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Comparison of RMS Value Measurement Algorithms of Non-coherent Sampled Signals

H. Hegeduš, P. Mostarac, R. Malarić

Department of Electrical Engineering Basics and Measurement, Faculty of Electrical Engineering and Computing, University in Zagreb, Unska3, 10000 Zagreb, Croatia, hrvoje.hegedus@fer.hr

Uncertainty and bias of RMS measurement of digitally non-coherent sampled signal is dependent on the algorithm used. This paper presents the new Averaging two subsets method for RMS value bias correction of non-coherent sampled signal. Methods for estimating RMS values in the time domain are also compared.

Keywords: RMS measurement methods, estimation algorithms, non-coherent sampling

1. INTRODUCTION

TODAY, high resolution analog to digital converters (ADC) are often used for precision measurements of voltage and current. The measurement uncertainty of the RMS value of the analog sinusoidal signal depends on the quality of the ADC and on the algorithms used for RMS estimation. This paper will focus only on the algorithms for RMS estimation of the sinusoidal signal.

The comparison of classical algorithms and windowing based algorithms has been described in [1, 2]. RMS value of the sinusoidal signals with more than 5 periods can be estimated with several windowing based algorithms with the uncertainty better then measurement uncertainty of present ADC systems.

The goal of this paper is to present a new method for estimating RMS value of the sinusoidal signal with less than 5 periods and to compare it with other RMS estimation algorithms. Comparison is done by calculating RMS value of the simulated signal of an exactly known RMS value, by random signal phase to simulate non-coherent sampling and with similar sampling rates to common ADCs.

2. THE ANALYSIS OF THE RMS VALUE MEASUREMENT

A. RMS estimation of sinusoidal signals

By definition, RMS estimation of analog signal $x(t)$ is based on the relation [4]:

$$X_{\mathrm{RMS}} = \sqrt{\frac{1}{T_{\mathrm{M}}}\int_0^{T_{\mathrm{M}}} x^2(t)dt}\,, \tag{1}$$

where T_{M} is time of measurement. Analog sinusoidal signal can be expressed as:

$$x(t) = X_{\mathrm{m}} \cdot \sin(\omega_{\mathrm{sig}} t + \varphi) \tag{2}$$

where X_{m} is signal amplitude, ω_{sig} is signal angular frequency and φ is signal phase relative to start of the measurement. RMS value of analog sinusoidal signal (2) can be calculated as:

$$X'_{\mathrm{RMS}} = \frac{X_{\mathrm{m}}}{\sqrt{2}}\sqrt{\left(1 - \frac{\sin(2\omega_{\mathrm{sig}} T_{\mathrm{m}} + 2\varphi) - \sin(2\varphi)}{2\omega_{\mathrm{sig}} T_{\mathrm{m}}}\right)}\,. \tag{3}$$

Time of measurement can be estimated by the number of signal periods:

$$T_{\mathrm{m}} = (M + \lambda)T_{\mathrm{sig}}, \quad M \in Z, \lambda \in \left[-\frac{1}{2}, \frac{1}{2}\right\rangle, \tag{4}$$

where M is integer number of signal periods and λ is decimal part of noninteger period. RMS value of the sinusoidal signal with $(M+\lambda)$ periods can be calculated using (5) or (6):

$$X'_{\mathrm{RMS}} = \frac{X_{\mathrm{m}}}{\sqrt{2}}\sqrt{\left(1 - \frac{\sin(4\pi\lambda + 2\varphi) - \sin(2\varphi)}{4\pi(M+\lambda)}\right)}\,, \tag{5}$$

$$X'_{\mathrm{RMS}} = \frac{X_{\mathrm{m}}}{\sqrt{2}}\sqrt{\left(1 - \frac{\sin(2\pi\lambda)\cos(2\pi\lambda + 2\varphi)}{2\pi(M+\lambda)}\right)}\,. \tag{6}$$

B. RMS estimation of coherently sampled sinusoidal signals

When sinusoidal signal is coherently sampled, an integer number of sinusoidal periods M is sampled that can be described by equation:

$$\lambda = 0 \quad \rightarrow \quad T_{\mathrm{m}} = MT_{\mathrm{sig}}, \quad M \in Z \tag{7}$$

The RMS value of sinusoidal signal (2) with integer number of periods can be calculated using (8):

$$X_{\mathrm{RMS}} = \frac{X_{\mathrm{m}}}{\sqrt{2}}. \tag{8}$$

Equation (8) shows that the RMS value of sinusoidal signal with integer number of periods is depended only on signal amplitude X_{m}.

