The Calmet C300 Calibrator under nonsinusoidal conditions - harmonics

Extended Specifications

Calmet
Calibration

Application note no 12

What is the Power/Energy Calibration under Nonsinusoidal Conditions?

Measuring electric and electronic instruments should be calibrated under conditions as similar to the actual conditions of their operation as possible – this applies in particular to electrical energy meters (EEM). An important group of tests on accuracy of EEMs includes verification requirements such as limits of disturbances effect such as, for example, harmonic components in current and voltage circuits.

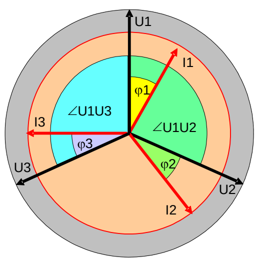
The EN 50470 for active meters introduces several new tests of the EEM under nonsinusoidal conditions, for example, in the presence of harmonics with content of the 5th harmonic voltage U_5=10% of fundamental voltage and of the 5th harmonic current I_5=40% of fundamental current. In this test should be used three phase configuration with balanced load with currents I=50%I_{max} (50A for I_{max}=100A) , the harmonic power factor equals cosφ_5=1, the fundamental and harmonic voltages are in phase at positive zero crossing.

The C300 as the most accurate solution for three phase power calibration under Sinusoidal and Nonsinusoidal Conditions in single case

The C300 is a single-box solution for reference-standard, three phase signals generation to test power quality analyzers, electricity meters, protection relays and similar equipment under sinusoidal and nonsinusoidal conditions.

It consists of independent three voltages and three currents channels, that can source up to 560V and 120A with typical accuracies as good as 0.02% or 200ppm under Sinusoidal Conditions. It can works both for single phase configuration with currents up to 360A and for three phase balanced and unbalanced configurations with currents up to 120A without need to use an additional current amplifier options.

The C300 can generate multi-harmonic distortion with independent superposition of harmonic components in each phase of current and voltage, with levels 0…100% and phase angle 0…360° of the first harmonic. **This application note presents Accuracy Calculations for Voltage (V), Current (I), Apparent Power (S), Active Power (P) and Reactive Power (Q) for determining the C300 Calibrator Specifications under Nonosinusoidal Conditions with multi-harmonic distortions.**



The C300 provides the accuracy
in a wide range of voltages and currents
required to verify the performance
of measuring instruments
under sinusoidal and nonsinusoidal conditions

Voltage, current and P, Q, S powers specifications of C300 Calibrator for sinusoidal conditions

Parameter	Range	Settings span	Resolution	Accuracy [1]		Maximum load
				class 0.02	class 0.05	
Voltage U	70V	0.5...70V	0.0001V	±0.02% of setting ±0.005% of range	±0.04% of setting ±0.01% of range	560mA@70V
	140V	1...140V	0.001V			280mA@140V
	280V	2...280V	0.001V			140mA@280V
	560V	5...560V	0.001V			70mA@560V
Current I	0,5A	0.005...0.5A	0.000001A	±0.02% of setting ±0.005% of range	±0.04% of setting ±0.01% of range	17V@0,5A
	6A	0.05...6A	0.00001A			8.5V@6A
	20A	0.2...20A	0.0001A			3.3V@20A
	120A	1...120A	0.001A			0.95V@60A 0.70V@120A
Frequency f		40...99.999Hz	0.001Hz	±0.002Hz	±0.002Hz	
		100...500Hz	0.001Hz	±0.010Hz	±0.010Hz	
Phase shift φ		0...±360°	0.01°	±0.05° [2]	±0.10° [2]	
Active power P		0...3x67200W	0.00001-1W	±0.02% [2] [3]	±0.05% [2] [3]	
React. power Q		0...3x67200var	0.00001-1var	±0.02% [2] [3]	±0.05% [2] [3]	
Appar. power S		0...3x67200VA	0.00001-1VA	±0.02% [2]	±0.05% [2]	
Energy	calculated from settings of power and time			±0.02% [2] [3]	±0.05% [2] [3]	

1) Absolute extended uncertainty under confidence level of 95% covers reference uncertainty of standards, stability in 12 months, influence quantities (ambient temperature in range +20…+26°C, humidity, power supply voltage and load in full operating range, frequency in range 45…65Hz) and nonlinearity. For frequency band below 45Hz and above 65Hz – linear rise up typically to double value for frequency 500Hz.

