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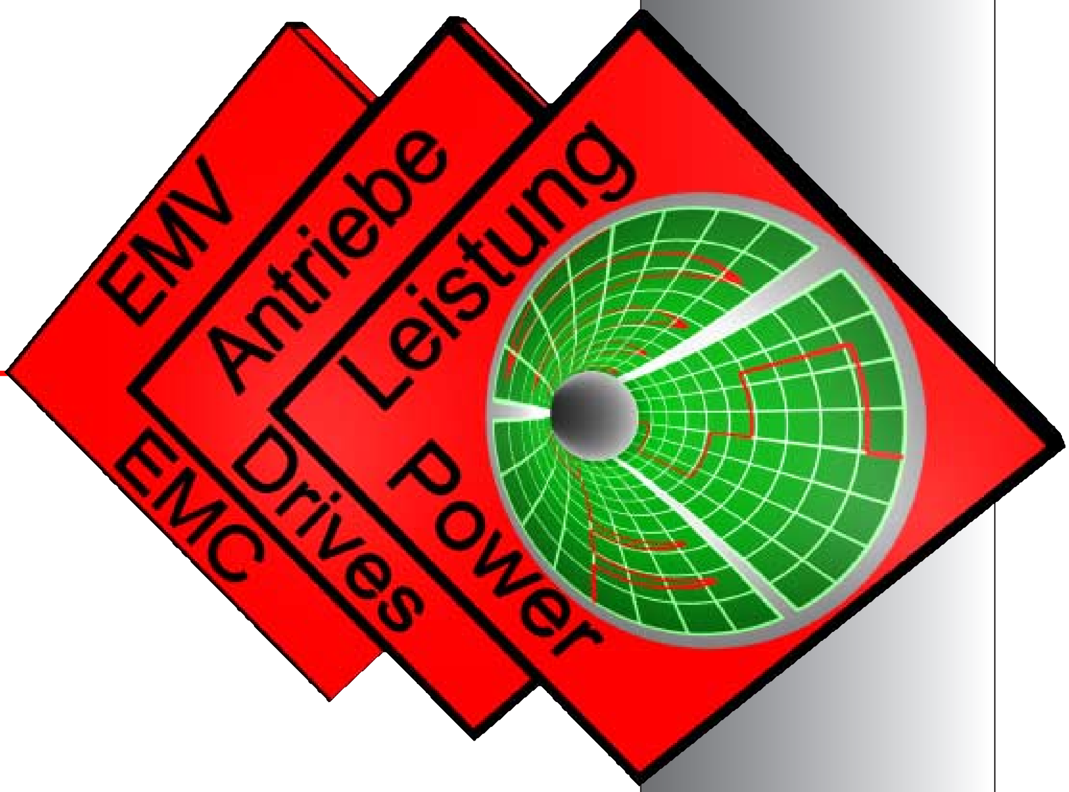

