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Report

MEASUREMENTS OF THE RACK MOUNTED PC'S FOR LHC EXPERIMENTS

Abstract

The design and rating of the LV distribution system for the LHC experiments requires a number of considerations related to network distortions caused by the rack mounted PC's (FARMRACK) for data processing. In the final stage there will be around 2000 rack mounted PC's installed per experiment.

When combining large quantities of identical PC power supplies, issues such as inrush current, harmonic voltage distortion and Neutral loading need to be considered.

The following document summarises the results of the measurements.

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1. INTRODUCTION

The design and rating of the LV distribution system for the LHC experiments requires a number of considerations related to network distortions caused by the rack mounted PC's (FARMRACK) for data processing. In the final stage there will be around 2000 rack mounted PC's installed per experiment.

When combining large quantities of PC's, issues such as inrush current, harmonic voltage distortion and Neutral loading need to be considered.

The following document summarises the results of the measurements.

2. MEASUREMENT SETUP

2.1 Measurement equipment

The currents were measured using clip-on current probes FLUKE 80i-110s. These current probes were directly clipped on the single-phase LV conductor and via BNC connector linked to the input channel of a LeCroy LC9374 1 GHz digital oscilloscope (serial No. 1813).

The current waveforms were recorded with a sampling frequency of 10 kHz or 25 kHz and subsequently post-processed using MATLAB.

The MATLAB routine calculates the RMS value of each data channel, minimum values, maximum values as well as the contents of individual harmonics and Total Harmonic Distortion THD(I). The THD is always given as percentage of the RMS value. The MATLAB routine also creates a number of diagrams and curves for the graphical representation of data.

Photo of Rack-mounted PC's

2.2 Measurement errors

For the current measurements, the following inaccuracies are to be considered:

- current probes, inaccuracy +/-3 %
- oscilloscope, inaccuracy +/-1 %
- additional error of 0.39% due to 8-bit oscilloscope ADC resolution $(+/-\frac{1}{256} = +/-0.39\%)$

Total error = $\sqrt{\left(3^2 + 1^2 + 0.39^2\right)} = 3.2\,\%$

Taking into consideration the individual relative errors of the different components of the measurement chain (current probe, oscilloscope), we obtain a value of ±3.2% (measurement error) for the precision of the measured currents. The MATLAB data post-processing routine adds a mathematical error which is difficult to quantify. Based on previous experiences, we estimate the overall precision of the harmonic measurements to be in the range of ±8% (measurement error + post-processing error).

3. INRUSH CURRENTS DURING ENERGIZATION

3.1 Causes and consequences of inrush currents

The power supply units used in the PC's are of the switch-mode type. The 230 V AC mains voltage is converted into a DC voltage through a single-phase diode bridge rectifier. This DC voltage is then stepped down using a DC/DC converter. In the moment of energization, the internal DC capacitor of the power supply draws a large charging current. If several single-phase PC's are switched on at the same time, the inrush currents of the individual PC's will be exactly in phase and will thus arithmetically add up. Different types of PC's have different amplitudes of inrush currents. None of the rack-mounted PC's measured had a soft-start system.

The inrush current of a large group of PC's switched on simultaneously will have the following effects on the LV distribution system:

- short voltage dip of up to 20 ms in the supplying voltage
- potential maloperation of overcurrent and differential protection if not setup correctly
- electro-dynamic forces due to high current peaks

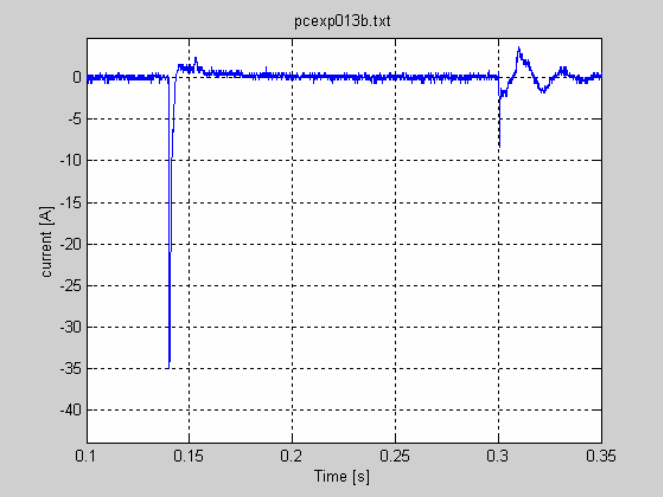
In order to limit or avoid these disturbing effects, it is recommended that only small groups of PC's are energized at a time. Combining different types of PC's in one group might also prove advantageous.

Due to the significant inrush currents it is not recommended to use differential protection in the LV distribution system. The settings for the overcurrent protection shall take into account the maximum inrush current of the largest group to avoid false trips (time delay and overcurrent settings).

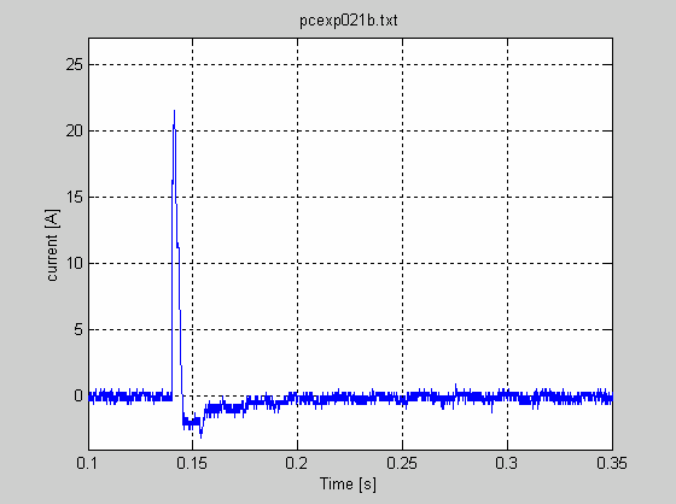
3.2 Inrush measurements

The rack mounted PC's showed violent inrush currents during the tests:

