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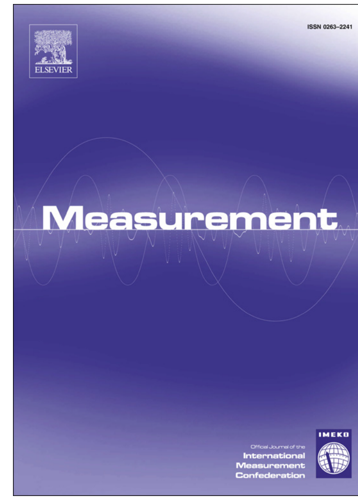


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# Power Measurement Accuracy Analysis in the Presence of Interharmonics

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**Abstract**

Interharmonics present in voltage/current signals affect the measurement accuracy of power quantities defined in standard IEEE 1459. In this paper, the measurement errors caused by the measurement time intervals not satisfying integral multiple periods of interharmonics are discussed. First, the mathematical models of power quantities between arbitrary frequency components are constructed. Next, four parameters that affect the power measurement accuracy are summarized, which are interharmonic frequency, measurement start time, voltage/current initial phase angle, and the length of measurement time intervals. The simulation results and corresponding analysis show the effects of each parameter on measurement accuracy. In conclusion, the maximum errors are always caused by interharmonics within particular frequency range which relates to the length of measurement time interval. Moreover, the relative errors of power quantities can be restricted within 1%, by using a time interval of 3 s, even if under the condition of selecting the worst measurement start time.

*Keywords:* Interharmonics, integration intervals, measurement start time, non-integer multiple period, power measurement accuracy

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## 1. Introduction

With the increase in complexity of power grids and the extensive use of various frequency conversion devices, as well as more appearances of nonlinear fluctuating loads such as electric arc furnaces, induction motors, mine hoists, electric welders, elevators, etc., it is commonly accepted that current and/or voltage signals often contain interharmonics of which frequencies are non-integer multiples of the fundamental frequency [1]-[3]. In addition to the typical problems of electrical equipment overheating and of shortened service life, interharmonics can cause new problems in the power grid, such as subsynchronous oscillations, voltage fluctuations and light flicker. Even when their amplitudes are low, they may cause many serious problems. Therefore, the accurate measurement of interharmonics has been widely discussed, and many algorithms for measuring interharmonics have been developed [4]-[8]. However, with regard to the presence of interharmonics, the measurement of power quantities that characterize the power flow in the grid has not been studied sufficiently and comprehensively.

The problem of power definition and measurement under nonsinusoidal conditions has been a hot topic of international concern for a long time [9]-[15]. The IEEE Working Group issued standard IEEE 1459 [15] in 2010, which covers the practical definitions of the newly determined power quantities. All of them have clear physical meaning and have been verified by experts. Measuring instruments designed according to these definitions have also been popularized and applied [16]. In the design of digital meters, it is necessary to sample the actual voltage and current signals first in a limited period of time. The sampling time length specified in standard IEEE 1459 is the integer multiple of the measured signal. Generally, according to the recommendation of IEC standard 61000-4-7, 10 fundamental frequency cycles (50 Hz system, corresponding to a length of 200 ms) are used [17]. However, if there are interharmonics contained in the measured signal, the length of the integration interval should be taken as an integer multiple of the measured signal. However, during the measurement of the actual power grid, if there is a time varying load, the period or frequency of each harmonic and interharmonic cannot be known in advance. In addition, if at least one of the interharmonic orders is an irrational number, then the observed waveform is not periodic (it is called nearly periodic). In such a case, the measurement time interval should be infinitely large to have a correct measurement. In modern digital meters, it is generally impossible to achieve an infinitely long measurement time window. Therefore, in the presence of interharmonics, the effects caused by the integration intervals on the power measurement accuracy are totally worthy of discussion.

Power quantities defined in standard IEEE 1459 can be divided into two categories by measurement methods. The first group are power quantities, including active power, reactive power, apparent power and power factor, which should be measured using the time method. The measurement instrument should be constructed by the principle of accumulating integration using voltage and current sampling values. This is mainly because the frequency domain method cannot fulfill accurate measurement and the calculation is very complex. That is, the error is minimal from the perspective of energy accumulation, and time domain integration is the easiest way to implement for instrumentation chips. The measurement errors using the time domain method mainly come from the truncation of the signal in the integration interval. Another type of power is the power quantities that must be calculated by the frequency domain method, such as the fundamental active power, the fundamental positive sequence active power, the fundamental apparent power, and the phase shift power factor. The errors are mainly derived from the truncation errors caused by the finite length time window and the fence effect of the frequency domain algorithm. There are many articles in which the performance of frequency domain analysis algorithms are analyzed, such as the window interpolation algorithm, the Prony algorithm, and the asynchronous sampling algorithm [4]-[5], [18]-[19]. However, the measurement accuracy of the first group of power quantities is not sufficiently comprehended [20]-[22], which will be mainly discussed in this paper.

In [20], the errors introduced 1) when the measurement time interval is not an exact multiple of the fundamental period and 2) in the presence of interharmonics in the voltage and/or current signals have been analyzed and explicitly calculated. The authors used relatively simple voltage and current signal models to analyze and calculate these two types of errors. However, when it came to the second type of errors, only the effect of the interharmonic frequency on the errors was analyzed. Other parameters and their effects on measurement accuracy were not further explored.

In [21], the authors mainly analyzed active power, voltage /current rms values, apparent power and the power factor of the system in the presence of integer harmonics, when the measurement time intervals are not integer multiples of the fundamental frequency period. The errors introduced by the desynchronization of measurement interval in the presence of 1) harmonics and 2) PLL affected by time-varying errors have been evaluated. Increased measurement time (increased number of fundamental frequency cycles included in the integration interval) was mentioned for improving the accuracy of power measurement. However, there is no analysis of the existence of interharmonics.

In [22], the authors mainly analyzed the energy measurement method considering interharmonics. The calculation formula of electric energy in the presence of interharmonics have been derived and then simplified by ignoring the power loss caused by the interaction of signal components with a frequency difference greater than 5 Hz. However, the conclusions of [22] were based on the fact that the measurement integration intervals are fixed to 10 fundamental frequency cycles (50 Hz system), and the effects of other parameters were not further explored. In addition, the calculation method adopted by [22] is the frequency domain, and the time domain measurement values were regarded as the true values for measurement accuracy analysis, which is contrary to the definition of IEEE 1459.

In standard IEEE 1459, there is also a system with nonlinear loads, which is given to explain the influence of the length of the measurement time window [15]. However, interactions of arbitrary frequency components are not analyzed. In addition, the conclusion is drawn without any analysis of measurement start time and initial phases of voltage/current components.

In this paper, four parameters that affect the measurement accuracy of powers in the presence of interharmonics are summarized. The interaction models of arbitrary frequency components are constructed for the first time. Therefore, the measurement errors of power quantities are further analyzed in order to propose a method for improving accuracy.