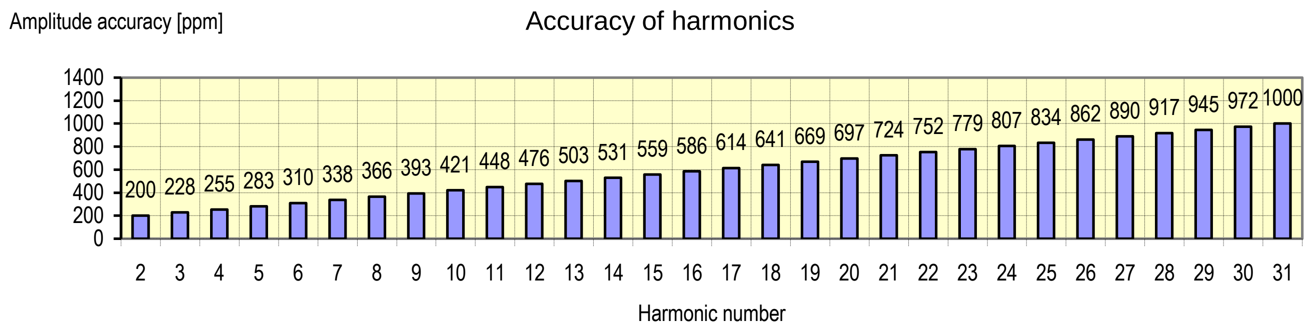
2) From 10% of current range and 30% of voltage range, in frequency range 45-65Hz.

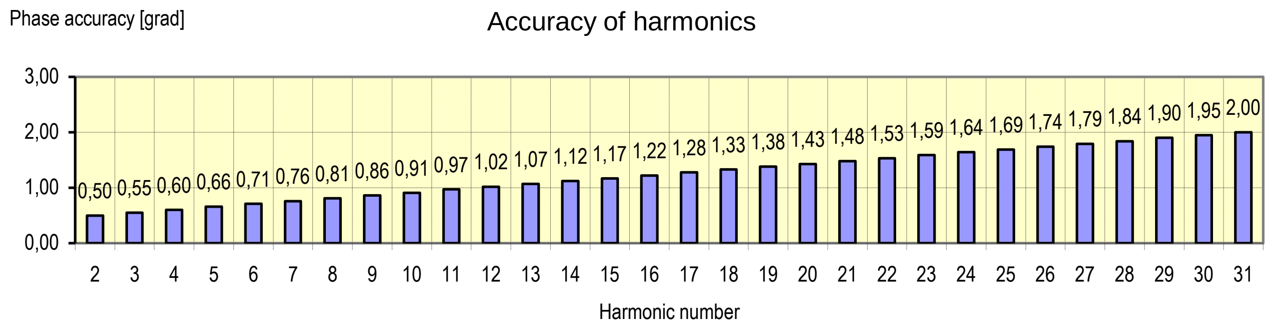
3) Uncertainty of power P(Q) under cosφ(sinφ)=1, for cosφ(sinφ)≠1 linear rise up typically to 0.15% (class 0.02) or 0.30% (class 0.05) for cosφ(sinφ)=0.5. For voltage and current below 10% of range uncertainty 0.005% of range value.

Harmonic specifications of C300 Calibrator for nonsinusoidal conditions

Parameter	Amplitude settings span	Phase settings span	Frequency settings span	Accuracy [4]		Possibility of settings
				amplitude	phase	
Harmonics	0…100% of fundamental	0…±360°	Up to 31st or to 3200Hz	±0.02% of output	±0.5°	Independent superposition of harmonic components in each phase of current and voltage

4) 0.02% of output and 0.5° for 2nd harmonic with linear rise to 0.10% of output and 2° for 31st harmonic.