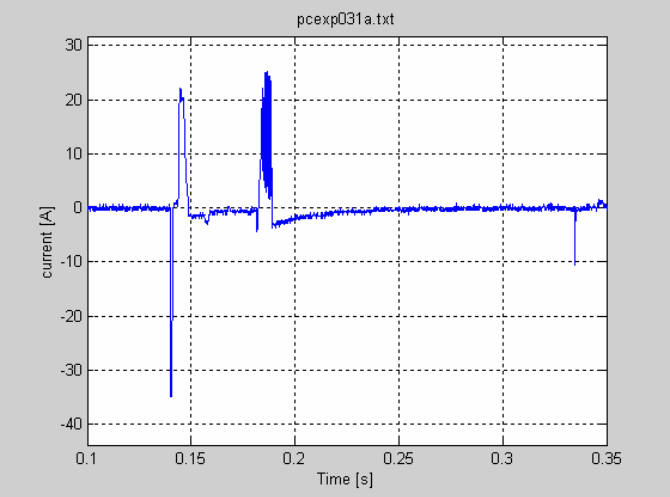
- LBFARM0009 MELROW single-CPU	80 x In	(measurement No. pcexp013b)
- BFARM0005ELONEX single-CPU	40 … 80 x In	(measurements No. pcexp021b and 21a)
- BFARM0040 ELONEX dual-CPU	45 x In	(measurement No. pcexp031a)



LBFARM0009 MELROW single-CPU (measurement No. pcexp013b)



BFARM0005ELONEX single-CPU (measurements No. pcexp021b and 21a)



BFARM0040 ELONEX dual-CPU (measurement No. pcexp031a)

4. CALCULATION OF STEADY-STATE CURRENT IN THE NEUTRAL

The neutral current in any symmetrical or unsymmetrical three-phase power system can be calculated as the vector sum of the individual phase currents Ir, Is and It. The angle between the three phase currents is $2\pi/3$.

$$\underline{I}^N = \underline{I}^R + \underline{I}^S + \underline{I}^T$$

$$\underline{I}^N(t) = \sum_{n=1}^{\infty} e^{j2\pi n f_0 t}(I_n^R + I_n^S e^{j4\pi n/3} + I_n^T e^{j2\pi n/3}) \qquad (1)$$

This gives the following expression for the fundamental component of the current (n=1):

$$\underline{\underline{I_1^N(t) = e^{j2\pi f_0 t}(I_1^R + I_1^S e^{j4\pi/3} + I_1^T e^{j2\pi/3})}} \qquad (2)$$

with $e^{j2\pi/3} = \cos\frac{2\pi}{3} + j\sin\frac{2\pi}{3} = \underline{a}$

and $e^{j4\pi/3} = \cos\frac{4\pi}{3} + j\sin\frac{4\pi}{3} = \cos\frac{2\pi}{3} - j\sin\frac{2\pi}{3} = \underline{a}^2$

For the fundamental component of a symmetrical four-wire LV system, the amplitudes of the three phase currents would be equal:

$$I_1 = I_1^R = I_1^S = I_1^T$$

Hence

$$\underline{I_1^N(t) = e^{j2\pi f_0 t}\ I_1\ (1 + e^{j4\pi/3} + e^{j2\pi/3})} \qquad (3)$$

and

$$\underline{I}_1^N(t) = 0 \qquad \text{because} \quad 1 + e^{j4\pi/3} + e^{j2\pi/3} = 1 + \underline{a}^2 + \underline{a} = 0$$

For the 3rd harmonic component (also for the 6th, 9th, 12th …etc.), the neutral current is the sum of the amplitudes of the three phase currents:

$$\underline{I}_3^N(t) = e^{j2\cdot3\pi f_0 t}(I_3^R + I_3^S e^{j4\cdot3\pi/3} + I_3^T e^{j2\cdot3\pi/3})$$

$$\underline{I}_3^N(t) = e^{j6\pi f_0 t}(I_3^R + I_3^S e^{j4\pi} + I_3^T e^{j2\pi})$$

$$\underline{I_3^N(t) = e^{j6\pi f_0 t}(I_3^R + I_3^S + I_3^T)} \qquad (4)$$

For the 5rd harmonic component, the neutral current is calculated as follows:

$$\underline{I}_5^N(t) = e^{j2\cdot5\pi f_0 t}(I_5^R + I_5^S e^{j4\cdot5\pi/3} + I_5^T e^{j2\cdot5\pi/3})$$

$$\underline{I_5^N(t) = e^{j10\pi f_0 t}(I_5^R + I_5^S e^{j20\pi/3} + I_5^T e^{j10\pi/3})} \qquad (5)$$

with $e^{j10\pi/3} = \cos\frac{10\pi}{3} + j\sin\frac{10\pi}{3}$

and $e^{j20\pi/3} = \cos\frac{20\pi}{3} - j\sin\frac{20\pi}{3}$

The presence of 3rd, 6th and 9th harmonic currents requires particular attention, as the neutral conductor carries the arithmetical sum of the harmonic currents of the three phases. Already small 3rd, 6th or 9th harmonic currents in the phases result in considerable RMS values in the neutral conductor.

The measurements show that the fundamental frequency and the 3rd, 5th and 9th harmonics account for 95% of RMS current in the phases and neutral.

The measurements show that the 3rd harmonic component phase current of individual PC's is usually in the order of 10 ... 30% of the fundamental component. In case of a very high 3rd harmonics in the phase currents, the neutral conductor could be overloaded. However, during the measurements performed on one rack the RMS current in the neutral conductor was only 60% of the largest phase current (see article 5.4.5).

In order to reduce the RMS current in the neutral as much as possible it is recommended to combine different types of PC's in one rack. This method averages the amount of 3rd harmonics generated per feeder and avoids the critical case where the 3rd harmonic equals 100% of fundamental phase current.

For an installation where the RMS neutral current is critical, the neutral shall be protected against overload. It is recommended to permanently monitor the RMS current in the neutral, within the switchboard as well as at the transformers LV side. The overload protection and monitoring devices shall be able to measure the fundamental component of the current as well as all harmonics up to at least n=13 (true RMS).

To minimise the fundamental component of the neutral current, the load of the three phases shall be balanced as much as possible. This approach maximises the number of PC's which can be supplied per LV feeder.