This paper is organized as follows. First, the definitions and measurement method of active power, rms values, apparent power and power factor are introduced in Section 2. Next, the mathematical models of the active power calculation term and the voltage/current rms value calculation terms between arbitrary frequency components are constructed in Section 3. Then, sub-items, which should be included in the true values of power quantities, are also explained, and the measurement errors of power quantities are further analyzed in Section 3. Afterward, the effects of each parameter on the measurement accuracy of power quantities are shown by the simulation results and corresponding analysis of the calculation example in Sections 4 and 5. Finally, the main conclusions of this paper are given.

## 2. Power Definitions and Power Measurement Method in Standard IEEE 1459

When designing the digital meters for measuring power quantities according to standard IEEE 1459, the following mathematical models will be referred to for the definitions of active power, voltage/current rms values, apparent power and power factor, and corresponding measurement methods.

Generally, supply voltage and load current have the following form

$$u(t) = U_0 + \sqrt{2}U_1\sin(\omega t + \alpha_1) + \sum_{h=2}^{H}\sqrt{2}U_h\sin(h\omega t + \alpha_h) + \sum_{i}\sqrt{2}U_i\sin(i\omega t + \alpha_i) \tag{1}$$

$$i(t) = I_0 + \sqrt{2}I_1\sin(\omega t + \beta_1) + \sum_{h=2}^{H}\sqrt{2}I_h\sin(h\omega t + \beta_h) + \sum_{i}\sqrt{2}I_i\sin(i\omega t + \beta_i) \tag{2}$$

where $\omega$ is the power system angular frequency, $h$ is the integer number that represents the harmonic order, $i$ is the non-integer number that represents the interharmonic order, $U_0$, $I_0$ are the dc voltage and dc current, and $\alpha_1$, $\alpha_h$, $\alpha_i$, $\beta_1$, $\beta_h$, $\beta_i$ are initial phases of fundamental voltage, the $h$th harmonic voltage , the $i$th interharmonic voltage, fundamental current, the $h$th harmonic current, and the $i$th interharmonic current, respectively.

The calculation model of active power specified in standard IEEE 1459 is

$$P = \frac{1}{kT}\int_{\tau}^{\tau+kT} u(t)i(t)dt \tag{3}$$

which means, the average value of instantaneous power in interval $[\tau, \tau + kT]$ is the active power, where $\tau$ is the measurement start time, $\tau + kT$ is the measurement end time, and $kT$ is supposed to be an integer multiple of the power system fundamental period.

The calculation model for the voltage rms value is

$$U = \sqrt{\frac{1}{kT}\int_{\tau}^{\tau+kT} u^2(t)dt} \tag{4}$$

The calculation model for the current rms value is

$$I = \sqrt{\frac{1}{kT}\int_{\tau}^{\tau+kT} i^2(t)dt} \tag{5}$$

When a digital meter is used for sampling and measuring, the measured value of active power should be expressed as the following, assuming that the number of samples in a measurement interval is $N$. The subscript $d$ stands for the quantities measured by means of a digital meter.

$$P_d = \frac{1}{N}\sum_{j=1}^{N} u(j)i(j) \tag{6}$$

The digital measurement of the voltage rms value is

$$U_d = \sqrt{\frac{1}{N}\sum_{j=1}^{N} u^2(j)} \tag{7}$$

The current rms value is measured in a similar way to the voltage rms value, and the measured result can be expressed as

$$I_d = \sqrt{\frac{1}{N}\sum_{j=1}^{N} i^2(j)} \tag{8}$$

The following description of the measurement and calculation of the rms values will only take the voltage rms value as the example.

Apparent power is defined and measured as the product of voltage rms value and current rms value

$$S_d = U_d I_d \tag{9}$$

The power factor is

$$PF_d = \frac{P_d}{S_d} \tag{10}$$

Equations (6), (7), (8), (9) and (10) can be implemented directly in a digital meter without any spectral analysis. It should be noted that the number of sampling points in one fundamental period should be an integer, otherwise the error of asynchronous sampling will be introduced into the measurement results.

## 3. Measurement Errors in the Presence of Interharmonics

In the presence of interharmonics, the measurement time intervals are often not satisfied with the integer multiple of the voltage/current signals. As a result, errors are caused in the measurement results of power quantities. Referring to (3), (4), and (5), this section first analyzes the sub-items in the measurement results of active power and rms values, which are cross products of each frequency component. The analysis results also apply to (6), (7) and (8), because they are digital measurement schemes of (3), (4) and (5). When the sampling frequency is high enough, the digital measurement results are consistent with the theoretical analysis results. Second, sub-items, which should be included in the true values of power quantities, are obtained. Finally, the measurement errors of active power, rms values, apparent power and power factor are calculated. As frequency deviations and frequency oscillations are not taken into consideration in this paper, there is $T = 2\pi/\omega$. Based on the above conditions, the following equations are derived.

### *3.1. Calculation Terms of Active Power and RMS Values*

Since the integer multiple periods of the fundamental component and the harmonic components are included in the time interval $[\tau, \tau+kT]$, cross products of fundamental component, dc component and arbitrary harmonics do not bring errors to the measurement of power quantities.

As for the interharmonics, the calculation of the active power generated by the $m$th voltage interharmonic component interacting with the $n$th current interharmonic component can be expressed as

$$
\begin{aligned}
P_{mn} &= \frac{1}{kT}\int_{\tau}^{\tau+kT} \sqrt{2}U_m \sin(m\omega t+\alpha_m) \times \sqrt{2}I_n \sin(n\omega t+\beta_n)dt \\
&= \frac{U_m I_n}{kT}\int_{\tau}^{\tau+kT} \{\cos[(m-n)\omega t+\alpha_m-\beta_n]-\cos[(m+n)\omega t+\alpha_m+\beta_n]\}dt \\
&= \frac{U_m I_n}{\omega kT}\{\frac{\sin[\omega(m-n)(kT+\tau)+\alpha_m-\beta_n]}{m-n}-\frac{\sin[(m-n)\omega\tau+\alpha_m-\beta_n]}{m-n} \\
&\quad -\frac{\sin[\omega(m+n)(kT+\tau)+\alpha_m+\beta_n]}{m+n}+\frac{\sin[(m+n)\omega\tau+\alpha_m+\beta_n]}{m+n}\}
\end{aligned}
\tag{11}
$$

The subscript of $P_{mn}$ means that the active power item is calculated by cross product of the $m$th voltage interharmonic component $u_m(t)$ and the $n$th current interharmonic component $i_n(t)$. The following names are all obedient to this law.

For the convenience of expression, let $\theta_1 = (m-n)\omega\tau + \alpha_m - \beta_n$, $\theta_2 = (m+n)\omega\tau + \alpha_m + \beta_n$. Rewrite (11) as

$$\begin{aligned} P_{mn} = \frac{U_m I_n}{\omega kT}\{&\frac{\sin[\omega(m-n)kT+\theta_1]}{m-n} - \frac{\sin(\theta_1)}{m-n} \\ &- \frac{\sin[\omega(m+n)kT+\theta_2]}{m+n} + \frac{\sin(\theta_2)}{m+n}\} \end{aligned} \tag{12}$$

where $\theta_1$ and $\theta_2$ are both related to the initial phase of the $m$th voltage interharmonic component and the initial phase of the $n$th current interharmonic component, as well as the start time of the measurement.