Theory

For the purpose of voltage accuracy calculation for nonsinusoidal outputs the following equations are used:

$$V_{RMS}^2 = \sum_1^N V_n^2$$

$$V_n = k_n \cdot V_1 \qquad \text{NOTE 1)}$$

$$V_1 = \frac{V_{RMS}}{\sqrt{1+k_2^2+\ldots+k_n^2}}$$

$$\left(V_{RMS} + u(V_{RMS})\right)^2 = \sum_1^N \left(V_n + u(V_n)\right)^2$$

$$u(V_{RMS}) = \sum_1^N c_n \cdot u(V_n) = \sum_1^N \frac{V_n}{V_{RMS}} \cdot u(V_n)$$

where:
V_{RMS} – rms value of the voltage,
V_n – rms value of harmonic,
k_n – harmonic distortion coefficient (relative voltage),
n – harmonic number (order),
V_1 – rms value of fundamental,
$u(V_n)$ – uncertainty of harmonic,
c_n – sensitivity coefficient,
$u(V_{RMS})$ – uncertainty of voltage with harmonics named as total amplitude uncertainty or Voltage Accuracy under nonsinusoidal conditions.

NOTE 1) Harmonic voltage, acc. to the EN 50160:2007 should be evaluated by their relative amplitude V_n related to the fundamental voltage V_1 ,
not to the rms value V_{RMS}
as it has been done, for example,
in the Fluke 6105A/6100B Electrical Power Standards

Nonsinusoidal Voltage Example 110V/60Hz

The voltage 110V rms at 60Hz comprising 30% 3rd harmonic and 10% 25th harmonic is generated from the 140V range.

Fundamental rms voltage is
V_1=110/√(1+0.3²+0.1²)=104.8809V

Accuracy of the fundamental is
$u(V_1)$=200ppm of output + 50ppm of range=
=0.000200x104.8809+0.000050x140=0.027976V

3rd harmonic value is
V_3=30%xV_1=0.3x104.8809=31.4643V

Accuracy of the 3rd harmonic is
$u(V_3)$=228ppmxV_1=0.000228x104.8809=0.023913V

25th harmonic value is
V_{25}=10%xV_1=0.1x104.8809=10.48809V

Accuracy of the 25th harmonic is
$u(V_{25})$=834ppmxV_1=0.000834x104.8809=0.087471V

Total amplitude uncertainty is
$u(V_{RMS})$=(104.8809/110)x0.027976+(31.4643/110)x0.023913+(10.48809/110)x0.087471=
=0.026674+0.006840+0.008340=0.041854V
or
$u(V_{RMS})/V_{RMS}$=0.041854/110=0.000380 (or 380ppm)

Voltage Accuracy is 110V±0.041854V

Non-sinusoidal Voltage Example

The waveform is a 60 Hz, 110 V rms waveform, from the 168 V range, comprising 10 % 95th harmonic, 30 % 3rd harmonic with the remainder contributed by the fundamental frequency. Using the 6100B voltage uncertainty values in "Voltage and Sine Amplitude Specifications" and "Voltage DC and Harmonic Specifications", determine the 1-year accuracy.