Please note that high currents in the neutral increases the voltages neutral–ground. In case of high 3rd harmonic currents in the neutral, the voltage neutral–ground has a frequency of 150 Hz. Additional investigations of this issue might be necessary to avoid EMC and safety problems.

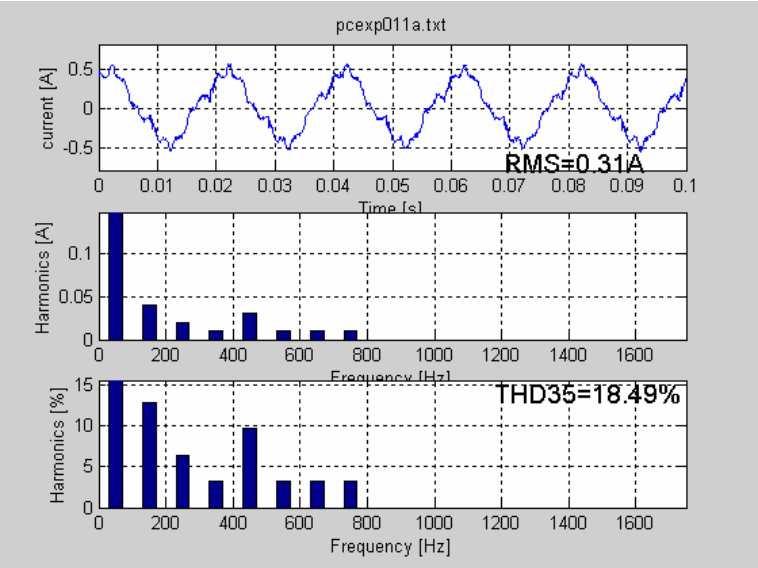
5. MEASUREMENTS OF HARMONICS

5.1 Harmonic spectrum of PC LBFARM0009 MELROW

For detailed information on the power supply unit, see [7].

5.1.1 Steady-state in idle mode

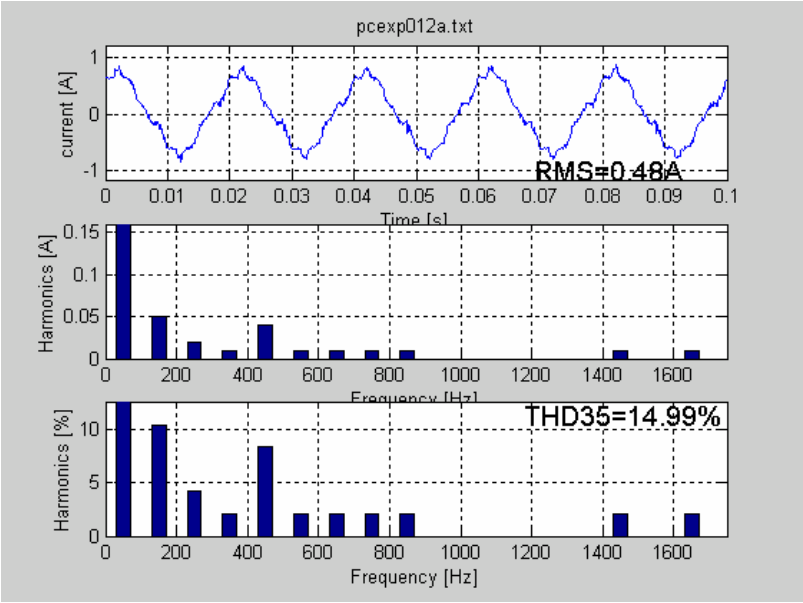
The following measurement concerns the steady-state current in idle mode of one individual PC. This PC is characterized by strong 3rd and 9th harmonics.



harmonics n	current [A]	Current [%]
1	0.31	99.76
2	0	0
3	0.04	12.87
4	0	0
5	0.02	6.44
6	0	0
7	0.01	3.22
8	0	0
9	0.03	9.65
10	0	0
11	0.01	3.22
12	0	0
13	0.01	3.22
14	0	0
15	0.01	3.22
16 … 35	0	0
THD(I) [%]		**18.49**
RMS [A]		**0.31**

5.1.2 Steady-state at maximum power

The following measurement concerns the steady-state current at maximum power (microprocessor in operation) of one individual PC. This PC is characterized by strong 3rd and 9th harmonics. Compared to idle mode, the relative contents of harmonics is slightly lower at maximum power. The RMS current ratio max. power / idle mode is 0.48A / 0.31A (=1.55).



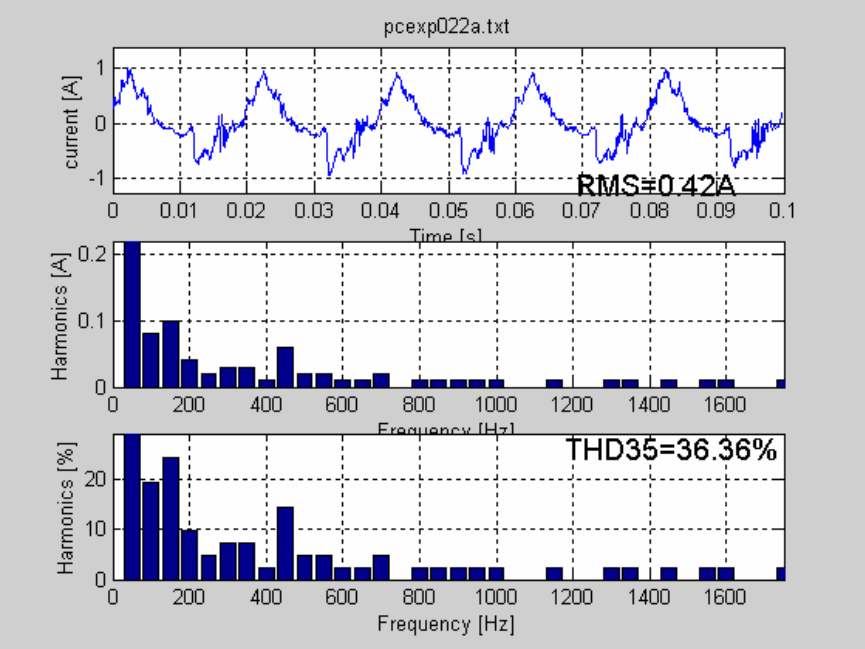
harmonics N	current [A]	current [%]
1	0.48	99.73
2	0	0
3	0.05	10.39
4	0	0
5	0.02	4.16
6	0	0
7	0.01	2.08
8	0	0
9	0.04	8.31
10	0	0
11	0.01	2.08
12	0	0
13	0.01	2.08
14	0	0
15	0.01	2.08
16	0	0
17	0.01	2.08
18 … 28	0	0
29	0.01	2.08
30 … 32	0	0
33	0.01	2.08
34 … 35	0	0
THD(I) [%]		**14.99**
RMS [A]		**0.48**