(12) can be transformed according to the trigonometric function formula. There is

$$\begin{aligned} P_{mn} = \frac{2U_m I_n}{\omega kT}\{&\frac{\sin[\frac{\omega}{2}(m-n)kT]\cos[\frac{\omega}{2}(m-n)kT+\theta_1]}{m-n} \\ &- \frac{\sin[\frac{\omega}{2}(m+n)kT]\cos[\frac{\omega}{2}(m+n)kT+\theta_2]}{m+n}\} \end{aligned} \tag{13}$$

Because of $\omega = 2\pi f = 2\pi/T$, (13) can be rewritten in a more compact way

$$\begin{aligned} P_{mn} &= \frac{U_m I_n \sin[(m-n)\pi k]\cos[(m-n)\pi k+\theta_1]}{(m-n)\pi k} \\ &\quad - \frac{U_m I_n \sin[(m+n)\pi k]\cos[(m+n)\pi k+\theta_2]}{(m+n)\pi k} \\ &= U_m I_n \cos[(m-n)\pi k+\theta_1]\mathrm{sinc}[(m-n)k] \\ &\quad - U_m I_n \cos[(m+n)\pi k+\theta_2]\mathrm{sinc}[(m+n)k] \end{aligned} \tag{14}$$

where $\mathrm{sinc}(x) = \sin(\pi x)/\pi x$ is the normalized sinc function. $\mathrm{sinc}(x)$ is an even function, of which the function value can be the largest when $x = 0$. Values fluctuate and decay as $x$ extends to both sides. When $x$ takes a non-zero integer, its function value is 0. cos function has its maximum and minimum limits, that is, $\cos[(m-n)\pi k+\theta_1] \in [-1,1]$, $\cos[(m+n)\pi k+\theta_2] \in [-1,1]$, and both of them fluctuate along the whole scan. As a result, the active power term $P_{mn}$ is mainly affected by the sinc function. For fixed $m$ and $n$ , the active power term will decrease as $k$ increases. When both $(m-n)k$ and $(m+n)k$ are non-zero integers, $P_{mn}$ should be 0. Therefore, when the value of $k$ is a certain positive integer, the frequency resolution of interharmonics is $f/k$.

When $(m-n)k=0$, $\mathrm{sinc}[(m-n)k]=1$. That is, the active power term generated by the $n$th voltage interharmonic component interacting with the $n$th current interharmonic component can be written as

$$P_{nn}=U_nI_n\cos(\alpha_n-\beta_n)-U_nI_n\cos(2n\pi k+\theta_2)\mathrm{sinc}(2nk) \tag{15}$$

If $2nk$ is a non-zero integer, $P_{nn}=U_nI_n\cos(\alpha_n-\beta_n)$. In this case, the active power calculation formula of the $n$th interharmonic has the same form as the active power calculation formula of the fundamental and the integer harmonic components specified in standard IEEE 1459. If $2nk$ is not a non-zero integer, the same conclusion can be drawn when $n\to\infty$ or $k\to\infty$.

We can find that (14) is suitable for any $m,n$, that is, whether $m,n$ are integers or not and whether $m=n$ or not, corresponding to arbitrary frequency components, (14) can be used to analyze the measured value of active power. However, it should be noted that the active power generated by the dc component interacting with the interharmonics needs to be analyzed separately. Calculation of the active power generated by the voltage dc component interacting with the $n$th current interharmonic component is taken as an example

$$\begin{aligned} P_{0n}&=\frac{1}{kT}\int_{\tau}^{\tau+kT}U_0\times\ \sqrt{2}I_n\sin(n\omega t+\beta_n)dt\\ &=\frac{\sqrt{2}U_0I_n}{2\pi nk}\{\cos[n\omega\tau+\beta_n]-\cos[n\omega(\tau+kT)+\beta_n]\}\\ &=\frac{\sqrt{2}U_0I_n}{n\pi k}\sin(n\pi k+n\omega\tau+\beta_n)\sin(n\pi k)\\ &=\sqrt{2}U_0I_n\sin(n\pi k+n\omega\tau+\beta_n)\mathrm{sinc}(nk) \end{aligned} \tag{16}$$

Since $\sin(n\pi k+n\omega\tau+\beta_n)\in[-1,1]$, the active power item $P_{0n}$ is also affected by the sinc function. For a fixed $n$, $P_{0n}$ will decrease as $k$ increases. When $nk$ is a non-zero integer, $P_{0n}$ should be 0.

Next, the measurement and calculation of rms values will be analyzed. The voltage rms value is expressed as the example here

$$U=\sqrt{\frac{1}{kT}\int_{\tau}^{\tau+kT}u^2(t)dt}=\sqrt{\sum_{m,n}U_{mn}}=\sqrt{\sum_{m\neq n}U_{mn}+\sum_{n}U_{nn}} \tag{17}$$

where

$$U_{mn} = \frac{1}{kT}\int_{\tau}^{\tau+kT} \sqrt{2}U_m\sin(m\omega t+\alpha_m)\times\ \sqrt{2}U_n\sin(n\omega t+\alpha_n)dt$$
$$= U_mU_n\cos[(m-n)\pi k+\theta_{\alpha 1}]\mathrm{sinc}[(m-n)k]$$
$$- U_mU_n\cos[(m+n)\pi k+\theta_{\alpha 2}]\mathrm{sinc}[(m+n)k] \quad (18)$$

where $\theta_{\alpha 1} = (m-n)\omega\tau + \alpha_m - \alpha_n$, $\theta_{\alpha 2} = (m+n)\omega\tau + \alpha_m + \alpha_n$.

Besides,

$$U_{nn} = U_n^2 - U_n^2\cos(2n\pi k + \theta_{\alpha 2})\mathrm{sinc}(2nk) \quad (19)$$

Similarly, (18) is suitable for any $m, n$. However, it should be noted that the voltage rms value generated by the dc component interacting with the interharmonics needs to be analyzed separately. The voltage dc component is multiplied by the $n$th voltage interharmonic component, and the integral in $[\tau, \tau + kT]$ is

$$U_{0n} = \sqrt{2}U_0U_n\sin(n\pi k + n\omega\tau + \alpha_n)\mathrm{sinc}(nk) \quad (20)$$

*3.2. True Values of Power Quantities*

In order to analyze measurement accuracy of power quantities in the presence of interharmonics, in addition to the measured values, the true values should be known. For interharmonics, standard IEEE 1459 only states that the measurement time interval should contain integer multiples of the periods of the interharmonics. Based on this, the following is an analysis of which sub-items should be included in the true values of power quantities.