C. RMS estimation of non-coherently sampled sinusoidal signal

In real measurements coherent sampling is often hard to carry out. In this case, the measured signal consist of non-integer number of periods $(M+\lambda)$ where $M \in Z$ and $\lambda \neq 0$. The expression for RMS value for non-coherently sampled signal can be estimated by using (5) or (6). It is not dependent only on signal amplitude but also on signal phase φ, integer number of sampled signal periods M and decimal part of the last sampled period λ. The difference between RMS value of non-coherently sampled sinusoidal signal X'_{RMS} (5) or (6) and RMS value of coherently sampled sinusoidal signal X_{RMS} (8) is the bias of the RMS measurement. The relative bias of the RMS value of non-coherent sinusoidal signal can be estimated using (10) or (11):

$$\delta_{\mathrm{RMS}} = \frac{X'_{\mathrm{RMS}} - X_{\mathrm{RMS}}}{X_{\mathrm{RMS}}}, \tag{9}$$

$$\delta_{\mathrm{RMS}} = \sqrt{\left(1 - \frac{\sin(4\pi\lambda + 2\varphi) - \sin(2\varphi)}{4\pi(M+\lambda)}\right)} - 1, \tag{10}$$

$$\delta_{\mathrm{RMS}} = \sqrt{\left(1 - \frac{\sin(2\pi\lambda)\cos(2\pi\lambda + 2\varphi)}{2\pi(M+\lambda)}\right)} - 1. \tag{11}$$

3. The analysis of methods for RMS value bias correction

A. Reducing RMS value bias by minimizing the decimal part of sinusoidal signal period

The bias of the RMS value can be reduced by minimizing the decimal part of period λ to the range defined by the number of samples per period of non-coherently sampled signal. Higher sampling rate ensures more samples per period and lower λ value.

When the analog sinusoidal signal is sampled with N_{SPP} number of samples per period, desired signal phase can be obtained by choosing between two samples. Range of signal phase error caused by non-coherent sampling φ_{S1} can be estimated as (12):

$$\varphi_{\mathrm{S}} \in \left[-\frac{1}{2}\frac{2\pi}{N_{\mathrm{SPP}}}, \frac{1}{2}\frac{2\pi}{N_{\mathrm{SPP}}} \right\rangle, \tag{12}$$

where N_{SPP} is number of samples per period of the sampled analog sinusoidal signal. Exact range of the decimal part of period λ_{S} can be estimated as (13):

$$\lambda_{\mathrm{S}} \in \left[-\frac{1}{N_{\mathrm{SPP}}}, \frac{1}{N_{\mathrm{SPP}}} \right\rangle, \tag{13}$$

where N_{SPP} is number of samples per period of the sampled analog sinusoidal signal. When the decimal part of period λ is in range defined by (13), the maximum expected bias of the RMS value can be calculated by finding maximum of the relation (11).

$$\delta_{\mathrm{RMS\,MAX}} = \left| \sqrt{\left(1 - \frac{\sin(2\pi\lambda_s)\cos(2\pi\lambda_s + 2(\varphi+\varphi_s))}{2\pi(M+\lambda_s)}\right)} - 1 \right|, \tag{14}$$

where φ is desired signal phase relative to start of the measurement, φ_{S1} is phase error caused by non-coherent sampling, M is integer number of periods and λ_{S} is decimal part of period. Equation (14) will have its maximum when the cosine part is equal to 1:

$$\cos(2\pi\lambda_s + 2(\varphi+\varphi_s)) = 1, \tag{15}$$

$$2\pi\lambda_s + 2(\varphi+\varphi_s) = 0. \tag{16}$$

For calculating approximated maximum expected bias of the RMS value, approximations for square root (17) and sine function (18) is used:

$$X \to 0 \quad \to \quad \sqrt{1+X} \approx 1 + \frac{X}{2}, \tag{17}$$

$$X \to 0 \quad \to \quad \sin(X) \approx X. \tag{18}$$

After using approximations (17) and (18) on (14), maximum bias of the RMS value can be approximately calculated as:

$$\delta_{\mathrm{RMS\,MAX}} \approx \frac{\lambda_{\mathrm{S}}}{2(M+\lambda_s)} \tag{19}$$