5.2 Harmonic spectrum of PC BFARM0005 ELONEX single-CPU 1U horizontal

For detailed information on the power supply unit, see [8].

5.2.1 Steady-state in idle mode

The following measurement concerns the steady-state current in idle mode of one individual PC. This PC is characterized by extremely strong 3rd and 9th harmonics. Further it shows an asymmetry between positive and negative half-wave, resulting in strong 2nd harmonics. The harmonic spectrum indicates that the PC power supply unit is of a very low quality.

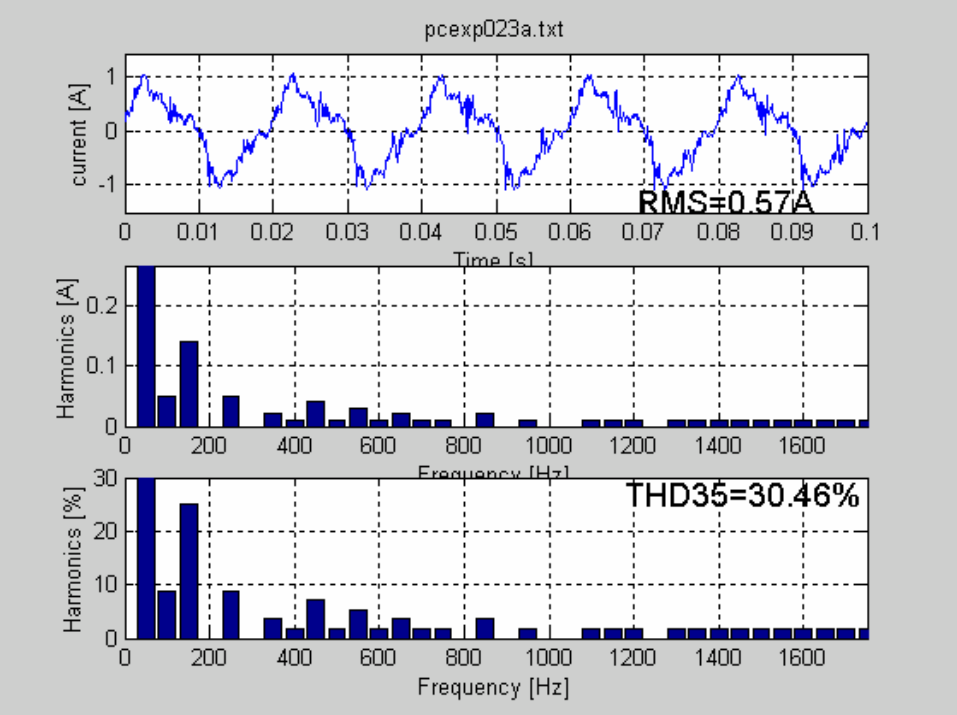


harmonics n	current [A]	current [%]
1	0.38	92.11
2	0.08	19.39
3	0.1	24.24
4	0.04	9.7
5	0.02	4.85
6	0.03	7.27
7	0.03	7.27
8	0.01	2.42
9	0.06	14.54
10	0.02	4.85
11	0.02	4.85
12	0.01	2.42
13	0.01	2.42
14	0.02	4.85
15	0	0
16	0.01	2.42
17	0.01	2.42
18	0.01	2.42

harmonics n	current [A]	current [%]
19	0.01	2.42
20	0.01	2.42
21	0	0
22	0	0
23	0.01	2.42
24	0	0
25	0	0
26	0.01	2.42
27	0.01	2.42
28	0	0
29	0.01	2.42
30	0	0
31	0.01	2.42
32	0.01	2.42
33	0	0
34	0	0
35	0.01	2.42
THD(I) [%]		**36.36**
RMS [A]		**0.42**

5.2.2 Steady-state at maximum power

The following measurement concerns the steady-state current at maximum power (microprocessor in operation) of one individual PC. This PC is characterized by strong 3rd and 9th harmonics. Further it shows an asymmetry between positive and negative half-wave, resulting in strong 2nd harmonics. Compared to idle mode, the relative contents of harmonics is slightly lower at maximum power. The RMS current ratio max. power / idle mode is 0.57A / 0.42A (=1.36).