When the interharmonic frequency in the signal is a determined constant, in order to obtain the true values of power quantities, an integer multiple of the signal period should be taken, that is, $KT = m_iT_i$, where $T_i$ is the period of each harmonic component, and $K$ and $m_i$ are both positive integers. Equations (3), (4), and (14) - (20) are used to calculate the active power and the voltage rms value in the integration interval $[\tau, \tau + KT]$. Because both $(m-n)K$ and

$(m+n)K$ are integers, there is

$$P_{\tau\sim\ \tau+KT} = U_0 I_0 + U_1 I_1 \cos(\alpha_1 - \beta_1) + \sum_{h=2}^{H} U_h I_h \cos(\alpha_h - \beta_h) + \sum_{i} U_i I_i \cos(\alpha_i - \beta_i) \tag{21}$$

$$U_{\tau\sim\ \tau+KT} = \sqrt{U_0^2 + U_1^2 + \sum_{h=2}^{H} U_h^2 + \sum_{i} U_i^2} \tag{22}$$

(21) and (22) are expressions of the true values of active power and the voltage rms value, respectively. Using such a definition, the contribution of each frequency component in the signal to the amount of power can be clearly seen, and the characteristics of the circuit can be better reflected when calculating the apparent power and power factor. Moreover, since the electric energy $W$ is the energy transmitted from the power source to the load for a period of time, this definition does not cause an error in the accurate measurement of $W$. It is only necessary to multiply the active power by the corresponding length of time to obtain $W$. In addition, (21) and (22) can perfectly conform to the power decomposition and redefinition in the frequency domain according to standard IEEE 1459.

According to the definitions of active power and the voltage rms value in equations (21) and (22), for the convenience of explanation, the term of equations (14) and (16) at $m \neq n$ are defined as the cross item of active power, and the term of equations (18) and (20) at $m \neq n$ are defined as the cross item of the square of the voltage rms value. Besides, the second sub-items of equations (15) and (19) are defined as the additional item of active power and the additional item of the square of the voltage rms value, respectively, that is

$$P_{cro} = P_{mn}, U_{cro}^2 = U_{mn}, m \geq 0, n \geq 0, m \neq n \tag{23}$$

$$\begin{aligned} &P_{add} = P_{nn} - U_n I_n \cos(\alpha_n - \beta_n), \\ &U_{add}^2 = U_{nn} - U_n^2, \\ &n > 0, n \text{ is non-integer} \end{aligned} \tag{24}$$

In the integration interval $[\tau, \tau + KT]$, the calculation of active power can be decomposed into the average of the active power in $i$ equal length intervals. Similarly, the calculation of the voltage rms value can be decomposed into the voltage rms value in $i$ equal length intervals. As the following, where $K = ik$

$$\begin{aligned}
P_{\tau\sim\ \tau+KT} &= \frac{1}{KT}\int_{\tau}^{\tau+KT} u(t)i(t)dt \\
&= \frac{1}{KT}[\int_{\tau}^{\tau+kT} u(t)i(t)dt + \int_{\tau+kT}^{\tau+2kT} u(t)i(t)dt + \cdots + \int_{\tau+(i-1)kT}^{\tau+KT} u(t)i(t)dt] \\
&= \frac{1}{KT}(kTP_{\tau\sim\ \tau+kT} + kTP_{\tau+kT\sim\ \tau+2kT} + \cdots + kTP_{\tau+(i-1)kT\sim\ \tau+KT}) \\
&= \frac{P_{\tau\sim\ \tau+kT} + P_{\tau+kT\sim\ \tau+2kT} + \cdots + P_{\tau+(i-1)kT\sim\ \tau+KT}}{i}
\end{aligned} \tag{25}$$

$$\begin{aligned}
U_{\tau\sim\ \tau+KT} &= \sqrt{\frac{1}{KT}\int_{\tau}^{\tau+KT} u^2(t)dt} \\
&= \sqrt{\frac{1}{KT}[\int_{\tau}^{\tau+kT} u^2(t)dt + \int_{\tau+kT}^{\tau+2kT} u^2(t)dt + \cdots + \int_{\tau+(i-1)kT}^{\tau+KT} u^2(t)dt]} \\
&= \sqrt{\frac{1}{KT}(kTU^2_{\tau\sim\ \tau+kT} + kTU^2_{\tau+kT\sim\ \tau+2kT} + \cdots + kTU^2_{\tau+(i-1)kT\sim\ \tau+KT})} \\
&= \sqrt{\frac{U^2_{\tau\sim\ \tau+kT} + U^2_{\tau+kT\sim\ \tau+2kT} + \cdots + U^2_{\tau+(i-1)kT\sim\ \tau+KT}}{i}}
\end{aligned} \tag{26}$$

Because of the presence of the cross items $P_{cro}$ and $U^2_{cro}$, as well as the additional items $P_{add}$ and $U^2_{add}$, there are errors between the measured values and the true values in each short interval. However, according to equation (21), (22), (25), (26), cross items and additional items offset to 0 in the process of aggregation to the long interval $[\tau, \tau + KT]$. The idea that neither the cross items nor the additional items should be included in the true values of power quantities is satisfied.

### *3.3. Measurement Errors of Active Power, RMS Values, Apparent Power and Power Factor*

In the integration interval $[\tau, \tau + kT]$, the measurement errors caused by the time interval $kT$ not satisfying the integer multiple period of the interharmonics can be expressed as follows.

In fact, the measurement error of active power is the sum of all the cross items and additional items of active power. The absolute error of active power

$$e_P = P_{meas} - P = \sum (P_{cro} + P_{add}) \tag{27}$$

As for the rms value, the absolute error has the following form

$$e_{U^2} = U^2_{meas} - U^2 = \sum (U^2_{cro} + U^2_{add}) \tag{28}$$

If the relative errors are used to indicate the relationship between the measured values and the true values of active power, voltage rms value and current rms value, there are

$$P_{meas} = P(1 + \varepsilon_P) \tag{29}$$

$$U^2_{meas} = U^2(1 + \varepsilon_{U^2}) \tag{30}$$

$$I^2_{meas} = I^2(1 + \varepsilon_{I^2}) \tag{31}$$

where $P$ is the true value of active power given by (21), and $U$ is the true value of voltage rms value given by (22). $\varepsilon$ represents the relative error.

Therefore, the measured value of apparent power should be

$$\begin{aligned} S_{meas} &= U_{meas} \times \ I_{meas} \\ &= \sqrt{U^2(1 + \varepsilon_{U^2}) \times \ I^2(1 + \varepsilon_{I^2})} \\ &= UI\sqrt{1 + \varepsilon_{U^2} + \varepsilon_{I^2} + \varepsilon_{U^2}\varepsilon_{I^2}} \end{aligned} \tag{32}$$

For the power factor, the measured value is

$$PF_{meas} = PF\frac{1 + \varepsilon_P}{\sqrt{1 + \varepsilon_{U^2} + \varepsilon_{I^2} + \varepsilon_{U^2}\varepsilon_{I^2}}} \tag{33}$$

where $PF$ is the true value of power factor.

Thus, when there are interharmonics contained in the voltage and current signals, errors will be caused in the measurement of active power and the rms value because the measurement time interval $kT$ does not satisfy the integer multiple period of the interharmonics. This will in turn lead to inaccurate measurement of apparent power and power factor.