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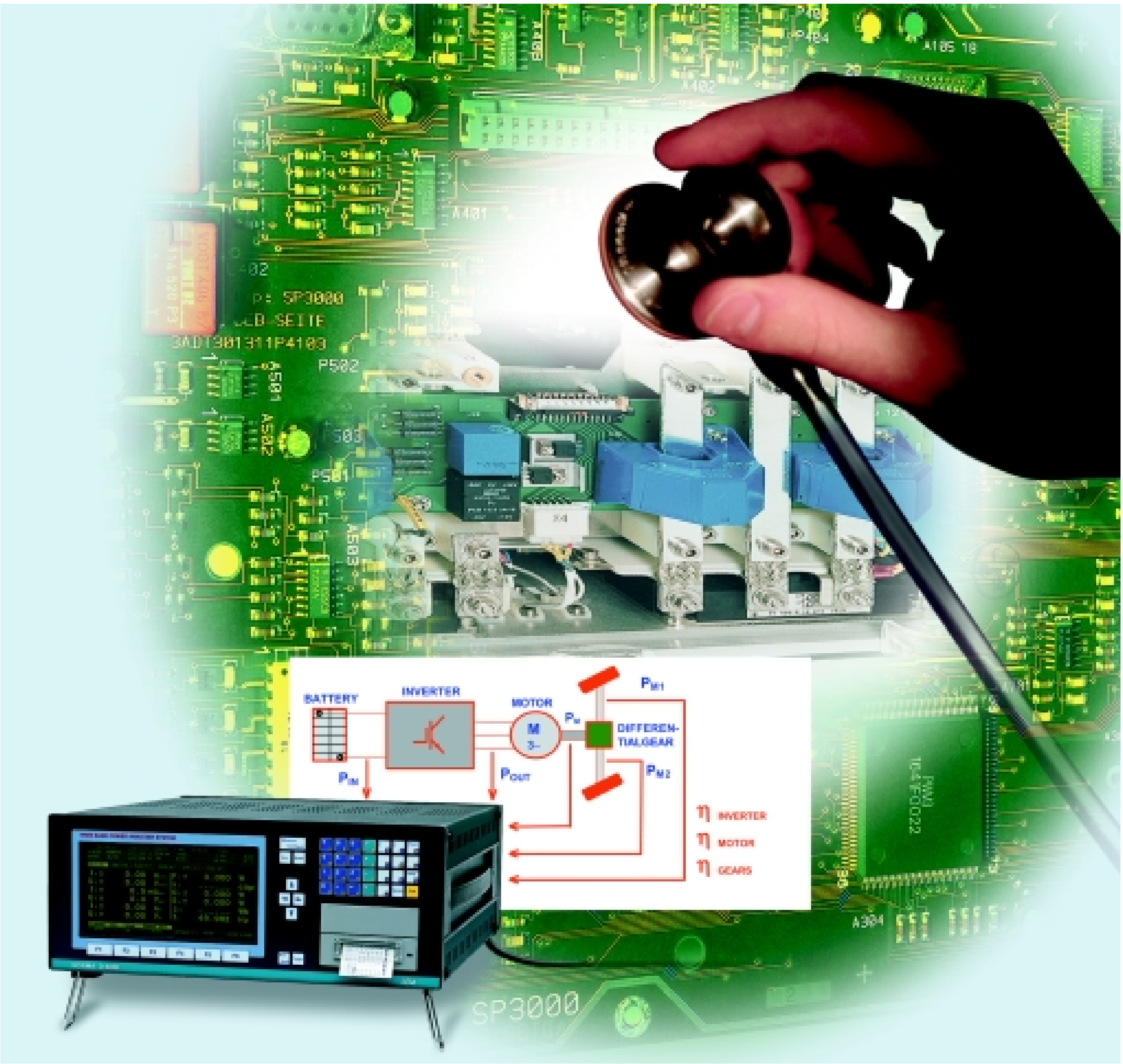
Technical
Information

Important characteristics of modern wide band power analyzers and their proof in a laboratory



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Important characteristics of modern wide band power analyzers and their proof in a laboratory

Article taken from the November 2000 edition of the PCIM Europe, author Horst Bezold

The following article shows the technical characteristics a wide band power meter needs to deliver precise results in power electronics applications and how to evaluate or proof them without advanced means in your laboratory.

This way the article supports all engineers who are interested in acquiring a power analyzer for the development of their power electronics components or drives.

Fundamentals of digital power meters

Modern digital power meters work – in a similar manner to digital oscilloscopes – by sampling a signal waveform and storing discrete values. In addition to this function, power meters multiply the sample values of two independent signals – in this case, voltage and current (Picture 1). To get accurate power values it is quite important that the values of both signals must be sampled at absolutely the same time. The integration of the calculated sample value p(t) over a given time results in an average value for active power P. The quadratic integration of the sample values of voltage u(t) and current i(t) gives the RMS values for voltage U and current I. A multiplication of the averaged values of voltage U_{RMS} and current I_{RMS} results in the apparent power S. The power factor is calculated by active power P through apparent power S.

$$P = \frac{1}{T} \cdot \int_0^T p(t)dt \quad \text{with} \quad p(t) = u(t) \cdot i(t)$$

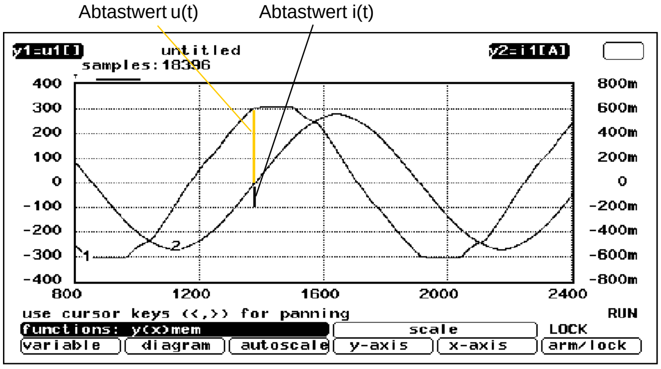
$$S = U_{RMS} \cdot I_{RMS} \quad \text{with} \quad U_{RMS} = \sqrt{\frac{1}{T} \cdot \int_0^T u^2(t)dt}$$

$$\text{and} \quad I_{RMS} = \sqrt{\frac{1}{T} \cdot \int_0^T i^2(t)dt}$$

$$PF = \lambda = \frac{P}{S}$$

Signal waveforms, rise times and frequency ranges in power electronics

The importance of the synchronous sampling of voltage and current when measuring low frequency, sinusoidal signals is low, but only at power factors of .5 and higher. However, when measuring signals with power factors less then .5 , or frequencies above 400 Hz, the time shift of one signal against the other caused by non-synchronous sampling is very critical. A time shift caused by any differences in the time each channel is sampled will result in a large error of the active power reading. This result is not usable.