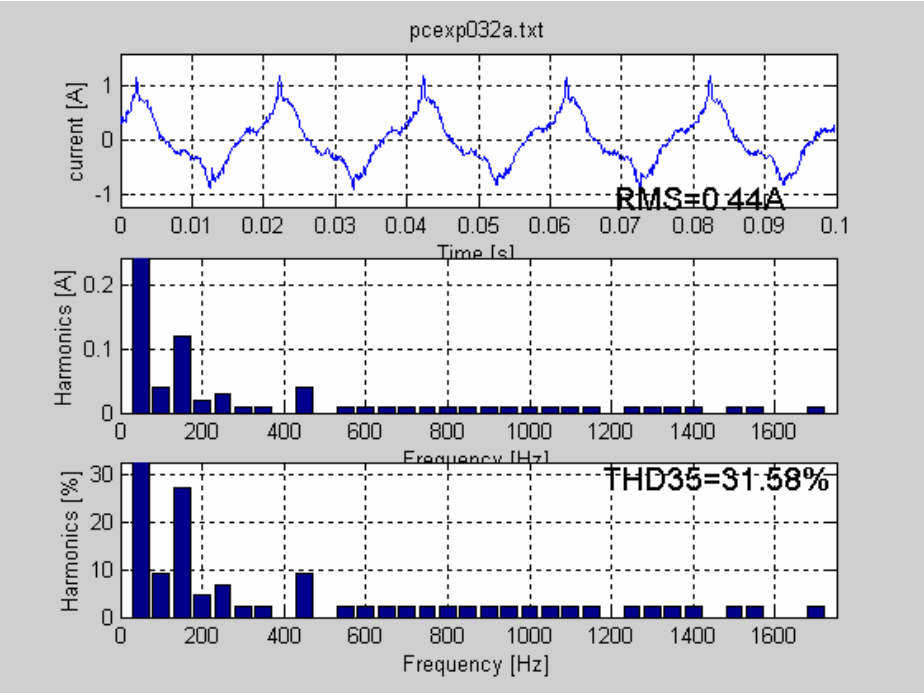
harmonics n	current [A]	current [%]
1	0.53	94.66
2	0.05	8.93
3	0.14	25
4	0	0
5	0.05	8.93
6	0	0
7	0.02	3.57
8	0.01	1.79
9	0.04	7.14
10	0.01	1.79
11	0.03	5.36
12	0.01	1.79
13	0.02	3.57
14	0.01	1.79
15	0.01	1.79
16	0	0
17	0.02	3.57
18	0	0

harmonics n	current [A]	current [%]
19	0.01	1.79
20	0	0
21	0	0
22	0.01	1.79
23	0.01	1.79
24	0.01	1.79
25	0	0
26	0.01	1.79
27	0.01	1.79
28	0.01	1.79
29	0.01	1.79
30	0.01	1.79
31	0.01	1.79
32	0.01	1.79
33	0.01	1.79
34	0.01	1.79
35	0.01	1.79
THD(I) [%]		**30.46**
RMS [A]		**0.57**

5.3 Harmonic spectrum BFARM0040 ELONEX dual-CPU 2.4GHz 1U horizontal

5.3.1 Steady-state in idle mode

The following measurement concerns the steady-state current in idle mode of one individual PC. This PC is characterized by very large 3rd harmonics. Further it shows an asymmetry between positive and negative half-wave, resulting in 2nd harmonics.

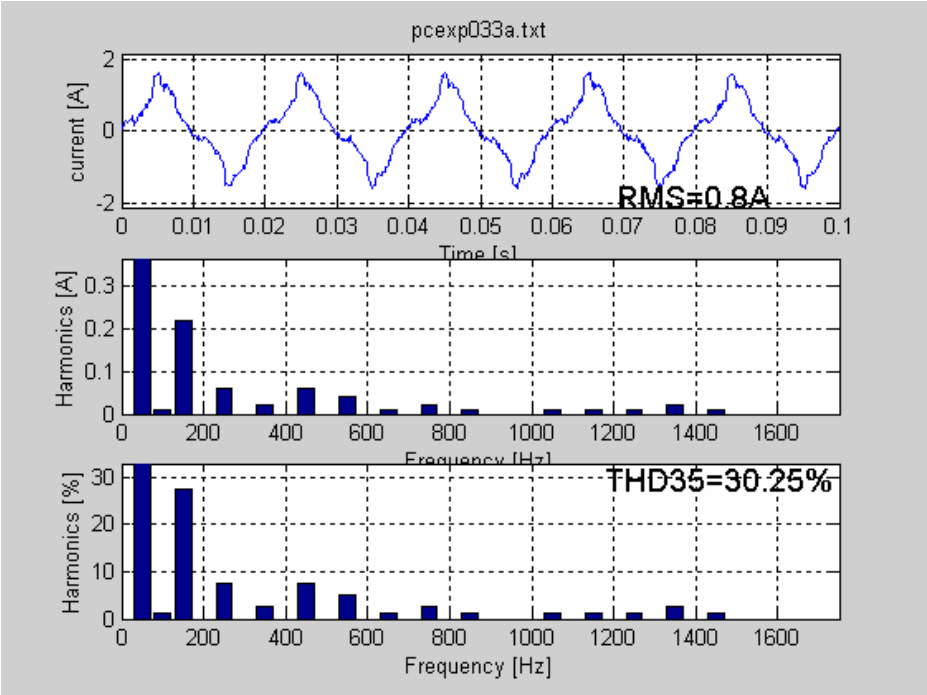


harmonics n	current [A]	current [%]
1	0.42	94.74
2	0.04	9.02
3	0.12	27.07
4	0.02	4.51
5	0.03	6.77
6	0.01	2.26
7	0.01	2.26
8	0	0
9	0.04	9.02
10	0	0
11	0.01	2.26
12	0.01	2.26
13	0.01	2.26
14	0.01	2.26
15	0.01	2.26
16	0.01	2.26
17	0.01	2.26
18	0.01	2.26

harmonics n	current [A]	current [%]
19	0.01	2.26
20	0.01	2.26
21	0.01	2.26
22	0.01	2.26
23	0.01	2.26
24	0	0
25	0.01	2.26
26	0.01	2.26
27	0.01	2.26
28	0.01	2.26
29	0	0
30	0.01	2.26
31	0.01	2.26
32	0	0
33	0	0
34	0.01	2.26
35	0	0
THD(I) [%]		**31.58%**
RMS [A]		**0.44**

5.3.2 Steady-state at maximum power

The following measurement concerns the steady-state current in idle mode of one individual PC. This PC is characterized by extremely strong 3rd harmonics. Further it shows an asymmetry between positive and negative half-wave, resulting in 2nd harmonics.
Compared to idle mode, the RMS current is about the double.
Compared to BFARM0005 ELONEX single-CPU 1U horizontal, the RMS current is about 40% higher.



