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The significance of the NPLC parameter in ensuring the stability and repeatability of measurement data acquired by reference multimeters

Znaczenie parametru NPLC w zapewnieniu stabilności i powtarzalności danych pomiarowych uzyskanych za pomocą multimetrów referencyjnych

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Abstract: This article contains an analysis of the NPLC (Number of Power Line Cycles) parameter, which affects the repeatability, stability, and the final uncertainty of measurement results. Based on the research, it was shown that measurements performed with NPLC values equal to or greater than 10 yielded almost identical measurement results, with comparable repeatability across successive measurement series for all analyzed multimeters. It was also demonstrated that for the 8588A multimeter, setting the NPLC parameter to 1 produced results nearly identical to those of other multimeters set to 10. The analysis of the obtained results also indicated the possibility of significantly shortening the time required to perform measurement procedures using such multimeters, which often serve as reference standards in laboratories and metrological institutes.

Keywords: metrology, reference multimeters, NPLC, stability, repeatability, voltage sources, uncertainty.

Streszczenie: Niniejszy artykuł zawiera analizę parametru NPLC (Number of Power Line Cycles), który ma wpływ na powtarzalność, stabilność i na ostateczną niepewność wyników pomiarów. Na podstawie badań wykazano, że pomiary realizowane przy NPLC o wartościach równych lub wyższych 10 dawały niemalże identyczne wyniki pomiarów, przy porównywalnej wartości powtarzalności kolejnych serii pomiarowych wszystkich analizowanych multimetrów. Wykazano także, że dla multimetru 8588A, ustawienie parametru NPLC równego 1 dało niemalże identyczny wynik w porównaniu do pozostałych multimetrów przy ustawieniu równym 10. Analiza otrzymanych wyników wykazała także możliwość znacznego skrócenia czasu wykonywania procedur pomiarowych z wykorzystaniem takich multimetrów, będących często wzorcami odniesienia w laboratoriach i instytutach metrologicznych.

Słowa kluczowe: metrologia, multimetry referencyjne, NPLC, stabilność, powtarzalność, źródła napięcia, niepewność

Introduction

The aim of this research is to compare the influence of the NPLC parameter on the stability and repeatability of measurements performed using reference multimeters with an 8.5-digit resolution. The research will yield guidelines on determining the optimal value of the NPLC parameter, based on the known metrological requirements of the planned measurements, and how this parameter affects a specific type of reference multimeter. The research conducted demonstrates a significant influence on the accuracy of measurements in the case of noisy signals, as presented in publications [1,2], where the impact of NPLC settings on measurement accuracy was analyzed. These findings are of significant importance in the field of electrical measurements and can greatly contribute to the improvement of measurement practices. The research is also intended to provide guidance on which reference multimeter and at what NPLC parameter settings will provide the most stable and repeatable results for metrological confirmation of reference voltage standards.

This paper focuses on the research of four types of reference multimeters with 8.5 digit resolution: 3458A manufactured by Keysight, 3458A (option 02) manufactured by Agilent Technologies, 8508A manufactured by Fluke and 8588A manufactured by Fluke

(Fig. 1). The multimeter manufactured by Keysight and Agilent Technologies are multimeters of the same type, but during the production period the manufacturer changed the company name.

Additionally, the older model manufactured by Agilent Technologies was available in option 02, which is characterized by a significantly lower maximum permissible error when measuring DC voltage. However, the results of the conducted research pertain to the tested multimeters, and it cannot be assumed that they are also applicable to other models of this type of multimeter. DC voltage measurements were carried out in the measurement range of 10 V and the corresponding range of 20 V in the 8508A multimeter.

a)
b)
c)

Fig. 1. Reference multimeters used in the experiments: Keysight/Agilent Technologies type: 3458A/3458A (02) (a), Fluke type: 8508A (b), Fluke type: 8588A (c) [3–4]