Picture 1: The signals u(t) and i(t) must be sampled at precisely the same time. The result is a sample value of the active power p(t) = u(t) · i(t)

Measuring signals in power electronics is even more of a challenge. Voltage and current waveforms are very distorted and sometimes even rectangular. That means that one sample value can be at the maximum amplitude of the signal and the next sample value may be zero. You can imagine, that in this case a non synchronous sampling of voltage and current leads to a huge error in the active power sample value even at unity PF.

Concerning synchronous sampling and precise measurement of the active power, the drives applications are relatively straightforward. Due to the inductances and capacitances in the motor winding the current is relatively sinusoidal. Only harmonics of the same order of current and voltage result in a harmonic of power. That means if the current is nearly sinusoidal there is hardly any power beyond the fundamental frequency of current and voltage. The fundamental frequency of drives applications is usually less than 1 kHz, on the other hand, for an optimisation of the mechanical torque at the shaft of a motor, the measurement of the fundamentals of voltage current and power is sufficient because only the RMS values of the fundamentals result in mechanical power at the shaft. For a precise evaluation of the switching losses in an inverter and a motor a power meter is necessary. This power meter must deliver precise results of the switching frequency and of the harmonics of the switching frequency. The switching frequency of modern inverters can be as high as 25 kHz. An evaluation of these high frequency losses is especially necessary when the motor current is extremely distorted because of small inductances and capacitances of the motor. Typical motors with very low impedances are highly dynamic drives and traction drives with high start up torque.

Measurement of electric power of high frequency applications like charge pumps is also challenging. Charge pumps or boost converters are high frequency chopper circuits, which transform the battery voltage of modern hand held electronics equipment like mobile phones into a signal usable for the electronic circuits without much losses in the chopper circuit. The switching frequencies of charge pumps are in the range of several 100 kHz.

Up till now the highest frequencies in power electronics applications and the most distorted signals you can find have been in the lighting industry. Modern electronic lighting ballast for energy saving lamps can have a switching frequency as high as 500 kHz. In the near future they will reach 1 MHz and higher. The impedance of the neon tube leads to similar distortion of voltage and current. Compared to charge pumps the voltage level is relatively high. This means that a power meter for modern lighting ballast needs to have a sufficient common mode rejection at very high frequencies.

Challenge of accurate loss calculations of highly efficient loads

Very often modern power meters offer an internal formula editor to make further calculations with measured results. In this case a multiple channel analyzer is able to calculate the losses of a load by calculating the difference between the input and the output power of a load. The problem of this calculation is, that the accuracy of the result depends on the efficiency of the load. The following example shows the different results of two different loads measured by the same power meter. The meter has a fundamental accuracy of 0.1 % for power, the first load has an efficiency of 50 % and the second load an efficiency of 95 %. The input power should be 100 Watts.

Load 1
Actual values
Input power: 100 W
Output power: 50 W
Losses: 50 W

Measured values (Worst Case)
Input power: 100,1 W
Output power: 49,9 W
Difference: 50,2 W
Error: 0,4 %

Load 2
Actual values
Input power: 100 W
Output power: 95 W
Losses: 5 W

Measured values (Worst Case)
Input power: 100,1 W
Output power: 94,9 W
Losses: 5,2 W
Error: 4,0 %

The instrument measures the power in both cases with a deviation of 0.2 W from the correct values. At load 1 this means a deviation of 0.4 %, at load 2 a deviation of 4 % concerning the actual losses. The accuracy of the result depends on the efficiency of the device under test. In modern power electronics applications efficiencies of 90 or 95 % are much more realistic than 50 %. For loss measurement by differential calculation a power meter of the highest accuracy is necessary.

Important characteristics of modern wide band power meters and their proof

In this chapter, the four most important characteristics

- Amplitude accuracy
- Bandwidth
- Phase angle errors of inputs and transducers
- Common mode rejection

of digital wide band power meters will be discussed. It describes how to evaluate the performance and the accuracy of a power analyzer. For this proof a voltage supply (AC or DC) and a frequency generator is necessary. This equipment should be available in most electronics laboratories.

Amplitude accuracy

The following signal waveforms show the importance of high amplitude accuracy. The amplitude accuracy is defined as the error of the measured value plus the error of the measuring range (% MV + % MR). The accuracy of the measuring range is especially important when significant components of the signal are in a low range. Automatic ranging will always adjust according the peak value of a signal.