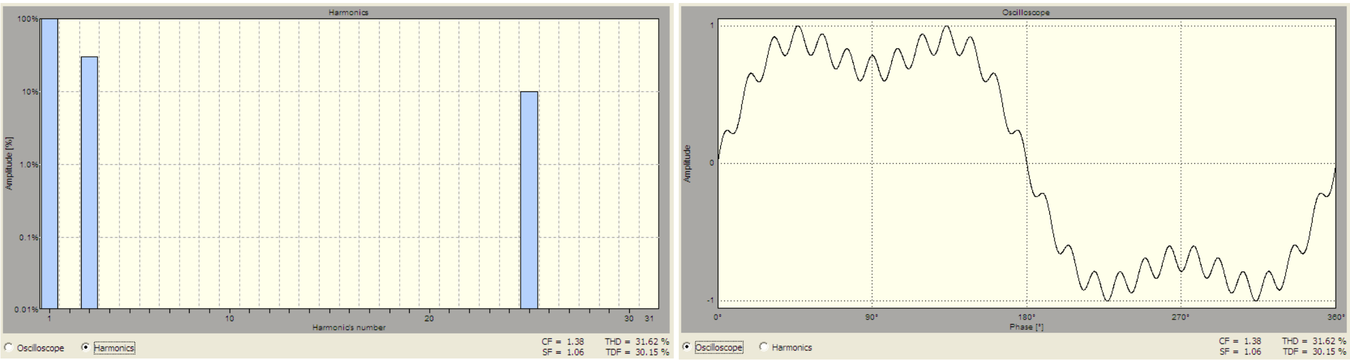
3rd Harmonic rms voltage = 0.3 x 110 = 33 V

95th Harmonic rms voltage = 0.1 x 110 = 11 V

Fundamental rms voltage = √(110² - 33² - 11²) = 104.3552 V

6105A/6100B Extended Specifications Fluke Corporation 17

Voltage waveform from Nonsinusoidal Voltage Example 110V/60Hz



Theory

For the purpose of apparent power accuracy calculation for nonsinusoidal outputs the following equations are used:

$$S = \sqrt{\sum_{1}^{N} V_n^2 \cdot \sum_{1}^{N} I_n^2}$$

$$\frac{u(S)}{S} = \sqrt{\left[\frac{u(V_{RMS})}{V_{RMS}}\right]^2 + \left[\frac{u(I_{RMS})}{I_{RMS}}\right]^2}$$

$$\frac{u(V_{RMS})}{V_{RMS}} = \sum_{1}^{N} \frac{V_n}{V_{RMS}} \cdot \frac{u(V_n)}{V_{RMS}}$$

$$\frac{u(I_{RMS})}{I_{RMS}} = \sum_{1}^{N} \frac{I_n}{I_{RMS}} \cdot \frac{u(I_n)}{I_{RMS}}$$

where:
V_{RMS} – rms value of the voltage,
V_n – rms value of the voltage harmonic,
I_n – rms value of the current harmonic,
n – harmonic number,
$u(V_{RMS})/V_{RMS}$ – uncertainty of the voltage,
$u(I_{RMS})/I_{RMS}$ – uncertainty of the current,
$u(V_n)/V_n$ – uncertainty of the harmonic voltage,
$u(I_n)/I_n$ – uncertainty of the harmonic current,
$u(S)/S$ – uncertainty of the apparent power.

Nonsinusoidal Apparent Power Example 110V/60Hz

The voltage 110V rms at 60Hz comprising 14% 3rd harmonic is generated from the 140V range. The current 7A rms at 60Hz comprising 10% 3rd and 4.29% 5th harmonics is generated from the 20A range.

Fundamental rms voltage is
V_1=110/√(1+0.14^2)=108.9376V

3rd harmonic rms voltage is
V_3=14%xV_1=0.14x108.9376=15.5126V

Uncertainty of the voltage is NOTE 2)
$u(V_{RMS})/V_{RMS}$=
=(V_1/V_{RMS})x{[$u(V_1)$]/V_{RMS}}+
+(V_3/V_{RMS})x{[$u(V_3)$]/V_{RMS}}=
=(108.9376/110)x0.000141+
+(15.5126/110)x0.000228=0.000172 (or 172ppm)

NOTE 2) Voltage and current outputs of the C300 are additionally precisely adjusted in Apparent Power Mode for achievements 200ppm accuracy of apparent power under sinusoidal conditions in voltage range from 21V (30% of 70V) to 560V and in current range from 0.05A (10% of 0.5A) to 120A.
$u(S_1)/S_1$=√{[$u(V_1)$]/V_1}^{2}+{[$u(I_1)$]/I_1}^{2}
200ppm=√(141ppm)^2+(141ppm)^2

