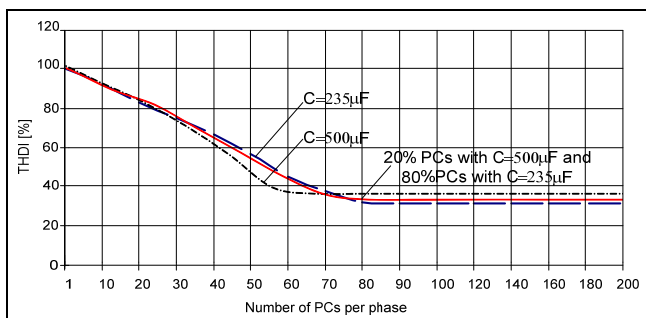


Figure 17.  $THDI=f(NPC)$  curve for PSU share in a cluster: 80% of PCs with  $C_1=235 \mu F$  and 20% of PCs with  $C_1=500 \mu F$  (Red, solid line). Dotted lines represent single type of PSU in a cluster.

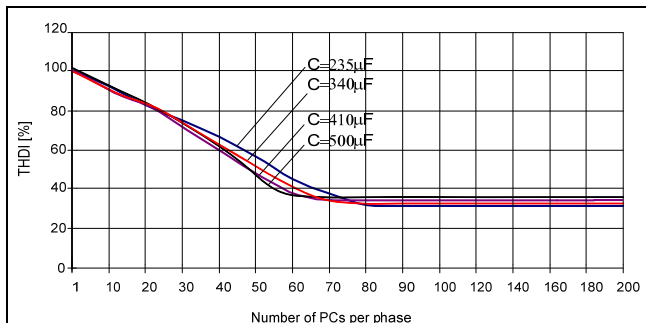


Figure 18.  $THDI=f(NPC)$  curves for PSU with  $C_1=235 \mu F$  (blue),  $C_1=340 \mu F$  (red),  $C_1=410 \mu F$  (violet) and  $C_1=500 \mu F$  (black).

## VIII. DISCUSSION

The new model represented with equations (5) and (6) is developed to ease calculation of  $THDI$  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  $C_1 = 235 \mu F$  and  $C_1 = 500 \mu F$ .

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

The second assumption should be considered in this paper. Due to above feature, the curve  $THDI=f(N_{PC}, 50-50\%)$  is taken as referent one for calculation of deviation of  $THDI=f(N_{PC})$  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  $THDI=f(N_{PC}, 50-50\%)$  (Fig.19-down). It can be seen that relative error in almost all cases is below  $\pm 5\%$ , while RMSE is significantly less then  $\pm 5\%$ .

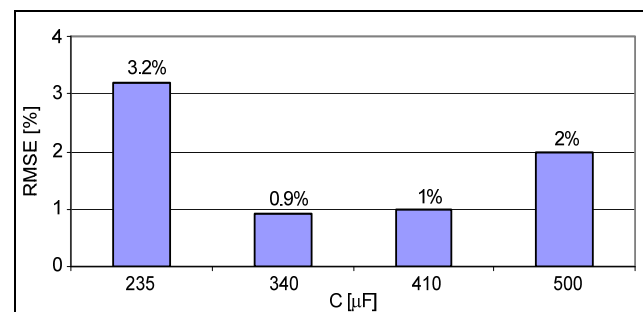
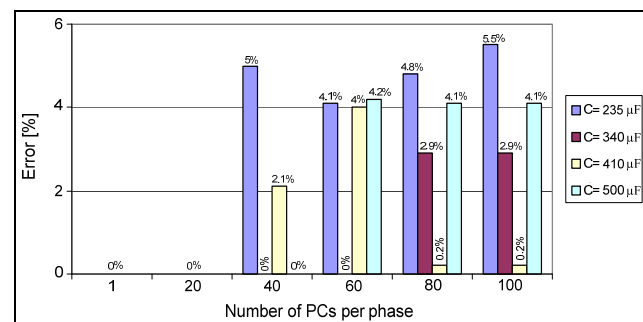


Figure 19. Deviation from  $THDI=f(N_{PC}, 50-50\%)$  curve expressed with relative error (up) and with root mean square error (down).

## 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  $THDI=f(N_{PC})$  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  $\pm 5\%$ , which is acceptable in practical engineering calculation.

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