To proof the amplitude accuracy of a power meter, an AC or DC voltage will be connected to two different voltage channels. In our example we apply 24 V DC to channel U1 and U2. The lowest voltage measuring range of the instrument is 25 V_{peak} and the highest 2100 V_{peak}. The evaluated analyzer offers the ability to calculate measured results. It calculates the deviation between both voltage channels in percent and displays this value as variable F1 on the screen.

Bandwidth

As mentioned previously, the switching frequencies of power electronics applications are as high as several 100 kHz already. The trend is rising. It is quite clear that an instrument, which measures power at these high frequencies, must also

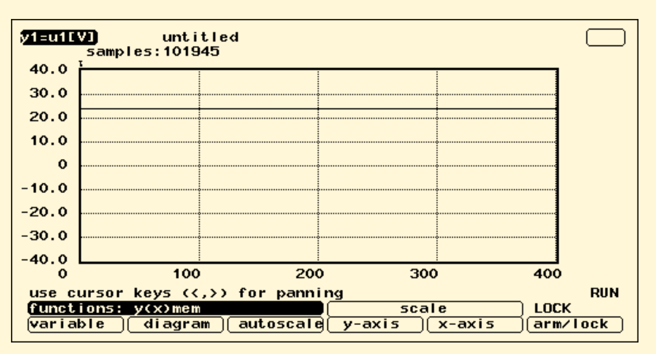


Fig. 2a DC Signal
Error of the range is not very important. All sample values are acquired in the right range.

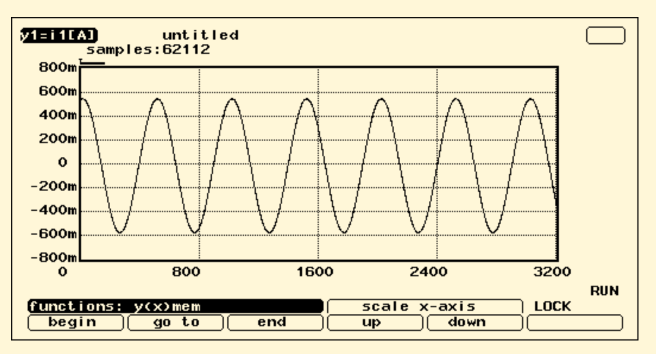


Fig. 2b Sinus signal
Range accuracy is more important. Several sample values are in a low range.

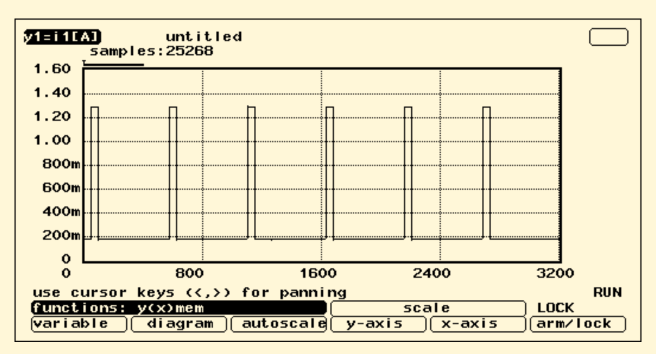
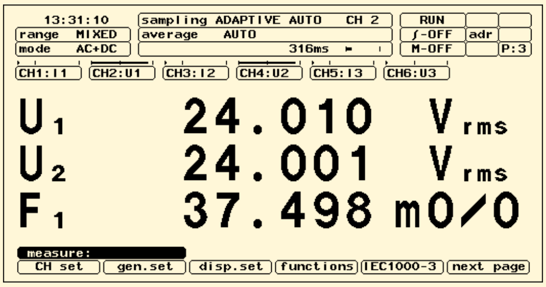
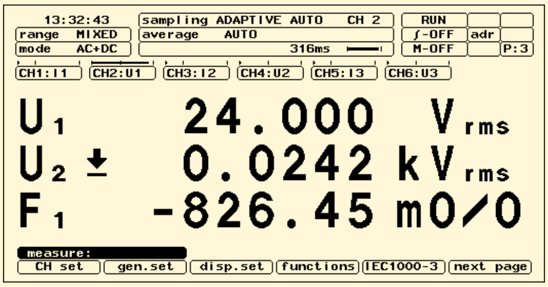


Fig. 2c Distorted wave form
Range error is very important. Most sample values are in a very low range.



```
13:31:10  sampling ADAPTIVE AUTO  CH 2   RUN
range  MIXED  average   AUTO             ∫-OFF  adr
mode   AC+DC                 316ms       M-OFF  P:3
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
U1      24.010  Vrms
U2      24.001  Vrms
F1      37.498  mO/O
measure:
CH set  gen.set  disp.set  functions  IEC1000-3  next page
```

Fig. 3a There is a deviation even when both channels are in the optimum range of 25 V_{peak}. The reason is that both channels are separate instruments. Each channel has its own power supply and A/D-conversion. The deviation between both channels is only a few m%.