Fundamental rms current is
I_1=7/√(1+0.1^2+0.0429^2)=6.91809A

3rd harmonic rms current is
I_3=10%xI_1=0.1x6.91809=0.691809A

5th harmonic rms current is
I_5=4.29%xI_1=0.0429x6.91809=0.296786A

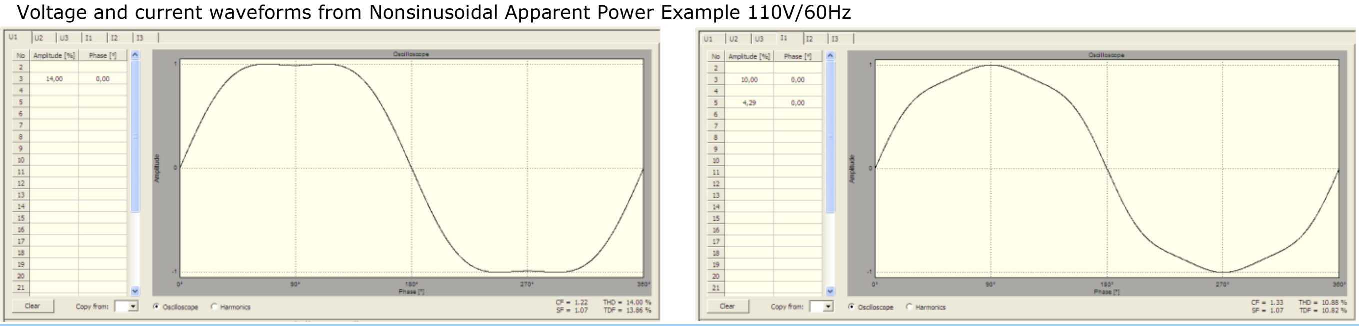
Uncertainty of the current is NOTE 2)
$u(I_{RMS})/I_{RMS}$=
=(I_1/I_{RMS})x{[$u(I_1)$]/I_{RMS}}+
+(I_3/I_{RMS})x{[$u(I_3)$]/I_{RMS}}+(I_5/I_{RMS})x{[$u(I_5)$]/I_{RMS}}=
=(6.91809/7)x0.000141+
+(0.691809/7)x0.000228+
+(0.296786/7)x0.000283=0.000174 (or 174ppm)

Uncertainty of the apparent power is
$u(S)/S$=√0.000172^2+0.000174^2=0.000244 (or 244ppm)

$u(S)$=0.000244x770=0.1879VA

Apparent power accuracy is 770VA±0.1879VA

Voltage and current waveforms from Nonsinusoidal Apparent Power Example 110V/60Hz



Theory

For the purpose of active power accuracy calculation for nonsinusoidal outputs the following equations are used:

$$P = \sum_{1}^{N} P_n = \sum_{1}^{N} V_n \cdot I_n \cdot \cos\varphi_n$$

$$\frac{u(P_n)}{P_n} = \sqrt{\left[\frac{u(V_n)}{V_n}\right]^2 + \left[\frac{u(I_n)}{I_n}\right]^2 + \left[u(\varphi_n)\right]^2}$$

$$u(\varphi_n) = \frac{\cos(\varphi + u(\varphi)) - \cos\varphi}{\cos\varphi}$$

$$u(P) = \sum_{1}^{N} \frac{P_n}{P} \cdot u(P_n)$$

where:
P – active power,
P_n – harmonic component of active power,
V_n – rms value of the voltage harmonic,
I_n – rms value of the current harmonic,
φ_n – phase angle of harmonic component,
n – harmonic number,
$u(V_n)/V_n$ – uncertainty of the harmonic voltage,
$u(I_n)/I_n$ – uncertainty of the harmonic current,
$u(\varphi_n)$ – uncertainty of the power factor,
$u(P_n)/P_n$ – uncertainty of the harmonic component of active power,
$u(P)$ – uncertainty of the active power.