The NPLC parameter, also often found in documentation under the name PLC, means the number of power supply cycles during which a single multimeter reading is averaged. Interference introduced by the power supply signal affects the operation of the analog-to-digital converter. It therefore affects the value measured by the multimeter–the measurement value changes depending on the phase of the power supply network. Thus, setting the parameter to a minimum value of 1 allows averaging the reading from the entire power supply signal cycle. Setting the parameter to a higher value improves the stability of the measurements performed. In the case of setting the parameter to a value of 1 at a power supply frequency of 50 Hz, a single measurement time is carried out no faster than 20 ms (1/50 of a second). In the case of a 60 Hz power supply network, this time is no shorter than 16.66 ms. Selecting the appropriate parameter value involves a compromise between stability, repeatability, and the duration of the measurements performed. As part of the research, a comprehensive set of measurements consisting of ten measurement series were carried out at intervals of at least four hours. Each of the ten series consisted of ten readings of each multimeter at different NPLC parameter settings. Measurements of the 3458A, 3458A-02, and 8588A multimeters were performed with NPLC parameter settings of 500, 100, 10, 1, and 0.1. In each case, measurements were performed with a resolution of 8.5 digits in these types of multimeters. In the case of the 8508A multimeter, the manufacturer does not allow manual selection of the parameter value. However, the technical documentation elucidates how the resolution setting and the activation or deactivation of the fast function influence the actual NPLC parameter value of the measurements conducted. Table 1 presents the settings and the corresponding PLC parameter value at which the measurements were performed as part of the tests.

Prior to the measurements, multimeters of the 3458A and 3458A (option 02) underwent an internal auto-calibration procedure, followed by further zeroing utilizing the ‘Math Null’ function, which compensates for any residual offset voltage. Due to their different metrological specificity, multimeters of the 8508A and 8588A types do not have an auto-calibration function. However, both multimeters (8508A and 8588A) were zeroed using the Zero Range function before measurements were taken. Zeroing was performed using a precision jumper, and high-quality Fluke test leads were used for measurements.

Table 1. The PLC settings and value of the 8508A multimeter type under which the tests were conducted [4]

Resolution	Fast mode	PLC value
8.5	OFF	1024
8.5	ON	256
7.5	ON	64
6.5	OFF	16
6.5	ON	1
5.5	ON	3.3 ms

A very stable voltage source, manufactured by Fluke type 732B, was used as a source of stable voltage at 10 V (Fig. 2) [5–7]. Below, based on the manufacturer›s documentation, Table 2 presents the stability of the 732B type voltage source at 10 V.

Table 2. DC Voltage source stability at 23°C ± 1°C according to the Fluke 732B Reference Standard [5]

Output Voltage	Stability [± ppm]		
	30 Days	90 Days	1 Year
10 [V]	0.3	0.8	2.0

However, based on the many years of observations carried out so far, it is evident that the actual annual stability of the 732B type voltage sources is at an even higher level. It does not exceed 0.5 ppm at 10 V. By applying the appropriate relations and calibrating this type of voltage source using a standard based on the Josephson effect, it is possible to estimate the exact value of the voltage source at 10 V with an accuracy of better than 0.3 ppm [8]. However, even assuming the stability at the level specified by the manufacturer means that this source will work very well for the planned tests. The above-mentioned voltage sources are resistant to the influence of environmental conditions (e.g. temperature, humidity), especially when used as group standards, which confirms their suitability for this type of research [10].

Novelty of the work

The originality of this research lies in addressing several issues related to NPLC parameter settings that have not been thoroughly studied concerning their impact on calibration and stability check results for measurement standards in laboratory settings with an undisturbed power supply network. This research examines four of the most commonly used types of reference multimeters to clarify how to choose the value of the NPLC parameter while achieving a balance between the duration of the measurement procedure and:

- the impact of a value of the NPLC parameter that is too low on the measurement results obtained with various types of multimeters,
- the influence of a value of the NPLC parameter that is too low on the repeatability of the measurement results obtained with various types of multimeters,
- the effect of a value of the NPLC parameter that is too low on the uncertainty of measurements performed with different types of multimeters.

The work also offers valuable guidance on selecting a reference multimeter for conducting calibrations and checks using reference multimeters. It particularly emphasizes choosing a reference multimeter for verifying the DC voltage reference standard in laboratories and metrology institutes.

Research and methods

The research was conducted by directly measuring the voltage source using the tested objects. The diagram of the measuring system is shown in the figure below (Fig. 2).