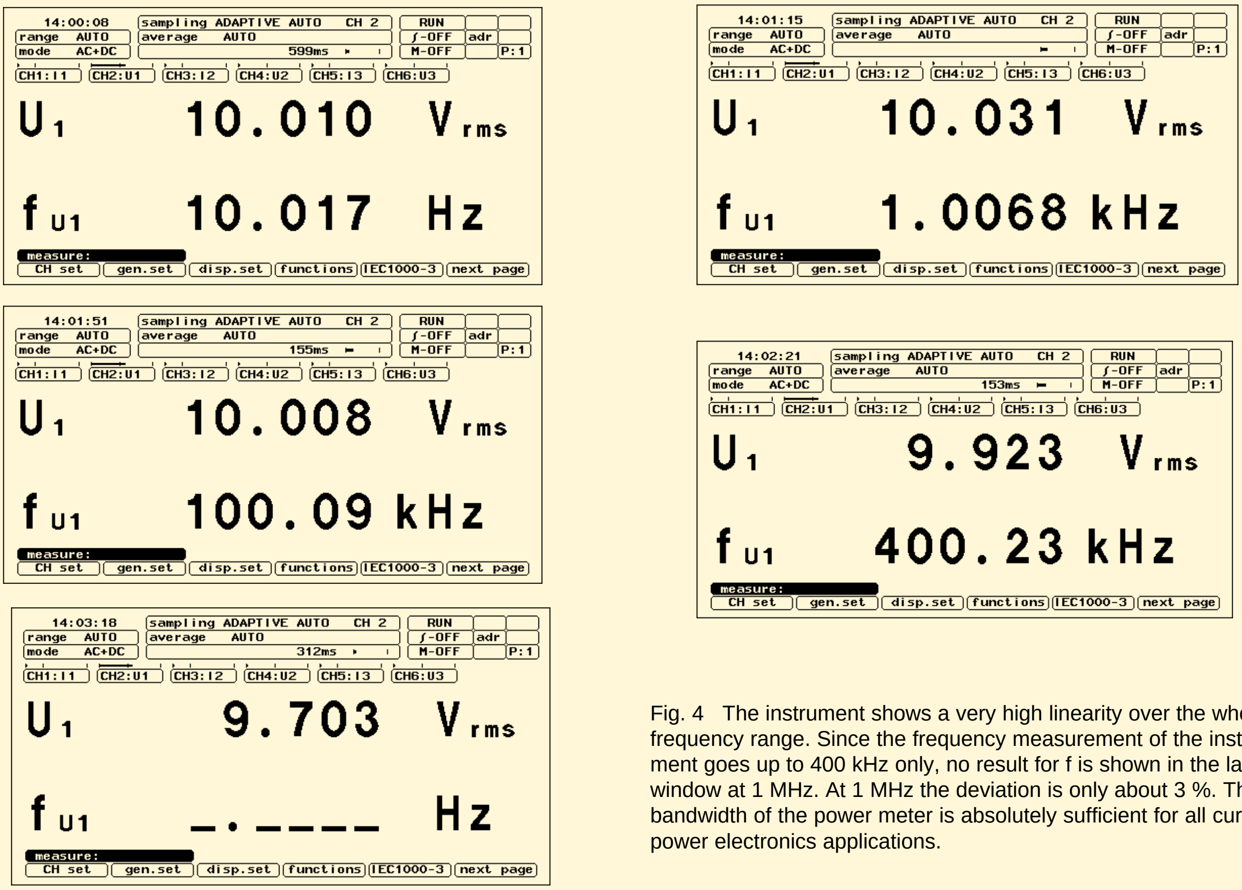
```
13:32:43  sampling ADAPTIVE AUTO  CH 2   RUN
range  MIXED  average   AUTO             ∫-OFF  adr
mode   AC+DC                 316ms       M-OFF  P:3
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
U1        24.000   Vrms
U2 ±      0.0242  kVrms
F1     -826.45    mO/O
measure:
CH set  gen.set  disp.set  functions  IEC1000-3  next page
```

Fig. 3b The measured value of 24 V is only about 1 % of the U2 range of 2100 V_{peak}. U1 is still in the range of 25 V_{peak}. The deviation between both channels is below 1 %. The instrument has excellent range accuracy.

have the right bandwidth to measure all signal components up to several 100 kHz. The bandwidth of the voltage channels of a power meter is relatively easy to check by connecting the channels to a frequency generator. Therefore the generator will be adjusted to a certain voltage level – in our case 10 V – and the frequency will be alternated from a few Hz up to several 100 kHz – in our case from 10 Hz to 1 MHz. The voltage deviation between 10 Hz and 1 MHz must be very low.