## 4. Parametric Analysis

In this section, parametric analysis of the formulas developed in the previous section is reported with reference to the interharmonics frequency $m$ and $n$, the length of integration intervals that refer to the cycle number $k$, the start time of measurement $\tau$, and the initial phases of the voltage and current signals.

### *4.1. Sensitivity to Interharmonics Frequency*

The relationship of the cross item $P_{mn}$ [see (14)] versus $n$, and $U_{mn}$ [see (18)] versus $n$, are separately shown in Figures 1 and 2 ($m = 1, n \in [0.5, 1.5]$), using the length of integration interval as the parameter. For the length of integration interval, one fundamental frequency cycle, the basic 10 fundamental frequency cycles (50 Hz system, corresponding to the length of 200 ms), and the very short time interval (3 s, corresponding to 150 fundamental frequency cycles for 50 Hz system), introduced by standard IEC 61000-4-7, are adopted to conduct the comparative analysis [17]. These three different lengths separately stand for the quick response time, the basic measurement time interval and the aggregation of basic time intervals. In addition, the reason for calculating the cross item $P_{mn}$ generated by the fundamental voltage interacting with the $n$th current interharmonic component, and the cross item $U_{mn}$ generated by the fundamental voltage interacting with the $n$th current interharmonic component, is that the amplitude of the fundamental voltage is large, and the corresponding error is more significant. According to the standard IEEE 519 for the interharmonics limits at a point of common coupling (PCC), the amplitude of the $n$th interharmonic component is considered as 2% of the fundamental amplitude

[23]. However, if the measurement is made at the user, the amplitude of the interharmonics will be larger, which leads to larger errors in the measurement of active power and rms values.

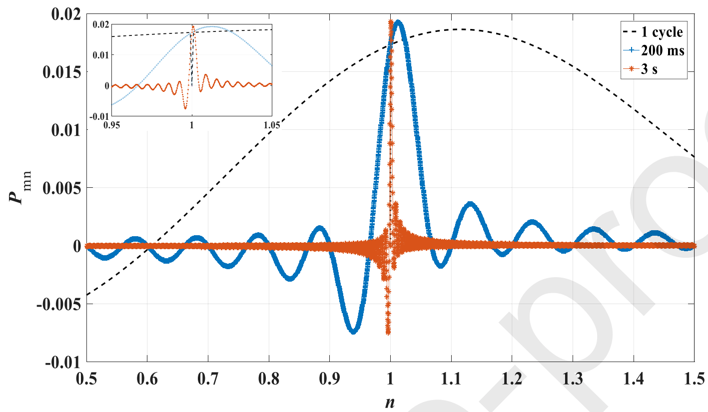



Figure 1: The cross item of active power $P_{mn}$ [see (14)] versus current interharmonic frequency order $n$. The amplitude of the $n$th current interharmonic component is $2\%pu$. Three curves represent the integration intervals using different lengths, which are 1 cycle, 200 ms and 3 s. Start time $\tau = 0s$, $m = 1$, $\alpha_1 = 30°, \beta_n = 0°$ are selected.

From Figures 1 and 2, we can see that the values of cross item $P_{mn}$ and $U_{mn}$ increase when $n$ is closer to 1. These maximum values can reach the same order of magnitude of the current interharmonics amplitude. When $\mid m - n \mid$ becomes larger, values of the cross items decline. It can be noted that for the integration interval of 200 ms, when $n \in (0.9, 1.1)$, the values of $P_{mn}$ and $U_{mn}$ are all larger. For the integration interval of 3 s, a similar conclusion can be drawn from the small figure shown in Figures 1 and 2. Combined with equations (14) and (18), it can be seen that, in general, the cross items of $(m-n) \in (-1/k, 1/k)$ cannot be ignored. In addition, it should be noted that when $m = n = 1$, the fundamental active power or the square of the fundamental voltage rms value are represented, and there is no error between the measured value and the true value. The value at this point is 0.

Next, $P_{nn}$ [see (15)] and $U_{nn}$ [see (19)] are analyzed. The relationship of the

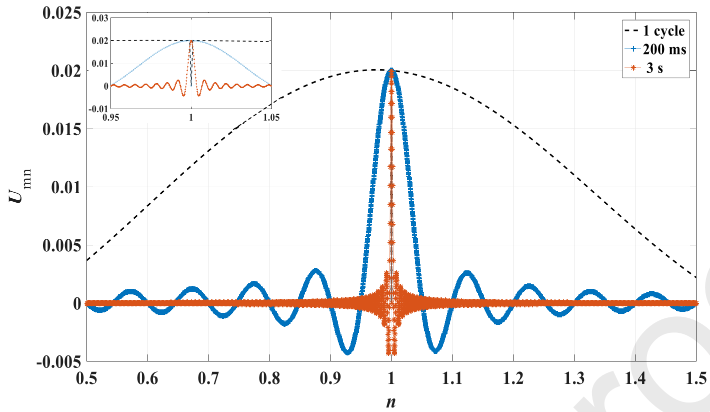



Figure 2: The cross item of the square of the voltage rms value $U_{mn}$ [see (18)] versus voltage interharmonic frequency order $n$. The amplitude of the $n$th voltage interharmonic component is $2\% pu$. Three curves represent the integration intervals using different lengths, which are 1 cycle, 200 ms and 3 s. Start time $\tau = 0s$, $m = 1$, $\alpha_1 = 30°, \alpha_n = 0°$ are selected.

additional items of $P_{nn}$ and $U_{nn}$ versus $n$, are separately shown in Figures 3 and 4 ($n \in (0, 1]$). We can see that these two items are very large when $n \to 0$. The maximum error can reach the same magnitude order of the interharmonics. When $n$ increases, these errors rapidly decline. Similarly, combined with equations (15) and (19), more consideration should be given to the interharmonic components of $n \in (0, 1/2k)$ with respect to $P_{nn}$ and $U_{nn}$.

The grid often has strict requirements for the dc component at a point of common coupling (PCC). However, on the load side, a large dc component may be generated due to the presence of many electrical equipment such as half-wave rectification. The relationship of the cross item $P_{0n}$ [see (16)] versus , and $U_{0n}$ [see (20)] versus $n$, are separately shown in Figures 5 and 6 ($n \in (0, 1]$). Similarly, combined with equations (16) and (20), more consideration should be given to the interharmonic components of $n \in (0, 1/k)$ with respect to $P_{0n}$ and $U_{0n}$.