harmonics n	current [A]	current [%]
1	0.77	95.81
2	0.01	1.24
3	0.22	27.37
4	0	0
5	0.06	7.47
6	0	0
7	0.02	2.49
8	0	0
9	0.06	7.47
10	0	0
11	0.04	4.98
12	0	0
13	0.01	1.24
14	0	0
15	0.02	2.49
16	0	0
17	0.01	1.24
18	0	0

harmonics n	current [A]	current [%]
19	0	0
20	0	0
21	0.01	1.24
22	0	0
23	0.01	1.24
24	0	0
25	0.01	1.24
26	0	0
27	0.02	2.49
28	0	0
29	0.01	1.24
30	0	0
31	0	0
32	0	0
33	0	0
34	0	0
35	0	0
THD(I) [%]		**30.25**
RMS [A]		**0.8**

5.4 Harmonic spectrum of the entire rack BFARM with all its PC's

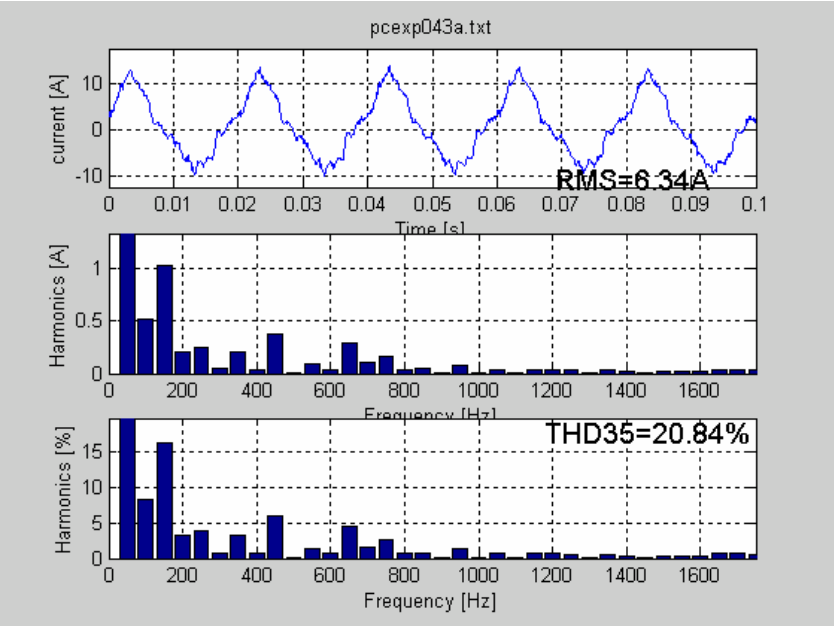
5.4.1 Distribution of PC's between the phases

The distribution of the individual PC's between the three phases is quite unbalanced. The following table shows the number of PC's connected to each phase.

Farm rack - PC distribution between the phases			
	MELROW	ELONEX mono	ELONEX dual
phase R	8	0	3
phase S	10	5	5
phase T	7	0	2

5.4.2 Steady-state at maximum power, phase R (11 PC's)

The following measurement concerns the steady-state current of the entire rack with all its PC's. The PC's are operating at maximum power. Compared to the harmonic spectra of the individual PC's, the harmonic distortion of the entire rack is much lower due to the effect of cancellation of harmonics with different phase angles. Still, the content of 3rd harmonic is relatively high.

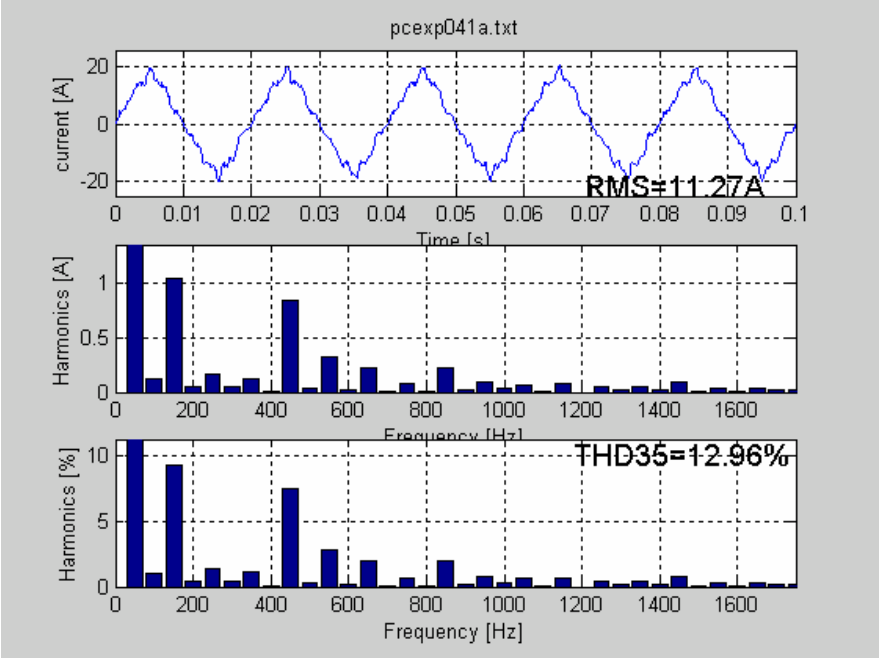


harmonics n	current [A]	current [%]
1	6.13	97.71
2	0.52	8.29
3	1.03	16.42
4	0.21	3.35
5	0.25	3.99
6	0.05	0.8
7	0.2	3.19
8	0.04	0.64
9	0.37	5.9
10	0.01	0.16
11	0.09	1.43
12	0.04	0.64
13	0.29	4.62
14	0.1	1.59
15	0.17	2.71
16	0.04	0.64
17	0.05	0.8
18	0.01	0.16

harmonics n	current [A]	current [%]
19	0.08	1.28
20	0.01	0.16
21	0.04	0.64
22	0.01	0.16
23	0.04	0.64
24	0.04	0.64
25	0.03	0.48
26	0.01	0.16
27	0.03	0.48
28	0.02	0.32
29	0.01	0.16
30	0.02	0.32
31	0.02	0.32
32	0.02	0.32
33	0.04	0.64
34	0.04	0.64
35	0.03	0.48
THD(I) [%]		**20.84**
RMS [A]		**6.34**

5.4.3 Steady-state at maximum power, phase S (20 PC's)

The following measurement concerns the steady-state current of the entire rack with all its PC's. The PC's are operating at maximum power. Compared to the harmonic spectra of the individual PC's, the harmonic distortion of the entire rack is much lower due to the effect of cancellation of harmonics with different phase angles. Still, the content of 3rd and 9th harmonic is relatively high.