Maximum bias of the RMS value (21) will be for maximum value of λ_{S} (20) from the range defined by (13):

$$\lambda_{\mathrm{S}} = \pm\frac{1}{N_{\mathrm{SPP}}}, \tag{20}$$

$$\delta_{\mathrm{RMS\,MAX}} \approx \frac{1}{2(M \cdot N_{\mathrm{SPP}} + 1)}. \tag{21}$$

Maximum expected bias of the RMS value expressed in ppm is calculated in Table I using (21) for some common parameters M and N_{SPP}.

TABLE 1. Maximum expected rms value bias (ppm)

Integer number of periods M	Number of samples per period N_{SPP}		
	100	1000	10000
1	5000	500	50
2	2500	250	25
5	1000	100	10
10	500	50	5

Maximum expected RMS value bias calculated for some common parameters M and N_{SPP} using equation (21).

B. Reducing RMS value bias by using the Single subset method

The bias of the RMS value of sinusoidal signal (11) is highly dependent on the signal phase that is shown in Fig.1.

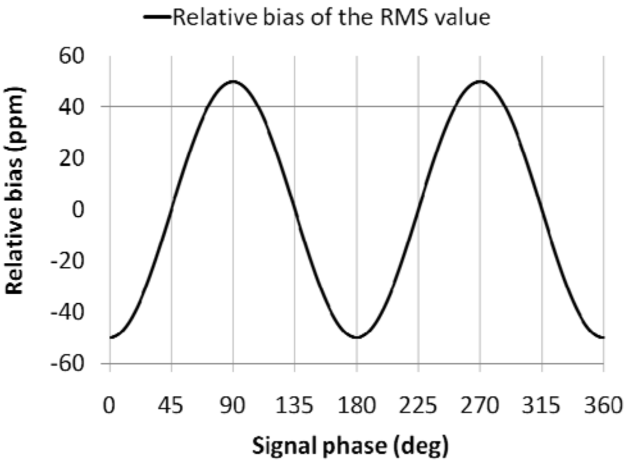

Fig.1. Relative bias of the RMS value of the sinusoidal signal using equation (11) with parameters $M = 5$, $N_{SPP} = 1000$ and $\lambda = 0.0005$ as a function of signal phase $0° < \varphi < 360°$

The bias of the RMS value can be reduced by extracting single subset from main sampled signal with certain signal phases φ where the influence of the RMS value bias is minimal. These phases can be calculated by equaling relation (11) with zero:

$$\delta_{\mathrm{RMS}} = \sqrt{\left(1 - \frac{\sin(2\pi\lambda)\cos(2\pi\lambda + 2\varphi)}{2\pi(M + \lambda)}\right)} - 1 = 0 \tag{22}$$

$$\cos(2\pi\lambda + 2\varphi) = 0 \qquad (23)$$

$$\varphi_{\mathrm{SS}} = \frac{\pi}{4} + k\frac{\pi}{2} - \lambda\pi, \quad k \in \mathrm{Z} \qquad (23)$$

$$\varphi_{\mathrm{SS}} \approx \{45°, 135°, 225°, 315°, ...\}, \quad \lambda \to 0 \tag{24}$$

The main disadvantage of this method is that minimal variation of signal phase from values defined in (23) is causing significant increase of the RMS value bias because the first deviation of function $\delta_{RMS}(\varphi)$ defined by equation (11) has its extremes for these phases.

Maximum expected bias of the RMS value estimated by the *Single subset method* can be calculated as (25):

$$\delta_{\mathrm{SS\,MAX}} = \left| \sqrt{\left(1 - \frac{\sin(2\pi\lambda_{\mathrm{S}})\cos(2\pi\lambda_{\mathrm{S}} + 2(\varphi + \varphi_{\mathrm{S}}))}{2\pi(M + \lambda_{\mathrm{S}})}\right)} - 1 \right| \tag{25}$$