In the above analysis, in addition to the frequency change of the interharmonics, the length of integration interval is also considered as a parameter. We

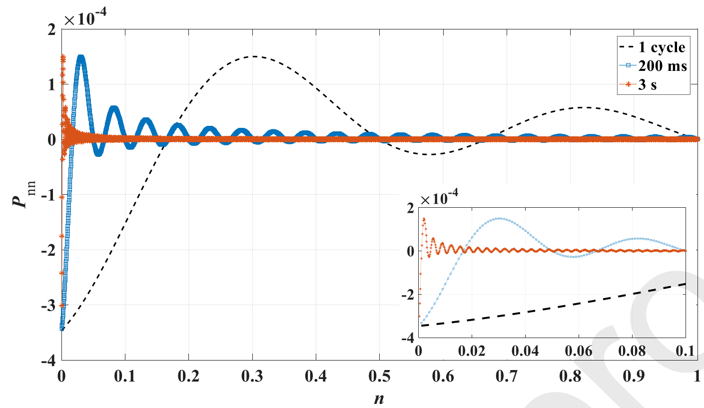



Figure 3: The additional item of active power $P_{nn}$ [see (15)] versus interharmonic frequency order $n$. The amplitude of the $n$th voltage and current interharmonic component is $2\%pu$. Three curves represent the integration intervals using different lengths, which are 1 cycle, 200 ms and 3 s. Start time $\tau = 0s$, $\alpha_n = 30°$, $\beta_n = 0°$ are selected.

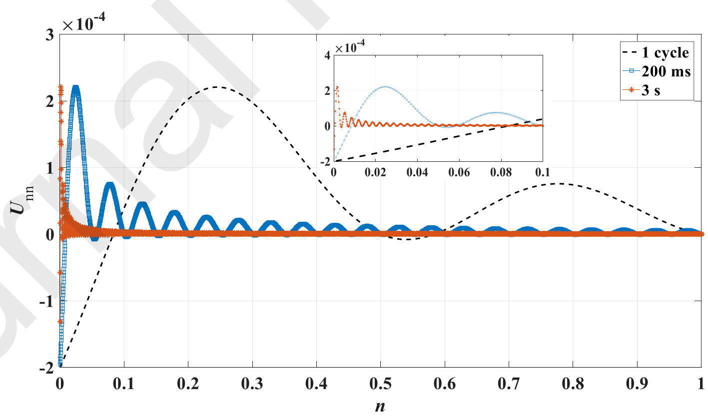



Figure 4: The additional item of the square of the voltage rms value $U_{nn}$ [see (19)] versus voltage interharmonic frequency order $n$. The amplitude of the $n$th voltage interharmonic component is $2\%pu$. Three curves represent the integration intervals using different lengths, which are 1 cycle, 200 ms and 3 s. Start time $\tau = 0s$, $\alpha_n = 30°$ are selected.

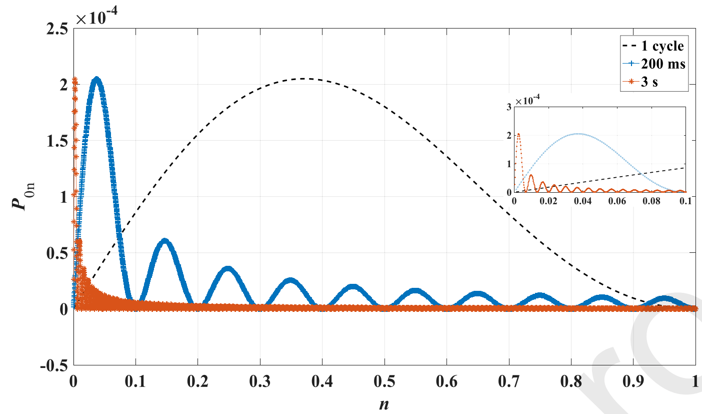



Figure 5: The cross item of active power $P_{0n}$ [see (16)] versus current interharmonic frequency order $n$. The amplitude of voltage dc component is $1\%pu$ while the amplitude of the $n$th current interharmonic component is $2\%pu$. Three curves represent the integration intervals using different lengths, which are 1 cycle, 200 ms and 3 s. Start time $\tau = 0s$, $\beta_n = 0°$ are selected.

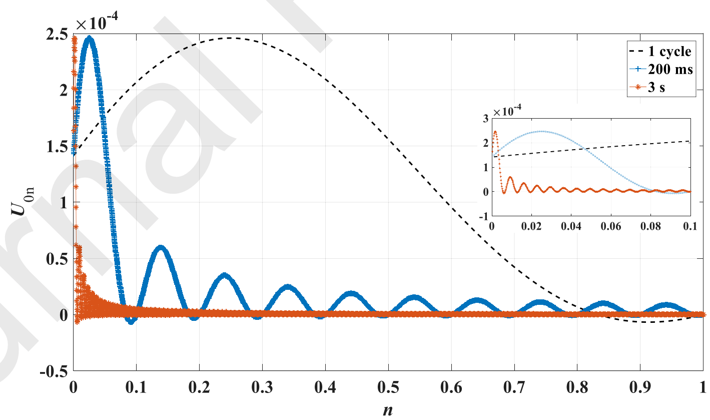



Figure 6: The cross item of the square of the voltage rms value $U_{0n}$ [see (20)] versus voltage interharmonic frequency order $n$. The amplitude of voltage dc component is $1\%pu$ while the amplitude of the $n$th voltage interharmonic component is $2\%pu$. Three curves represent the integration intervals using different lengths, which are 1 cycle, 200 ms and 3 s. Start time $\tau = 0s$, $\alpha_n = 0°$ are selected.

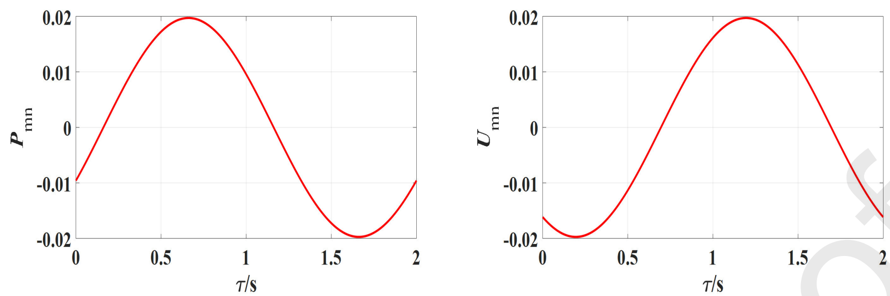
can see that the measurement errors caused by interharmonics can be greatly mitigated when the interval length is 3 s (corresponding to 150 fundamental frequency cycles for the 50 Hz system). However, the maximum measurement error is consistent in the integration intervals of different lengths. There is only the difference between interharmonic components in the range of $(m-n) \in (-1/k, 1/k)$ or $n \in (0, 1/k)$, and these interharmonics are still very worthy of attention, especially the interharmonics near the fundamental component and integer harmonic components with large amplitude, which have great impacts on the accuracy of power measurement. The complete parametric analysis of the length of integration intervals will be shown in section 4.3.

### *4.2. Sensitivity to the Measurement Start Time and Initial Phases of Voltage and Current*

The relationship of the cross item $P_{mn}$ versus the measurement start time $\tau$, and $U_{mn}$ versus $\tau$, are separately shown in Figures 7(a) and 7(b) ($m = 1, n = 0.99, \alpha_1 = 30°, \beta_n = 0°$, 10 fundamental frequency cycles length of integration interval). We can find that the values of $P_{mn}$ and $U_{mn}$ exhibit sinusoidal fluctuations when the measurement start time $\tau$ changes. Moreover, other cross items and additional items have similar change pattern to $P_{mn}$ and $U_{mn}$.