The 10 V point measurements were made on the 10 V range of the 3458A, 3458A-02, and 8588A multimeter types. In the case of the 8508A type, measurements were performed within the 20 V measurement range, as this multimeter is not equipped with a 10 V measurement range. To perform the analysis, a series of graphs (Figs. 3–6) was prepared, showing the average values of measurements with each multimeter for all the NPLC parameter values.

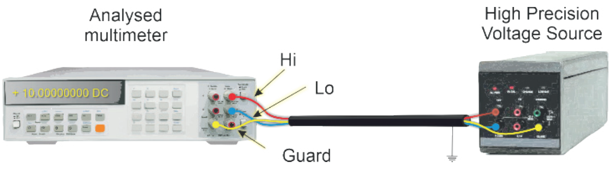

Fig. 2. Measurement system diagram showing the Fluke type 732B precision voltage source used in the study

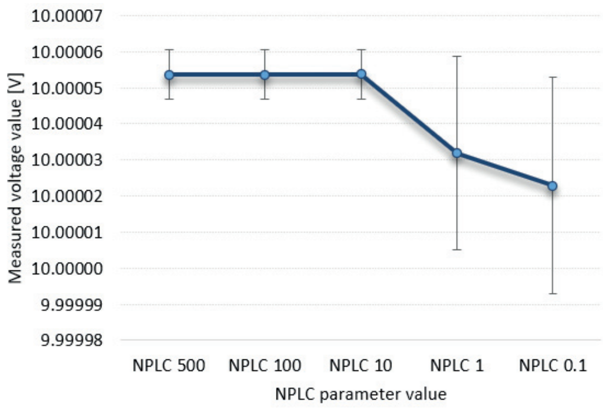

Fig. 3. Measurement of 10 V on 10 V measurement range results obtained with a 3458A multimeter

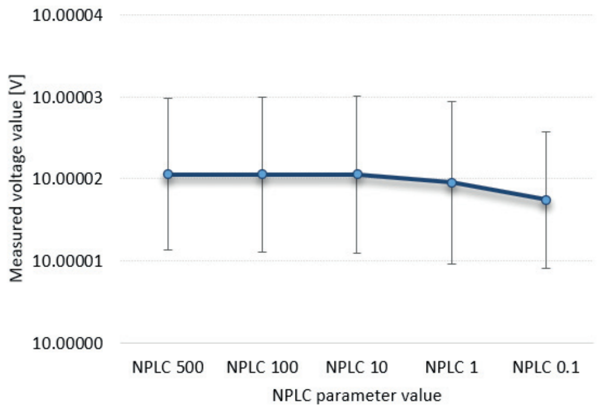

Fig. 4. Measurement of 10 V on 10 V measurement range results obtained with a 3458A-02 multimeter

The error bars visible at each point on the graphs indicate the spread of the average values from all measurement series. The discrepancy in the results obtained between subsequent multimeters is not the most crucial element here (Tab. 3), because it results from the value of the current correction of each multimeter on a specific measurement range. From the metrological and mutual consistency aspect of measurement results, it is essential that the differences of the measured value

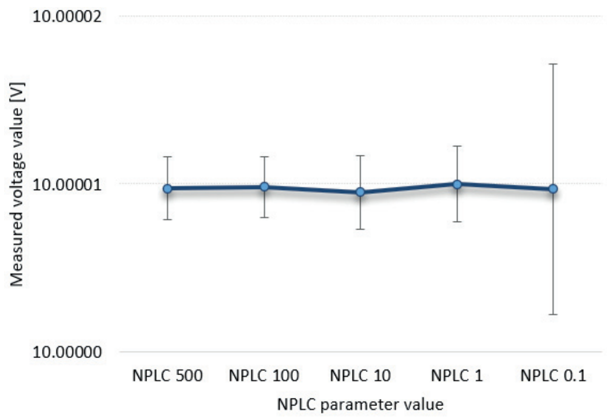

Fig. 5. Measurement of 10 V on 10 V measurement range results obtained with a 8588A multimeter