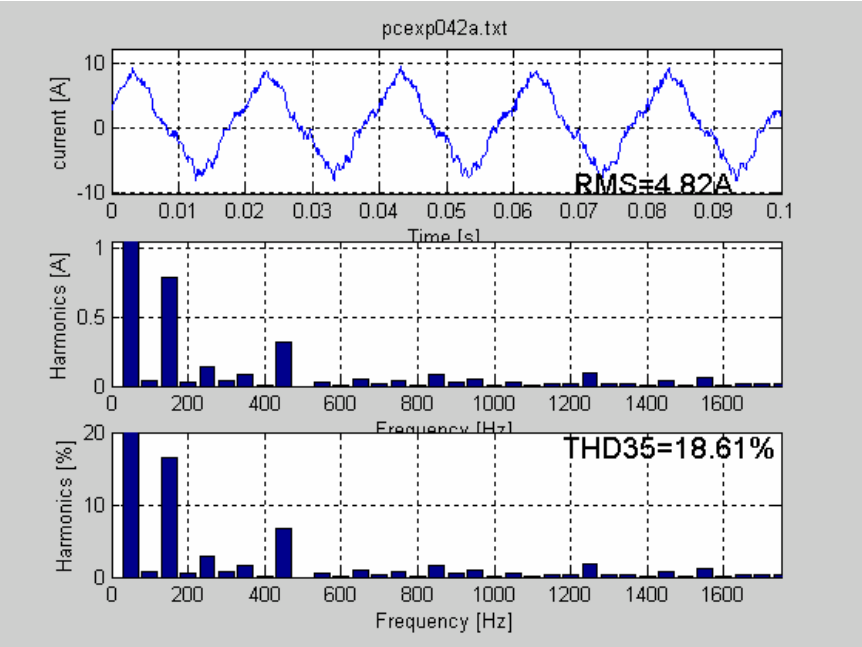


harmonics	current	current
n	[A]	[%]
1	11.16	99.16
2	0.12	1.07
3	1.05	9.33
4	0.05	0.44
5	0.16	1.42
6	0.05	0.44
7	0.13	1.16
8	0.01	0.09
9	0.85	7.55
10	0.03	0.27
11	0.32	2.84
12	0.02	0.18
13	0.23	2.04
14	0.01	0.09
15	0.08	0.71
16	0.01	0.09
17	0.22	1.95
18	0.02	0.18

harmonics	current	current
n	[A]	[%]
19	0.09	0.8
20	0.04	0.36
21	0.07	0.62
22	0.01	0.09
23	0.08	0.71
24	0	0
25	0.05	0.44
26	0.02	0.18
27	0.05	0.44
28	0.02	0.18
29	0.09	0.8
30	0.01	0.09
31	0.03	0.27
32	0.01	0.09
33	0.04	0.36
34	0.02	0.18
35	0.02	0.18
THD(I) [%]		**12.96**
RMS [A]		**11.27**

5.4.4 Steady-state at maximum power, phase T (9 PC's)

The following measurement concerns the steady-state current of the entire rack with all its PC's. The PC's are operating at maximum power. Compared to the harmonic spectra of the individual PC's, the harmonic distortion of the entire rack is much lower due to the effect of cancellation of harmonics with different phase angles. Still, the content of 3rd and 9th harmonic is relatively high.



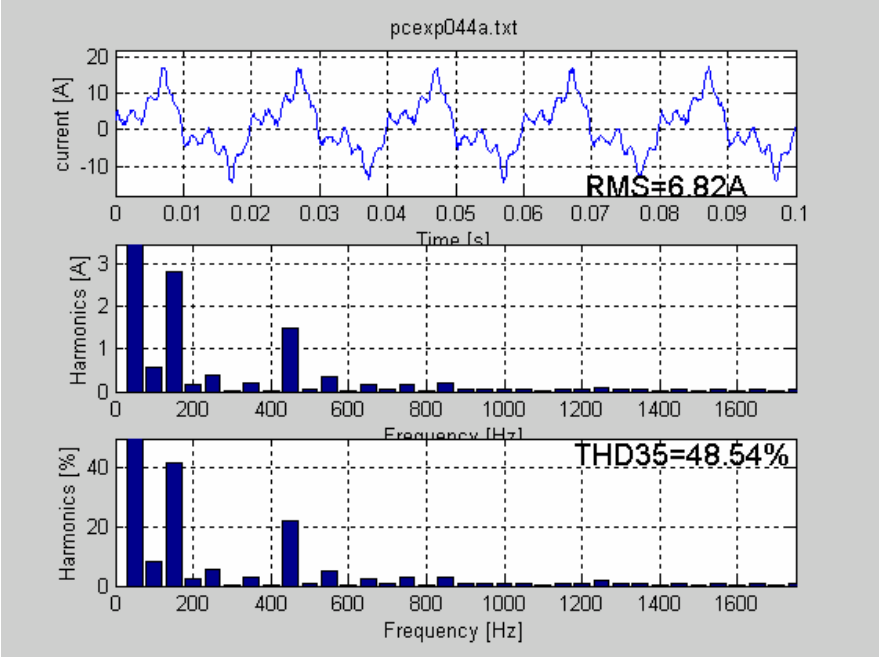
harmonics n	current [A]	current [%]
1	4.67	98.18
2	0.04	0.84
3	0.79	16.61
4	0.03	0.63
5	0.14	2.94
6	0.04	0.84
7	0.08	1.68
8	0.01	0.21
9	0.32	6.73
10	0	0
11	0.03	0.63
12	0.01	0.21
13	0.05	1.05
14	0.02	0.42
15	0.04	0.84
16	0.01	0.21
17	0.08	1.68
18	0.03	0.63

harmonics n	current [A]	current [%]
19	0.05	1.05
20	0.01	0.21
21	0.03	0.63
22	0.01	0.21
23	0.02	0.42
24	0.02	0.42
25	0.09	1.89
26	0.02	0.42
27	0.02	0.42
28	0.01	0.21
29	0.04	0.84
30	0.01	0.21
31	0.06	1.26
32	0.01	0.21
33	0.02	0.42
34	0.02	0.42
35	0.02	0.42
THD(I) [%]		**18.61**
RMS [A]		**4.82**

5.4.5 Steady-state at maximum power, Neutral conductor

The following measurement concerns the steady-state current in the Neutral conductor of the entire rack with all its PC's. The PC's are operating at maximum power. There are 11 PC's connected to phase R, 20 PC's to phase S and 9 PC's to phase T.