The relationship of the cross item $P_{mn}$ versus the initial phases $\alpha_m$ and $\beta_n$ is shown in Figure 8 ($m = 1, n = 0.99$, the measurement start time $\tau = 0s$, 10 fundamental frequency cycles length of integration interval). The variation ranges of $\alpha_m$ and $\beta_n$ are $(-\pi, \pi]$, respectively. We can find that the unpredictable initial phases also have great impacts on the value of the cross item $P_{mn}$. When the initial phases of the frequency components are different, different measurement results will be obtained. In addition, other cross items and additional items have similar change pattern to $P_{mn}$.

From what has been discussed above, we can safely draw the conclusion that different measurement results may be obtained for the same voltage and current signal using a time window of the same length, because the measurement start




(a) (b)

Figure 7: The cross item $P_{mn}$ (a) and $U_{mn}$ (b) versus the measurement start time $\tau$. $m = 1, n = 0.99$. The amplitude of the current interharmonic component is $2\%pu$. $\alpha_1 = 30°, \beta_n = 0°$ are selected. Length of integration intervals is 10 fundamental frequency cycles (200 ms).

time is random during the power measurement. In addition, the initial phases of each frequency component can also affect the measurement results.

### *4.3. Sensitivity to the Length of Integration Intervals*

In general, the length of integration intervals can be represented by the number of fundamental frequency cycles $k$ during the measurement. In Figure 9 (a)-(f), the maximum values of the cross items $P_{mn}$ and $U_{mn}$, the maximum values of the additional items of $P_{nn}$ and $U_{nn}$, as well as the maximum values of the cross items $P_{0n}$ and $U_{0n}$ versus $k$, are separately shown. For each $k$, the maximum values are obtained under 50,000 numerical simulation tests. During the tests, the $m$th and $n$th frequency components correspond to those in Figures 1-6, respectively, the initial phase angles of each voltage and current component change in the range of $(-\pi, \pi]$, and the measurement start time is selected in the range of $0 \sim\ 20s$ randomly.

From Figure 9, we can see that increasing the length of integration intervals cannot reduce the maximum errors of cross items and additional items. Some interharmonics of specific frequency can always cause large measurement errors. However, from the analysis above, these maximum errors are always caused by interharmonics in the range of $(m - n) \in (-1/k, 1/k)$ or $n \in (0, 1/k)$. Moreover,

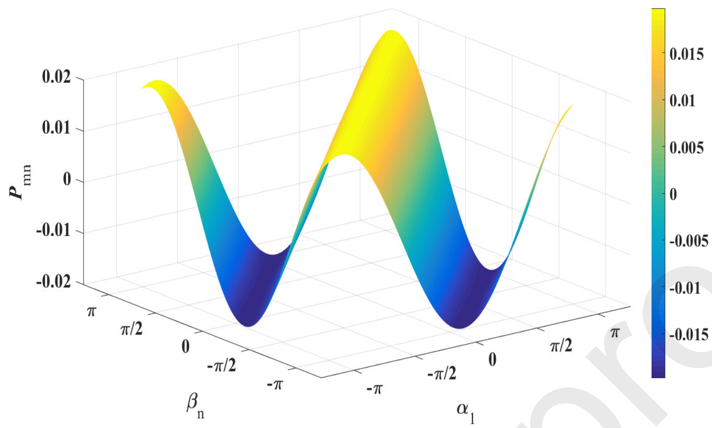



Figure 8: The cross item $P_{mn}$ versus the initial phases $\alpha_m$ and $\beta_n$. $m = 1, n = 0.99$. The amplitude of the current interharmonic component is $2\%pu$. Start time $\tau = 0s$ is selected. Length of integration intervals is 10 fundamental frequency cycles (200 ms).

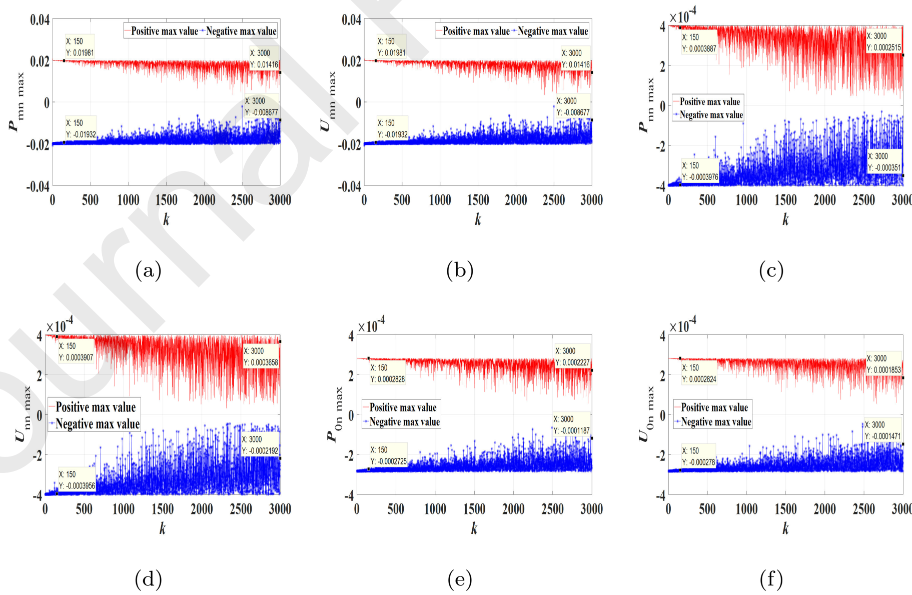



Figure 9: The maximum measurement errors versus the length of integration intervals.

when $k$ increases, interharmonics contained in these ranges are less. In addition, the positive and negative errors may cancel each other out in the presence of many interharmonics of different frequencies. In this way, it will show that the total measurement error gradually decreases as the length of the integration interval increases. The simulation example given in the next section will specify this situation.

## 5. Simulation Test

This test is to calculate the active power, voltage and current rms values, apparent power and power factor of the system with the nonlinear loads given in standard IEEE 1459. The signal model is given in (1) and (2), in which the phasors of the studied signal are summarized in Table 1. The measurement and calculation method is regulated in Section 2. In order to indicate the difference between the measured values of power quantities at different measurement start times, the sliding time windows are used on both current and voltage signals, and the sliding step is one sampling time interval. The measured values of each power quantity when time window slides are shown in Figure 10. The relationship of maximum relative errors of each power quantity versus the length of time windows is shown in Figure 11 (measurements start at different times).

As can be seen from Figure 10, when the measurement start time is different, the measured power values change. This shows that the random measurement start time will also cause more uncertainty in the measurement results when measuring the power quantities of an actual signal.