Phase angle errors of inputs and transducers

In the beginning of the article, we described that for the calculation of the electrical power a sample value u(t) has to be multiplied with a sample value i(t). In power electronics applications it is clear that the digital sampling of u(t) and i(t) has to be absolutely synchronous and that a phase angle error of the analog inputs leads to a time shift between voltage and current. Within a few nano or microseconds the signals at power electronics applications alternate from maximum potential to zero and back to maximum potential. To multiply sample values of voltage and current, which really belong together, neither the analog inputs nor the instrument, probes or transducers may cause a time shift between the signals. You can check the phase accuracy of the inputs and the synchronisation of the sampling by applying a low voltage output signal of a frequency generator synchronously to the voltage and the current input of a power meter. Almost all power analyzers offer the possibility to connect external shunts or clamps with voltage output to the current input of the instru-



```
14:00:08  sampling ADAPTIVE AUTO  CH 2   RUN
range  AUTO   average   AUTO             ∫-OFF  adr
mode   AC+DC                 599ms       M-OFF  P:1
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
U1      10.010  Vrms
fU1     10.017  Hz
measure:
CH set  gen.set  disp.set  functions  IEC1000-3  next page
```

```
14:01:15  sampling ADAPTIVE AUTO  CH 2   RUN
range  AUTO   average   AUTO             ∫-OFF  adr
mode   AC+DC                             M-OFF  P:1
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
U1      10.031  Vrms
fU1     1.0068  kHz
measure:
CH set  gen.set  disp.set  functions  IEC1000-3  next page
```

```
14:01:51  sampling ADAPTIVE AUTO  CH 2   RUN
range  AUTO   average   AUTO             ∫-OFF  adr
mode   AC+DC                 155ms       M-OFF  P:1
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
U1      10.008  Vrms
fU1     100.09  kHz
measure:
CH set  gen.set  disp.set  functions  IEC1000-3  next page
```

```
14:02:21  sampling ADAPTIVE AUTO  CH 2   RUN
range  AUTO   average   AUTO             ∫-OFF  adr
mode   AC+DC                 153ms       M-OFF  P:1
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
U1       9.923  Vrms
fU1     400.23  kHz
measure:
CH set  gen.set  disp.set  functions  IEC1000-3  next page
```

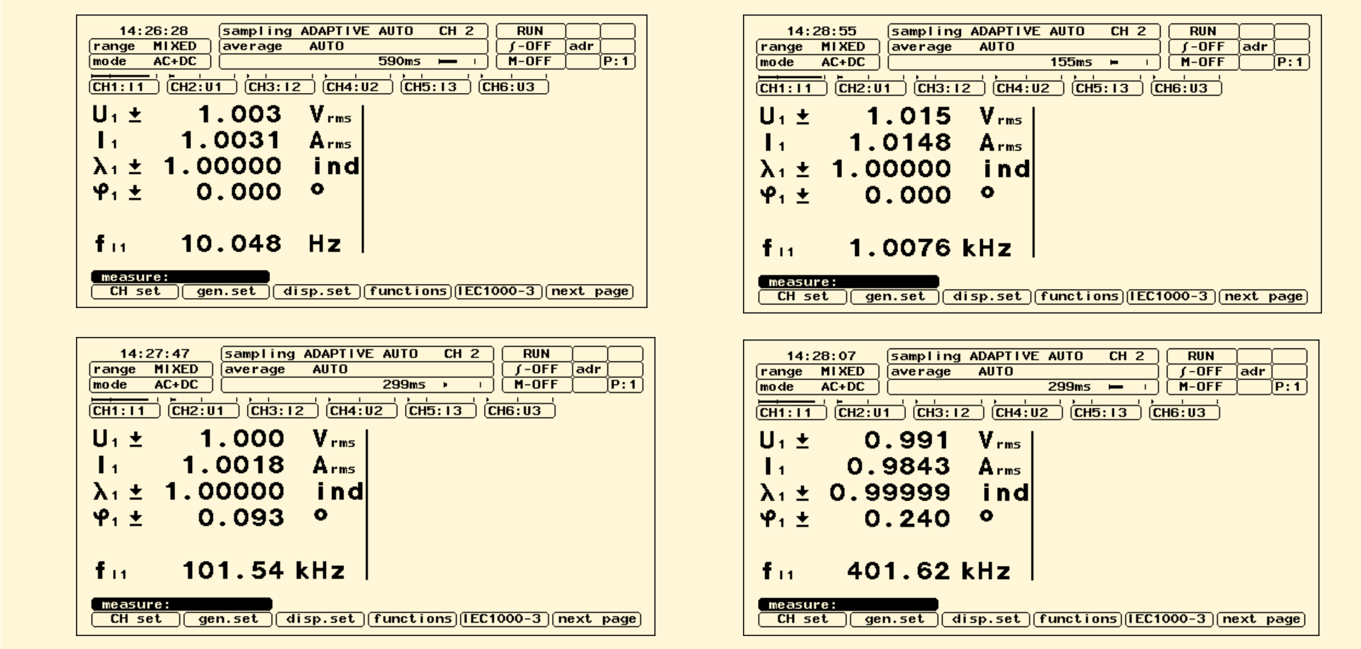
```
14:03:18  sampling ADAPTIVE AUTO  CH 2   RUN
range  AUTO   average   AUTO             ∫-OFF  adr
mode   AC+DC                 312ms       M-OFF  P:1
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
U1       9.703  Vrms
fU1     _._____ Hz
measure:
CH set  gen.set  disp.set  functions  IEC1000-3  next page
```