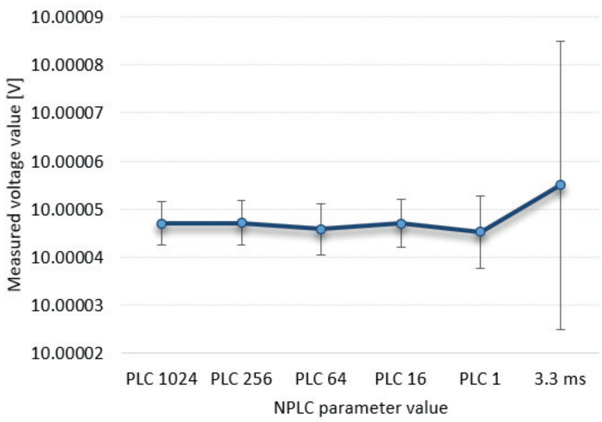

Fig. 6. Measurement of 10 V on 20 V measurement range results obtained with a 8508A multimeter

in relation to the unknown actual value of the voltage source do not exceed the value of the expanded uncertainty of the measurements performed and the measured values of the source, expanded by the value of measurement uncertainty of each of the multimeters, overlap. If the determined reference values, taking into account the range of the calculated measurement uncertainty, did not overlap, it would mean that one of the multimeters does not meet the adopted measurement specification, or an error was made in estimating the uncertainty that had a significant impact on the estimated value of uncertainty. All multimeters used for measurements have actual calibration certificates confirming their compliance with the adopted specification; therefore, their uncertainty ranges should overlap.

It should be noted that each point shown on the graphs represents the average of 10 measurement series, with each series comprising 10 readings from each multimeter at each NPLC setting (1). This means that each point is, in fact, the average reading of 100 readings taken at that NPLC setting. Therefore, this sample can be considered representative, and possible conclusions can be drawn from it.

$$W_{avg} = \frac{\sum_{s=1}^{L_s} W_{av}\left(\frac{\sum_{o=1}^{L_o} W_o}{L_o}\right)}{L_s} \tag{1}$$

where:
W_{avg} measured value being the average of all measurement series,
W_{av} – average value of the single measured series,
W_o – the value of a single multimeter measurement of a given measurement series (multimeter indication),
L_o – number of readings in each measurement series,
L_s – number of measurement series.

In data analysis, visible error bars at every point are extremely important. Since the average value of ten readings is often used in metrology as a series of representative measurements, the conducted tests also consist of a series of ten readings, and the visible error bars illustrate the dispersion between these averages.

$$X_r = \frac{\max(W_{av=1\ldots10}) - \min(W_{av=1\ldots10})}{2} \tag{2}$$

where:
X_r – spread value of a given multimeter at the selected NPLC setting,
$W_{av=1\ldots10}$ – average value of subsequent measurement series.

To better illustrate the differences in the scatter of various multimeters, the scales of the graphs in each case are identical and are set to 0.00001 V, or 1 ppm of the measured value.

In order to estimate the uncertainty of the measurements performed, four main components should be taken into account [9]. The first is the uncertainty resulting from the scatter of the multimeter readings u_1, calculated as the product of the experimental standard deviation and the number of measurements (3):

$$u_1 = \frac{s(W_{avg})}{\sqrt{n}} = \sqrt{\frac{1}{n(n-1)}\sum_{j=1}^{n}\left(W_{av}(j) - \overline{W_{avg}}\right)^2} \tag{3}$$

where:
n – number of measurement series.

Another component of is the uncertainty resulting from the resolution of the multimeter readings X_m (4):

$$u_2 = \frac{X_m}{\sqrt{12}} \tag{4}$$

The third is the uncertainty resulting from the assumed highest permissible error u_3, most often taken at the level specified in the manufacturer's specification (5):

$$u_3 = \frac{\delta_m \cdot W_{avg} + \delta_R \cdot R}{\sqrt{3}\ \text{(or value 1.96)}} \tag{5}$$

Table 3. Averaged measurement results, including the spread value (X_r) and the difference between the result and the result obtained at the maximum NPLC value of the multimeter ($W_{avg} - W_{avgNLPCmax}$)