After using approximations for square root (17) and sine function (18), approximated value of maximum expected bias of the RMS value can be calculated as (26):

$$\delta_{\mathrm{SS\,MAX}} \approx \left| \frac{\varphi_{\mathrm{S}}\,\lambda_{\mathrm{S}}}{M + \lambda_{\mathrm{S}}} \right| \tag{26}$$

Maximum expected bias of RMS value (25) and (26) is for parameters (27) and (28):

$$\lambda_{\mathrm{S}} = -\frac{1}{N_{\mathrm{SPP}}} \tag{27}$$

$$\varphi_{\mathrm{S}} = \frac{1}{2}\frac{2\pi}{N_{\mathrm{SPP}}} \tag{28}$$

Approximated value of the maximum expected bias of the RMS value for the *Single subset method* is:

$$\delta_{\mathrm{SS\,MAX}} \approx \frac{\pi}{N_{\mathrm{SPP}}(M \cdot N_{\mathrm{SPP}} - 1)} \tag{29}$$

Maximum expected bias of the RMS value (29) estimated by the *Single subset method* for some common parameters M and N_{SPP} is calculated in Table 2. Values show significant reduction of RMS value bias calculated by the Single subset method in comparison to values in Table 1.

Table 2. Maximum expected RMS value bias (ppm) for Single subset method

Integer number of periods M	Number of samples per period N_{SPP} 100	1000	10000
1	3.2E+02	3.1E+00	3.1E-02
2	1.6E+02	1.6E+00	1.6E-02
5	6.3E+01	6.3E-01	6.3E-03
10	3.1E+01	3.1E-01	3.1E-03

Maximum expected RMS value bias for Single subset method calculated for few common parameters M and N_{SPP} using equation (29).

C. Reducing RMS value bias by using the Averaging two subsets method

The idea of the *Averaging two subsets method* is to extract two signal subsets of the same length from the main sampled signal with certain signal phases to get maximal and minimal bias of RMS value of each subset. By averaging RMS values of these two subsets, RMS value bias can be significantly minimized.

Minimum and maximum of function $\delta_{RMS}(\varphi)$ defined by (11) can be calculated as:

$$\frac{\mathrm{d}\delta_{RMS}}{\mathrm{d}\varphi} = 0 \;\Rightarrow\; \varphi = k\frac{\pi}{2} - \lambda\pi, \quad k \in \mathrm{Z} \tag{30}$$

$$\varphi \approx \{0°, 90°, 180°, 270°, ...\}, \quad \lambda \to 0 \tag{31}$$

To extract two signal subsets of one whole signal period from the main signal with 90° phase difference between the subsets, the sampled signal must contain at least one and half signal period. The example of sampled signal and two signal subsets are shown in Fig.2.

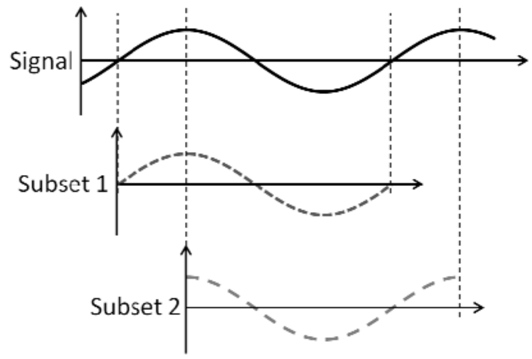

Fig.2. Signals “Subset 1” and “Subset 2” extracted from the main sampled signal.

Subset 1 should have its cosine part equal to one and Subset 2 equal to minus one:

$$\cos(2\pi\lambda + 2\varphi_1) = 1 \tag{32}$$

$$\cos(2\pi\lambda + 2\varphi_2) = -1 \tag{33}$$

$$\varphi_1 = k\pi - \pi\lambda \quad k \in Z \tag{34}$$

$$\varphi_2 = k\pi - \pi\lambda + \frac{\pi}{2} \quad k \in Z \tag{35}$$

RMS values of Subset 1 and Subset 2 can be calculated as (36) and (37):

$$X'_{RMS\,1} = \frac{X_m}{\sqrt{2}}\sqrt{\left(1 - \frac{\sin(2\pi\lambda_S)\cos(2\pi\lambda_S + 2(\varphi_1 + \varphi_{S1}))}{2\pi(M + \lambda_S)}\right)} \tag{36}$$