Fig. 4 The instrument shows a very high linearity over the whole frequency range. Since the frequency measurement of the instrument goes up to 400 kHz only, no result for f is shown in the last window at 1 MHz. At 1 MHz the deviation is only about 3 %. The bandwidth of the power meter is absolutely sufficient for all current power electronics applications.

ment. In our test we apply a 1 V signal to both the current and the voltage input and adjust the scaling of the current to 1 A/V. On the screen the variables U_{RMS}, I_{RMS}, power factor l and the phase angle j between voltage and current are displayed. Since the same signal is applied to both channels, the result of the power factor must be 1.0 and the phase angle must be 0°. The frequency will be alternated from a few Hz to several 100 kHz.

It is clear that a phase shift caused by probes or transducers leads to the same deviation in active power as a phase shift of the inputs. Therefore it is very important to use the right probes and transducers. The probes are a smaller problem since most power meters are able to measure power electronics voltage signals directly. Regarding current transducers you normally have to trust in the specifications of the manufacturer since only a very few calibration laboratories are able to measure voltage, current and power at wide bandwidth and high current. But there is one fact. The highest amplitude accuracy combined with the smallest phase angle error is offered in the high precision coaxial shunts (picture 2). These components are extremely low inductive and low capacitive. The bandwidth is in the MHz-range and the typical phase angle error up to 100 A_{RMS} is in the range of 0.1° at 100 kHz. Another advantage is that shunts are passive components, which do not cause an offset. The main disadvantage is that output of the shunts is not galvanically separated from the measured potential. This means that the power meter, which works with shunts, needs a sufficient common mode rejection at high frequencies.


Fig. 6 Wide band coax shunts with very small phase angle failure.



```
14:26:28   sampling ADAPTIVE AUTO   CH 2    RUN
range  MIXED  average   AUTO                ∫-OFF  adr
mode   AC+DC                  590ms         M-OFF      P:1
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
U1 ±      1.003   Vrms
I1       1.0031   Arms
λ1 ±    1.00000   ind
φ1 ±      0.000   °

fI1      10.048   Hz
measure:
CH set  gen.set  disp.set  functions  IEC1000-3  next page
```

```
14:28:55   sampling ADAPTIVE AUTO   CH 2    RUN
range  MIXED  average   AUTO                ∫-OFF  adr
mode   AC+DC                  155ms         M-OFF      P:1
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
U1 ±      1.015   Vrms
I1       1.0148   Arms
λ1 ±    1.00000   ind
φ1 ±      0.000   °

fI1      1.0076   kHz
measure:
CH set  gen.set  disp.set  functions  IEC1000-3  next page
```

```
14:27:47   sampling ADAPTIVE AUTO   CH 2    RUN
range  MIXED  average   AUTO                ∫-OFF  adr
mode   AC+DC                  299ms         M-OFF      P:1
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
U1 ±      1.000   Vrms
I1       1.0018   Arms
λ1 ±    1.00000   ind
φ1 ±      0.093   °

fI1      101.54   kHz
measure:
CH set  gen.set  disp.set  functions  IEC1000-3  next page
```

```
14:28:07   sampling ADAPTIVE AUTO   CH 2    RUN
range  MIXED  average   AUTO                ∫-OFF  adr
mode   AC+DC                  299ms         M-OFF      P:1
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
U1 ±      0.991   Vrms
I1       0.9843   Arms
λ1 ±    0.99999   ind
φ1 ±      0.240   °

fI1      401.62   kHz
measure:
CH set  gen.set  disp.set  functions  IEC1000-3  next page
```

Fig. 5 The power meter shows at 100 kHz a small phase angle failure of about 0.1° between voltage and current. At 400 kHz the phase shift is less than 0.3°. The phase angle accuracy of the tested analyzer is very high.