Multimeter	3458A					
NPLC	500	100	10	1	0.1	
W_{avg} [V]	10.00005366	10.00005359	10.00005372	10.00003188	10.00002292	
X_r [V]	0.00001362	0.00001369	0.00001372	0.00005381	0.00006027	
$W_{avg} - W_{avgNLPCmax}$ [ppm]	–	−0.01	0.01	−2.18	−3.07	
X_r [ppm]	1.36	1.37	1.37	5.38	6.03	
Multimeter	**3458A-02**					
NPLC	500	100	10	1	0.1	
W_{avg} [V]	10.00002053	10.00002051	10.00002053	10.00001954	10.00001746	
X_r [V]	0.00001850	0.00001889	0.00001917	0.00001985	0.00001666	
$W_{avg} - W_{avgNLPCmax}$ [ppm]	–	0.00	0.00	−0.10	−0.31	
X_r [ppm]	1.85	1.89	1.92	1.99	1.67	
Multimeter	**8588A**					
NPLC	500	100	10	1	0.1	
W_{avg} [V]	10.00000974	10.00000982	10.00000951	10.00000999	10.00000970	
X_r [V]	0.00000375	0.00000362	0.00000439	0.00000449	0.00001489	
$W_{avg} - W_{avgNLPCmax}$ [ppm]	–	0.01	−0.02	0.03	0.00	
X_r [ppm]	0.37	0.36	0.44	0.45	1.49	
Multimeter	**8508A**					
NPLC	1024	256	64	16	1	3.3 ms
W_{avg} [V]	10.00004702	10.00004711	10.00004578	10.00004700	10.00004520	10.00005500
X_r [V]	0.00000891	0.00000928	0.00001050	0.00001000	0.00001500	0.00006000
$W_{avg} - W_{avgNLPCmax}$ [ppm]	–	0.01	−0.12	0.00	−0.18	0.80
X_r [ppm]	0.89	0.93	1.05	1.00	1.50	6.00

where:
δ_m – relative error of reading value (ppm reading),
δ_r – relative error of range value (ppm range),
R – measurement range.

The last component of u_4 is the uncertainty of calibration confirming the compliance of the instrument with the adopted specification (6):

$$u_4 = \frac{U_c}{k} \tag{6}$$

where:
U_c – calibration uncertainty,
k – coverage factor.

The expanded uncertainty of the measurements is ultimately expressed by the formula (7):

$$U(W_{avg}) = k \cdot \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2} \tag{7}$$

The principal, dominant component having the most significant impact on the final resultant expanded uncertainty of measurements is the $u_3$component, resulting from the specification given in the manufacturer's documentation. The final calculated uncertainty of the measurements ranges from 3.1 ppm (for the 8588A multimeter) to 7.7 ppm (for the 3458A multimeter).

Table 4. Uncertainty of the result of measurements obtained with a particular multimeter

Measurement voltage value	10 [V]
Measurement range	10 [V]/20 [V]
3458A	7.7 [ppm]
3458A-02	4.0 [ppm]
8508A	3.6 [ppm]
8588A	3.1 [ppm]

Discussion

When analyzing the obtained measurement results, it should be assumed that the most accurate measurement result possible was obtained with the maximum NPLC value. This result is the reference to which the remaining obtained measurement results were compared. In the case of multimeters type 3458A, 3458A-02, and 8588A, the maximum value of the NPLC parameter at which the tests were conducted was 500. In the case of the 8508A multimeter, due to the specificity of the multimeter's operation, the highest value of the NPLC parameter was 1024 (value at the Resl 8, fast off setting).

Within the conducted research, the most crucial observation is represented by the differences in the average values of individual measurement series depending on the set value of the NPLC parameter. These differences inform us about the reliability of the obtained measurement results in the case of shortening the measurement time by setting a lower NPLC parameter.

The second most important parameter is the value of the dispersion of all average results, depending on the set value of the NPLC parameter. This parameter expresses the dependence of the repeatability of the obtained measurement results on the set NPLC parameter.