$$X'_{RMS\,2} = \frac{X_m}{\sqrt{2}}\sqrt{\left(1 - \frac{\sin(2\pi\lambda_S)\cos(2\pi\lambda_S + 2(\varphi_2 + \varphi_{S2}))}{2\pi(M + \lambda_S)}\right)} \tag{37}$$

where range of the decimal part of period λ_S is defined in (13) and range of the phase offsets φ_{S1} and φ_{S2} is defined by the number of samples per period N_{SPP} in equation (38):

$$\{\varphi_{S1}, \varphi_{S2}\} \in \left[-\frac{1}{2}\frac{2\pi}{N_{SPP}}, \frac{1}{2}\frac{2\pi}{N_{SPP}}\right\rangle \tag{38}$$

After using (34) and (35) on (36) and (37) it can be calculated:

$$X'_{RMS\,1} = \frac{X_m}{\sqrt{2}}\sqrt{\left(1 - \frac{\sin(2\pi\lambda_S)\cos(2\varphi_{S1})}{2\pi(M + \lambda_S)}\right)} \tag{39}$$

$$X'_{RMS\,2} = \frac{X_m}{\sqrt{2}}\sqrt{\left(1 + \frac{\sin(2\pi\lambda_S)\cos(2\varphi_{S2})}{2\pi(M + \lambda_S)}\right)} \tag{40}$$

Different sign of sine and cosine part under square root in (39) and (40) is caused by 90° phase offset of the second signal subset relative to the first signal subset. Arithmetic mean of RMS values of the first and second signal subset can be estimated as:

$$X_{ATS} = \frac{X'_{RMS\,1} + X'_{RMS\,2}}{2} \tag{41}$$

After using (39) and (40) on (41), RMS value estimated by the *Averaging two subset* method can be calculated as (42)

$$X_{ATS} = \frac{X_m}{\sqrt{2}}\left(\frac{1}{2}\sqrt{\left(1 - \frac{\sin(2\pi\lambda_S)\cos(2\varphi_{S1})}{2\pi(M + \lambda_S)}\right)} + \right. \\ \left. + \frac{1}{2}\sqrt{\left(1 + \frac{\sin(2\pi\lambda_S)\cos(2\varphi_{S2})}{2\pi(M + \lambda_S)}\right)}\right) \tag{42}$$

By using approximations for square root (17), RMS value can be approximately calculated as:

$$X_{ATS} \approx \frac{X_m}{\sqrt{2}}\left(1 - \frac{\sin(2\pi\lambda_S)[\cos(2\varphi_{S1}) - \cos(2\varphi_{S2})]}{8\pi(M + \lambda_S)}\right) \tag{43}$$

Both phase offsets φ_{S1} and φ_{S2} are rather small and have similar values so the difference between them is also a rather small number:

$$\varphi_{S1} \approx \varphi_{S2} \approx \varphi_S \tag{44}$$

After using assumption (44) on equation (43), RMS value estimated by the *Averaging two subset* method is approximately equal to RMS value of sinusoidal signal with integer number of periods with zero bias:

$$X_{ATS} \approx \frac{X_m}{\sqrt{2}} = X_{RMS} \tag{45}$$

Relative bias of RMS values calculated by the *Averaging two subsets* method can be calculated by equations (46) and (47):

$$\delta_{ATS} = \frac{X_{ATS} - X_{RMS}}{X_{RMS}}, \tag{46}$$

$$\delta_{ATS} = \frac{1}{2}\sqrt{\left(1 - \frac{\sin(2\pi\lambda_S)\cos(2\varphi_{S1})}{2\pi(M + \lambda_S)}\right)} + \\ + \frac{1}{2}\sqrt{\left(1 + \frac{\sin(2\pi\lambda_S)\cos(2\varphi_{S2})}{2\pi(M + \lambda_S)}\right)} - 1 \tag{47}$$

Maximum expected bias can be calculated by using equation (48) with ranges of λ_S, defined by (13) and ranges of φ_{S1} and φ_{S2} defined by (38).

$$\delta_{\mathrm{ATS\,MAX}} = \left| \frac{1}{2}\sqrt{\left(1-\frac{\sin(2\pi\lambda_S)\cos(2\varphi_{S1})}{2\pi(M+\lambda_S)}\right)} + \frac{1}{2}\sqrt{\left(1+\frac{\sin(2\pi\lambda_S)\cos(2\varphi_{S2})}{2\pi(M+\lambda_S)}\right)} - 1 \right| \tag{48}$$