In Figure 11, when the length of the measurement time interval is 10 fundamental frequency cycles (50 Hz system, corresponding to a length of 200 ms), the maximum relative error of active power is 7.51%, and the maximum relative errors of the voltage rms value and current rms value are 0.43% and 5.49%, respectively. Besides, the maximum relative error of apparent power is 5.31% and the maximum relative error of the power factor is 2.63%. As a

Table 1: Phasors of the Studied Signal

| $h$ | $U_h\angle\alpha_h$(V) | $I_h\angle\beta_h$(A) |
|---|---|---|
| 0.0217 | $3.5\times\ 10^{-4}\angle-90.0$ | $1.48\angle80.2$ |
| 0.0433 | $1.4\times\ 10^{-3}\angle-107.3$ | $2.26\angle-8.4$ |
| 0.957 | $0.16\angle-75.5$ | $0.92\angle-173.5$ |
| 0.978 | $0.56\angle-97.2$ | $2.24\angle-193.2$ |
| 1.0 | $70.71\angle-7.2$ | $70.71\angle-42.4$ |
| 1.022 | $0.46\angle-82.9$ | $1.75\angle-178.9$ |
| 1.043 | $0.35\angle-104.3$ | $0.91\angle-202.3$ |
| 3.0 | $5.02\angle-76.0$ | $19.09\angle18.3$ |
| 4.268 | $0.95\angle176.4$ | $5.43\angle-87.0$ |
| 5.0 | $3.18\angle-114.0$ | $7.64\angle-15.8$ |
| 7.0 | $2.33\angle-142.0$ | $3.68\angle-43.2$ |
| 9.0 | $1.13\angle-165.0$ | $1.41\angle-69.0$ |

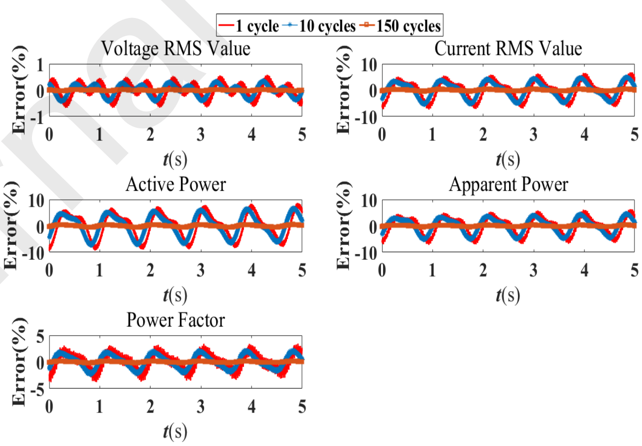



Figure 10: Smoothed power quantities versus the time for three different values of time window length $kT$, $k=1, k=10, k=150$.

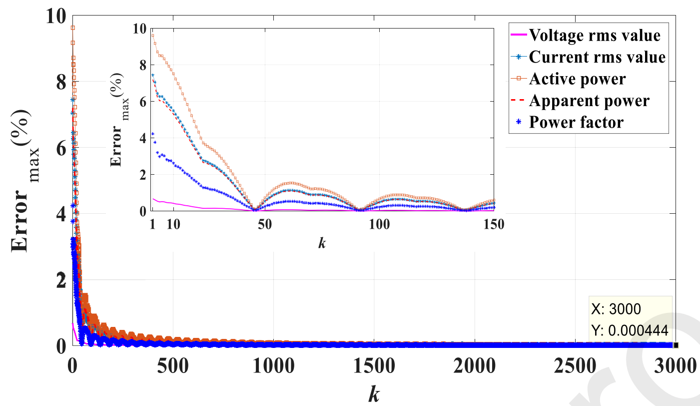



Figure 11: The maximum relative errors of active power, voltage rms value, current rms value, apparent power and power factor versus the length of measurement time intervals.

comparison, when the length of the measurement time interval is 150 fundamental frequency cycles (50 Hz system, corresponding to a length of 3 s), the measurement relative errors of the above power quantities can be reduced by one order of magnitude, and all of these relative errors are controlled within 1%. The maximum relative errors of active power, voltage rms value, current rms value, apparent power, and power factor are 0.60%, 0.03%, 0.44%, 0.43%, and 0.21%, respectively. Moreover, when the length of the measurement time interval increases to 3000 fundamental frequency cycles (50 Hz system, corresponding to a length of 1 min), the measurement relative errors of the above power quantities can be reduced by four orders of magnitude. Therefore, the length of the measurement time interval can be appropriately selected according to the interharmonic content and the measurement accuracy requirement during the power measurement.

It can also be noticed that the measurement accuracy of each power quantity is very high when the length of the measurement time interval is 45, 46 or 90 $\sim$ 93 fundamental frequency cycles, even higher than the measurement accuracy when the time interval contains 150 fundamental frequency cycles. This is because in such conditions, the sinc function of theoretical formulas equals to 0 or nearly equals to 0. However, this phenomenon does not have regularity. For different voltage and current signals, it is difficult to determine the length of the measurement time interval in which the measurement error is close to 0 when the interharmonics contained is different. Therefore, the length of the measurement time interval of 3 s or 1 min should generally be used to improve the power measurement accuracy.

When the sampling frequency is high enough, the actual measurement results are consistent with the theoretical analysis results. In simulation tests of this paper, a high sampling frequency should be adopted, that is, the errors caused by sampling frequency can be ignored.

## 6. Conclusion

The interharmonics present in the voltage and current signals affect the measurement accuracy of the power quantities defined in standard IEEE 1459. In this paper, the mathematical models of the active power calculation term and the voltage and current rms value calculation terms between arbitrary frequency components are constructed for the first time, and the power measurement errors affected by four parameters are analyzed. The simulation results show the influence of each parameter on the measurement accuracy of power quantities.

The interharmonics near the fundamental component and integer harmonic components with large amplitude have great impacts on the accuracy of power measurement. Increasing the length of integration intervals cannot reduce the maximum errors of cross items and additional items. These maximum errors are always caused by interharmonics in the range of $(m - n) \in (-1/k, 1/k)$ or $n \in (0, 1/k)$. However, when $k$ increases, interharmonics contained in these ranges are less. In addition, the positive and negative errors may cancel each other out because of the presence of many interharmonics of different frequencies in the actual signals. In this way, it will show that the total measurement error gradually decreases as the length of the integration interval increases. When the length of the measurement time interval is 150 fundamental frequency cycles

(50 Hz system, corresponding to a length of 3 s), the measurement relative errors of active power, voltage and current rms value, apparent power and power factor can all be reduced by one order of magnitude, and all of these relative errors are controlled within 1%. Moreover, when the length of the measurement time interval increases to 3000 fundamental frequency cycles (50 Hz system, corresponding to a length of 1 min), the measurement relative errors of the above power quantities can be reduced by four orders of magnitude. Therefore, the length of the measurement time interval can be appropriately selected according to the interharmonic content and the measurement accuracy requirement during the power measurement.

From the practicality of measurement, parameters such as initial phase angle and measurement start time are random and unpredictable. Although they have a large influence on the measurement accuracy, due to the existence of uncertainty, it is difficult to ensure the condition of satisfying the minimum error during measurement. Therefore, it is generally impossible to improve the power measurement accuracy by changing the measurement start time. However, for any signal and measurement started at any time, as long as the length of the measurement integration interval is long enough, the power and rms value measurement errors can be restricted within the required range, even if under the condition of selecting the worst measurement start time.

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