For the 3458A type multimeter, a clear difference can be observed on the graph (Fig. 3) between the measurement results obtained at NPLC 500, 100, and 10, and the results obtained at NPLC 1 and 0.1. The results obtained at NPLC 100 and 10 differ from the value at NPLC 500 by only 0.01 ppm, while the results at NPLC with a lower value (1 and 0.1) are characterized by a difference exceeding -2 ppm, which in the case of measurements carried out with a reference multimeter is a disqualifying difference. The scatter of the obtained results observed during the tests is also significantly larger in the case of NPLC, with values of 1 and 0.1, amounting to over 5 ppm. This is a significantly larger value compared to the scatter obtained at NPLC 500, 100, and 10, which reached a maximum of 1.37 ppm. A scatter value exceeding 5 ppm would also have a significant impact on the final uncertainty of the measurements performed.

In the case of the 3458A-02 type multimeter, the tests showed an astonishing result. The measurement results obtained at NPLC 1 and 0.1 do not differ significantly from the results obtained at higher NPLC values. A slight deviation can be observed on the graph (Fig. 4). However, the value of the deviation of the result at NPLC 1 in relation to the result at NPLC 500 is only –0.1 ppm, and at NPLC 0.1, it is only -0.31 ppm. The repeatability of the measurements obtained at all NPLC values is also very comparable, with each case being below 2 ppm. The most repeatable results were obtained at NPLC 0.1. It is surprising that despite the fact that this is a model from the same family of multimeters as the 3458A type multimeter, the test results are so different. Although according to the manufacturer's documentation, the multimeter has better stability parameters than the 3458A multimeter, its test results at NPLC values of 500, 100, 10 and 1 have poorer repeatability, while at NPLC values of 0.1 they have insignificantly better repeatability.

The next Fluke 8588A multimeter delivered the best results during the tests (Fig. 5). All measurement results, including those obtained at NPLC 0.1, were characterized by a difference from the result obtained at NPLC 500 of a maximum of 0.03 ppm. The average result obtained at the lowest NPLC value (i.e., 0.1) differed from the result obtained at NPLC 500 by a value lower than 0.005 ppm. The repeatability of the results obtained at each of the set NPLC values was also the best, and, apart from measurements at NPLC 0.1, was below 0.5 ppm in each case. Only in the case of measurements at NPLC 0.1 did it exceed the value of 1 ppm, amounting to exactly 1.49 ppm.

Due to the specificity of operation, the tests of the 8508A multimeter were carried out with a larger number of NPLC parameter variants. The test results, presented in Fig. 6, indicate that the measurements carried out with the parameter above NPLC 1 are very similar, with differences in the maximum point of -0.12 ppm. The difference in the result at NPLC 1 is slightly larger, amounting to -0.18 ppm, which does not disqualify the obtained results. The spread between the obtained measurement series with NPLC values above 1 fluctuates around 1 ppm, and with an NPLC value equal to 1 it is higher and amounts to 1.5 ppm. The measurements with the NPLC setting at 3.3 ms were slightly worse. The deviation of the obtained result was 0.8 ppm, and the spread between the measurement series, demonstrating the repeatability of the device, was as much as 6 ppm.

Conclusions

Based on the conducted studies, the main conclusion can be drawn that measurements performed at NPLC values equal to or higher than 10 yielded almost identical measurement results with comparable repeatability values in subsequent measurement series. This means that in the vast majority of applications, there is no need to extend the operating time and perform measurements at the highest NPLC parameter value, because the results obtained at NPLC equal to 10 are almost identical, and the obtained measurement dispersion should not affect the final uncertainty of the measurements performed. Measurements at a lower NPLC parameter value than 10 may give results with a deviated value and be characterized by a dispersion that affects the final measurement uncertainty. The measurement results obtained with the 8588A multimeter deserve special attention, which also, in the case of the NPLC parameter 1, gave almost identical results with a very comparable dispersion value.

Analyzing of the obtained results, it can be concluded that the 8588A multimeter represents the optimal choice for conducting calibrations and verifying DC voltage reference standards within metrology laboratories and institutes. The tests, which were conducted at the 10 V measurement point, affirm the high effectiveness of this device under specified conditions. However, since the study was confined to a single measurement range, the results do not permit definitive conclusions regarding the accuracy of measurements across other voltage ranges. Further research that encompasses a broader measurement range could yield more comprehensive data regarding the versatility of this multimeter.

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