To calculate approximated maximum expected bias (52), the following three approximations based on Taylor series are used:

$$\sqrt{1+X} \approx 1+\frac{X}{2}-\frac{X^2}{8} \tag{49}$$

$$\sin(x) \approx x \tag{50}$$

$$\cos(x) \approx 1-\frac{x^2}{2!} \tag{51}$$

$$\delta_{\mathrm{ATS\,MAX}} \approx \frac{1}{2}\frac{\lambda_S\left(\varphi_{S1}^2-\varphi_{S2}^2\right)}{M+\lambda_S} + \frac{1}{16}\frac{\lambda_S^2\left(\left(1-2\varphi_{S1}^2\right)^2+\left(1-2\varphi_{S2}^2\right)^2\right)}{(M+\lambda_S)^2}. \tag{52}$$

Maximum expected bias of RMS value (48) and (52) is for parameters (53) and (54):

$$\lambda_S = -\frac{1}{N_{SPP}} \tag{53}$$

$$\varphi_{S1} = \varphi_{S2} = \frac{1}{2}\frac{2\pi}{N_{SPP}} \tag{54}$$

Table 3. Maximum expected RMS value bias (ppm) for Averaging two subsets method

Integer number of periods M	Number of samples per period N_{SPP}		
	100	1000	10000
1	1.3E+01	1.3E-01	1.3E-03
2	3.1E+00	3.1E-02	3.1E-04
5	5.0E-01	5.0E-03	5.0E-05
10	1.2E-01	1.3E-03	1.3E-05

Maximum expected RMS value bias for the Averaging two subsets method (32) calculated for few common parameters M and N_{SPP}.

Maximum expected bias of RMS value estimated by the *Averaging two subsets* method for some common parameters M and N_{SPP} is calculated using (52) with parameters (53) and (54) and presented in Table 3. Values exhibit significant reduction of RMS value bias calculated by the *Averaging two subsets* method in comparison to values calculated by the Single subset method in Table 2 and values calculated by minimizing decimal part of period in Table 1.

4. THE SIMULATION OF RMS ESTIMATION ALGORITHMS

A. *Realization of methods in NI LabVIEW*

The Single subset method and the *Averaging two subsets* method are developed and tested in NI LabVIEW development system [5]. For measurement of sampled signal phase and frequency both methods use built in functions like *Extract single tone information* that analyzes whole sampled signal to achieve the best result. Signal phase and frequency can be also measured with other algorithms [6, 7]. This step is very important because accuracy of both methods depends on the accuracy of the signal phase and frequency measurement. After that step, beginning and length of signal subsets can be calculated and signal subset extracted to calculate RMS value.

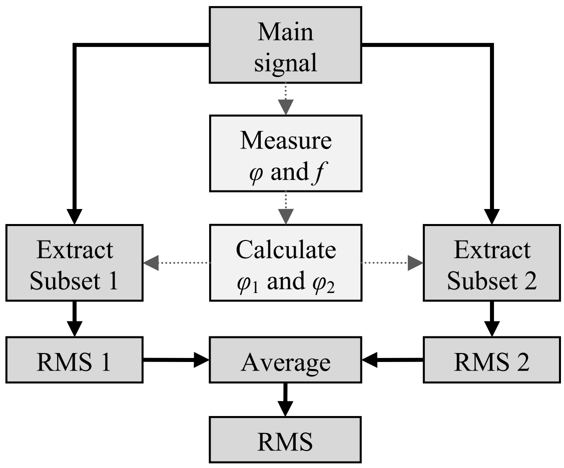

Fig.3. Block diagram of the Averaged two subset method algorithm.

After Subset 1 and Subset 2 extraction, RMS values of both Subset 1 and Subset 2 are calculated using the classical method with Rectangular window. Finally, RMS is calculated by averaging RMS values of Subset 1 and Subset 2.

B. *Testing methodology*

Testing is realized by simulating non-coherent sinusoidal signal of known RMS value that can be compared to the results of tested methods for RMS measurement. The results are presented in graphs depending on the number of signal periods (Fig.4. - graph x-axis).