Nonsinusoidal Active Power Example 110V/60Hz

The voltage 110V rms at 60Hz comprising 14% 3rd harmonic is generated from the 140V range. The voltage 3rd harmonic has 0° phase angle relative to the voltage fundamental. The current 7A rms at 60Hz comprising 10% 3rd and 4.29% 5th harmonics is generated from the 20A range. The current fundamental phase is +12° relative to the voltage fundamental. The current 3rd harmonic has +25° phase angle relative to the current fundamental and +61° (=25°+3x12°) phase angle relative to the 3rd voltage harmonic. As the current of 5th harmonic is not matched by a voltage 5th harmonic, there is no 5th harmonic power component.

Voltage, current and power at the fundamental are
$V_1=110/\sqrt{(1+0.14^2)}=108.9376V$
$I_1=7/\sqrt{(1+0.1^2+0.0429^2)}=6.91809A$
$P_1=V_1I_1\cos\varphi_1=$
$=108.9376x6.91809x0.978148=737.172W$

Uncertainty of voltage, current, power factor and power component at the fundamental are NOTE 3)
$u(V_1)/V_1=141ppm$
$u(I_1)/I_1=141ppm$
$u(\varphi_1)=[\cos(12+0.05)-\cos(12)]/\cos(12)=186ppm$
$u(P_1)/P_1=\sqrt{141^2+141^2+186^2}=273ppm$
$u(P_1)=0.000273x737.1727=0.201248W$

NOTE 3) Voltage and current outputs of the C300 are additionally precisely adjusted in Active Power Mode for achievements 200ppm accuracy of active power at PF=1 under sinusoidal conditions in voltage range from 21V (30% of 70V) to 560V and in current range from 0.05A (10% of 0.5A) to 120A.
$u(P_1)/P_1=\sqrt{\{[u(V_1)]/V_1\}^2+\{[u(I_1)]/I_1\}^2+\{u(\varphi_1)\}^2}$
$200ppm=\sqrt{(141ppm)^2+(141ppm)^2+(1ppm)^2}$

Voltage, current and power for the 3rd harmonic are
$V_3=14\%xV_1=0.14x108.9376=15.5126V$
$I_3=10\%xI_1=0.1x6.91809=0.691809A$
$P_3=V_3I_3\cos\varphi_3=$
$=15.5126x0.691809x0.484810=5.202863W$

Uncertainty of voltage, current, power factor and power component for the 3rd harmonic are
$u(V_3)/V_3=228ppm$
$u(I_3)/I_3=228ppm$
$u(\varphi_3)=[\cos(61+0.55)-\cos(61)]/\cos(61)=17363ppm$
$u(P_3)/P_3=\sqrt{228^2+228^2+17363^2}=17366ppm$
$u(P_3)=0.017366x5.202863=0.09035W$

Total active power is
$P=737.172+5.2029=742.3749W$

Uncertainty of the active power is
$u(P)=(737.172/742.3749)x0.201248+$
$+(5.202863/742.3749)x0.09035=0.20047W$
$u(P)/P=0.20047/742.3749=0.000270$ (or 270ppm)

Active power accuracy is 742.3749W±0.2005W

Non-sinusoidal Reactive Power (Q) Accuracy Calculations

Theory

For the purpose of reactive power calculation under sinusoidal conditions the following equation is used:

$$Q = V_{RMS} \cdot I_{RMS} \cdot \sin\varphi$$

There are many theories for the purpose of reactive power calculation under nonsinusoidal conditions – in standard version of the C300 is supported Budeanu method:

$$Q = \sum_{1}^{N} Q_n = \sum_{1}^{N} V_n \cdot I_n \cdot \sin\varphi_n$$

and the following equations are used for calculation of reactive power accuracy for nonsinusoidal outputs:

$$\frac{u(Q_n)}{Q_n} = \sqrt{\left[\frac{u(V_n)}{V_n}\right]^2 + \left[\frac{u(I_n)}{I_n}\right]^2 + \left[u(\varphi_n)\right]^2}$$