The current consists of a 50 Hz-component due to the phase unbalances, as well as large quantities of 3rd and 9th harmonics accumulating in the Neutral (calculation of these currents see article 4). All other frequencies cancel out to a large degree.



harmonics n	current [A]	current [%]
1	5.89	87.38
2	0.56	8.31
3	2.79	41.39
4	0.16	2.37
5	0.39	5.79
6	0.03	0.45
7	0.19	2.82
8	0.01	0.15
9	1.47	21.81
10	0.06	0.89
11	0.35	5.19
12	0.01	0.15
13	0.16	2.37
14	0.06	0.89
15	0.18	2.67
16	0.03	0.45
17	0.21	3.12
18	0.04	0.59

harmonics n	current [A]	current [%]
19	0.04	0.59
20	0.05	0.74
21	0.05	0.74
22	0.02	0.3
23	0.07	1.04
24	0.07	1.04
25	0.11	1.63
26	0.04	0.59
27	0.05	0.74
28	0.01	0.15
29	0.04	0.59
30	0.01	0.15
31	0.07	1.04
32	0.02	0.3
33	0.04	0.59
34	0.02	0.3
35	0.05	0.74
THD(I) [%]		**48.54**
RMS [A]		**6.82**

The following table contains the harmonic current measured in the phases and in the Neutral. Based on the currents measured in the three phases, the harmonic spectrum of the Neutral was calculated according to the equations given in article 4.

The comparison of the two right columns precisely proves the agreement between calculations and measurements (see number marked in blue colour). At the same time it is confirmed that the calculation method is correct and the measurement setup had only small measurement errors (see last column).

		R	S	T	N	*N*	*N (error)*
		meas [A]	meas [A]	meas [A]	meas [A]	*calc [A]*	*calc – meas [% of RMS]*
	1	6.13	11.16	4.67	**5.89**	***5.90***	0.1
	2	0.52	0.12	0.04	**0.56**	***0.45***	-1.7
	3	1.03	1.05	0.79	**2.79**	***2.87***	1.2
	5	0.25	0.16	0.14	**0.39**	***0.10***	-4.2
	6	0.05	0.05	0.04	**0.03**	***0.14***	1.6
	7	0.2	0.13	0.08	**0.19**	***0.10***	-1.3
	9	0.37	0.85	0.32	**1.47**	***1.54***	1.0
	11	0.09	0.32	0.03	**0.35**	***0.27***	-1.2
	12	0.04	0.02	0.01	**0.01**	***0.07***	0.9
	13	0.29	0.23	0.05	**0.16**	***0.22***	0.8
RMS [A]		***6.34***	***11.27***	***4.82***	***6.82***	***6.76***	***-0.9***
THD(I) [%]		***20.84***	***12.96***	***18.61***	***48.54***	***48.97***	

5.5 Summary of Measurement Results

Inrush current
Inrush currents of up to 80 times nominal currents for up to 20 ms were recorded at the worst case.

RMS current in the neutral
Based on measurements on one rack, the Neutral current was about 60% of the largest phase current.

$$\frac{measured\ RMS\ of\ neutral\ current}{measured\ RMS\ of\ phase\ current} = 0.6$$

During the measurements, the load was not well balanced over the three phases. A more symmetrical load (connecting more PC's to the same feeder) would lead to higher 3rd harmonics and to RMS ratios of up to 1.0

It is recommended to use a design ratio of

$$\frac{rated\ RMS\ of\ neutral \max current}{\max.\ RMS\ of\ phase\ current} = 1.0$$

when choosing the component ratings of the LV distribution system, which should be sufficient for most types of PC's under almost symmetrical load conditions.

However, certain types of PC's arranged in perfect three-phase symmetry might reach a theoretical ratio above 1.0, therefore the definitive quantities of the PC's per feeder shall be decided during installation on a per-case basis.

When determining theses quantities, the currents of the three phases and of the neutral shall be measured and documented carefully for the PC's running at maximum power.

6. CONCLUSIONS

6.1 Due to the significant inrush currents it is not recommended to use differential protection in the LV distribution system (safety aspects to be discussed with Safety Commission SC). The inrush current (peak) can be as high as 80 times nominal current for up to 20 ms.

6.2 From the network point of view, the power supply units of the measured rack-mounted PC's were of a relatively low quality, having a large generation of harmonics and high inrush currents. The integrated Active Power Factor Correction of these PC's had no beneficial impact on harmonics and inrush currents. If CERN decides to purchase rack mounted PC's with APFC, they should preferably have very low or no inrush currents and a low contents of harmonics.

6.3 The neutral conductor of the main components (e.g. switchboard, transfo, cables) shall be protected against overload.

6.4 The overcurrent protection of the phases and the neutral shall take into consideration the fundamental and harmonic components of the currents in phases and neutral (true RMS).

6.5 To take advantage of the effect of attenuation and to average 3rd harmonic spectra and inrush currents, it is recommended to connect different types of PC's to the same outgoing LV feeder.

6.6 To minimise the fundamental component of the neutral current and to maximise the number of PC's which can be supplied by one LV feeder, the load of the three phases shall be balanced as much as possible.

6.7 The current in the neutral conductor is mainly a 3rd harmonic current. The recommended design ratio for the rating the neutral of components of the LV distribution network is

$$\frac{rated\ \ RMS\ of\ \ neutral\ \max\ current}{\max .\ RMS\ of\ \ phase\ current} = 1.0$$

When determining the definitive quantities of PC's connected to each feeder on a per-case basis, the currents of the three phases and of the neutral shall be measured and documented carefully for the PC's running at full power.

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