Methods were tested on sinusoidal signals with number of samples per period $N_{SPP} = 1000$ and number of periods $1.5 < M < 8$ (in steps of 0.02 periods). For each step 500 measurements have been performed on different signals with random signal phase $0° \le \varphi < 360°$ and random signal frequency from $f = 50\pm0.5$ Hz. In Fig.4 the value of maximum relative bias of these 500 RMS measurements is shown. The arithmetic mean of these 500 measurements could show about 10 times better results of the bias of RMS value but in this paper only the maximum bias of RMS value (the worst case) is presented.

C. Simulation results

The results of the simulation of RMS value measurement with the *Single subset* method and the *Averaging two subsets* method is shown in Fig.4. The bias of the RMS values estimated with both methods is lower than maximum expected RMS value bias of these methods calculated by equations (29) and (48).

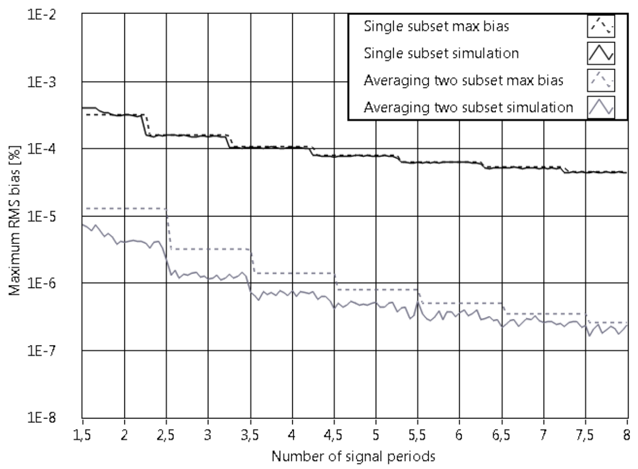

Fig.4. Comparison of simulated RMS value measurement with the *Single subset* method and the *Averaging two subsets* method with maximum expected RMS value bias estimated by equations (29) and (48) based on simulated sinusoidal signal $N_{SPP} = 1000$, $f = 50±0.5$ Hz, $0° \leq \varphi < 360°$.

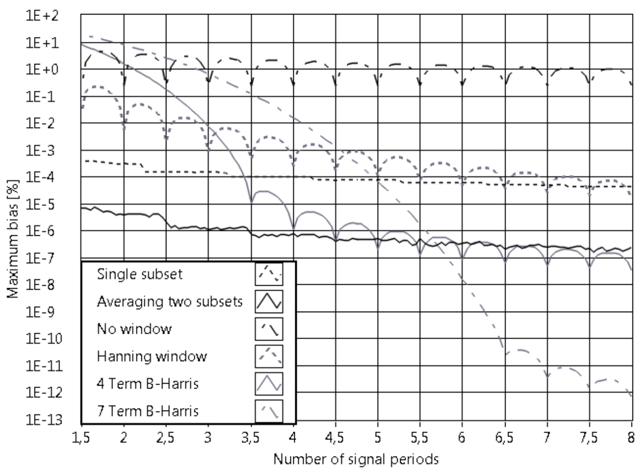

Fig.5. Comparison of RMS value measurement based on the *Single subset* method and the *Averaging two subsets* method with windowing algorithms: Rectangular (no window), Hanning, 4 Term B-Harris, 7 Term B-Harris based on simulated sinusoidal signal $N_{SPP} = 1000$, $f = 50±0.5$ Hz, $0° \leq \varphi < 360°$.

The results of RMS value measurement with the Single subset method and the Averaging two subsets method are compared with Rectangular, Hanning, 4 Term B-Harris and 7 Term B-Harris windowing algorithms in Fig.5. *Averaging two subsets* method reduces RMS value bias of non-coherently sampled sinusoidal signals better than any known windowing algorithms for signals from $M = 1.5$ to $M = 5$ periods.

5. CONCLUSION

The simulation results of the *Single subset* method and the *Averaging two subsets* method showed that RMS value bias is considerably reduced. These two methods are superior to all known windowing algorithms for signals with low period number.

The new proposed *Averaging two subsets* method can be used in applications where both high precision and speed of RMS value measurement is important [8, 9]. In future work, the method will be tested for signals with higher harmonics, presence of noise, and the influence of analog to digital converters with different conversion resolution.

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