$$u(\varphi_n) = \frac{\sin(\varphi + u(\varphi)) - \sin\varphi}{\sin\varphi}$$

$$u(Q) = \sum_{1}^{N} \frac{Q_n}{Q} \cdot u(Q_n)$$

where:
Q – reactive power,
Q_n – harmonic component of reactive power,
V_n – rms value of the voltage harmonic,
I_n – rms value of the current harmonic,
φ_n – phase angle of harmonic component,
n – harmonic number,
$u(V_n)/V_n$ – uncertainty of the harmonic voltage,
$u(I_n)/I_n$ – uncertainty of the harmonic current,
$u(\varphi_n)$ – uncertainty of the power factor,
$u(Q_n)/Q_n$ – uncertainty of the harmonic component of reactive power,
$u(Q)$ – uncertainty of the reactive power.

Nonsinusoidal Reactive Power Example 230V/50Hz

The voltage 230V rms at 50Hz comprising 10% 3rd harmonic is generated from the 280V range. The voltage 3rd harmonic has 0° phase angle relative to the voltage fundamental. The current 100A rms at 50Hz comprising 40% 3rd harmonic is generated from the 120A range. The current fundamental phase is +95° relative to the voltage fundamental. The current 3rd harmonic has +5° phase angle relative to the current fundamental and +110° (=95°+3x5°) phase angle relative to the 3rd voltage harmonic.

Voltage, current and power at the fundamental are
$V_1=230/\sqrt{(1+0.1^2)}=227.723$V
$I_1=100/\sqrt{(1+0.4^2)}=86.2069$A
$Q_1=V_1 I_1 \sin\varphi_1=$
$=227.723 \times 86.2069 \times 0.996195=19556.6$var

Uncertainty of voltage, current, power factor and power component at the fundamental are NOTE 4)
$u(V_1)/V_1=141$ppm
$u(I_1)/I_1=141$ppm
$u(\varphi_1)=[\sin(95+0.05)-\sin(95)]/\sin(95)=77$ppm
$u(Q_1)/Q_1=\sqrt{141^2+141^2+77^2}=214$ppm
$u(Q_1)=0.000214 \times 19556.6=4.18511$var

NOTE 4) Voltage and current outputs of the C300 are additionally precisely adjusted in Reactive Power Mode for achievements 200ppm accuracy of reactive power at PF=1 under sinusoidal conditions in voltage range from 21V (30% of 70V) to 560V and in current range from 0.05A (10% of 0.5A) to 120A.
$u(Q_1)/Q_1=\sqrt{\{[u(V_1)]/V_1\}^2+\{[u(I_1)]/I_1\}^2+\{u(\varphi_1)\}^2}$
$200\text{ppm}=\sqrt{(141\text{ppm})^2+(141\text{ppm})^2+(1\text{ppm})^2}$

Voltage, current and power for the 3rd harmonic are
$V_3=10\% \times V_1=0.1 \times 227.723=22.7723$V
$I_3=40\% \times I_1=0.4 \times 86.2069=34.4828$A
$Q_3=V_3 I_3 \sin\varphi_3=$
$=22.7723 \times 34.4828 \times 0.939693=737.896$var

Uncertainty of voltage, current, power factor and power component for the 3rd harmonic are
$u(V_3)/V_3=228$ppm
$u(I_3)/I_3=228$ppm
$u(\varphi_3)=[\sin(110+0.55)-\sin(110)]/\sin(110)=3540$ppm
$u(Q_3)/Q_3=\sqrt{228^2+228^2+3540^2}=3554$ppm
$u(P_3)=0.003554 \times 737.896=2.62248$var

Total reactive power is
$Q=19556.6+737.896=20294.5$var

Uncertainty of the reactive power is
$u(Q)=(19556.6/20294.5) \times 4.18511+$
$+(737.896/20294.5) \times 2.62248=4.12839$var
$u(Q)/Q=4.12839/20294.5=0.000203$ (or 203ppm)

Reactive power accuracy is 20294.5var±4.18511var

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high quality and reasonably price.

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Pub ID: C300 AN12 EN 2014-07