Common mode rejection

The common mode rejection is a measure of the quality of the instrument regarding the error caused by capacitive currents from the input channels to the housing of the instrument. In low frequency applications this current is never a problem. In high frequency power electronics applications this capacitive current leads to a voltage drop at the low lead of the input amplifiers and – depending on the current – to a deviation of the measuring result.

You can test whether a power meter is useable for your application concerning common mode rejection. To proof this you must make two voltage, current and power measurements. The first measurement is at your typical load to get the nominal values. For the second measurement you remove the high lead of the shunt and connect it to the low lead of the shunt. This means that the shunt is still on the high potential but there is no current through the shunt and therefore no voltage drop at the shunt. The displayed current and power at the second measurement is the result of the voltage drop caused by capacitive currents to the housing of the instrument. The values should be only a fraction of a percent or in the range of PPM of the nominal values.

Measurement of mechanical values for the calculation of the motor efficiency in EMC polluted environment of a frequency inverter

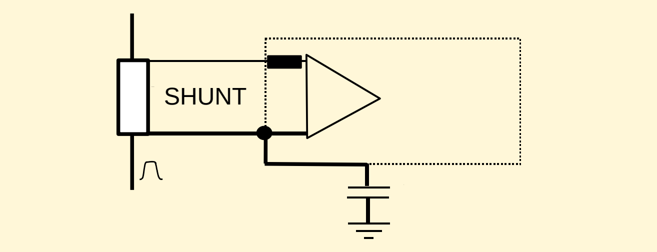


Fig. 7 Current input of a power meter: The capacitive current is lead through the low lead of the input amplifier to the housing of the instrument. A typical channel capacity of about 0.2 nF and a voltage rise time of about 500 V/ms causes a capacitive current of I = C · du/dt = 1 A. The voltage drop at the low lead caused by this current leads to a deviation in the measuring result.

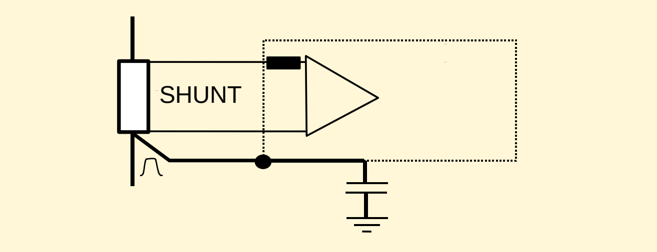
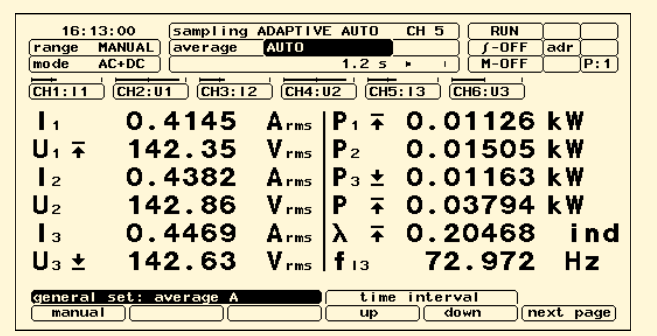
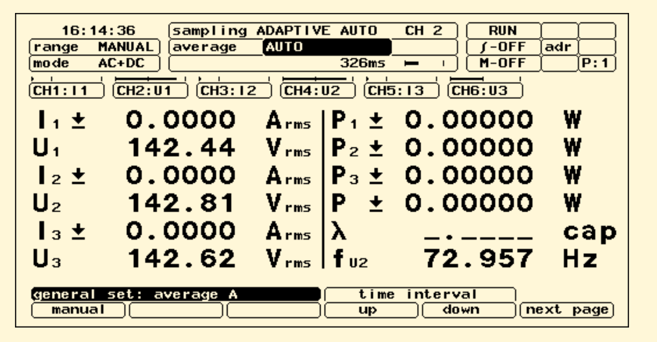


Fig. 8 Solution – GUARD technique: The GUARD is a second shield on shunt potential, lead and channel housing. There is still a capacitive current through this shield but this current doesn't cause a voltage drop at the low lead of the amplifier.



```
16:13:00   sampling ADAPTIVE AUTO  CH 5   RUN
range  MANUAL  average  AUTO              ∫-OFF  adr
mode   AC+DC                1.2 s         M-OFF       P:1
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
I1       0.4145  Arms | P1 ⤒  0.01126 kW
U1 ⤒   142.35   Vrms | P2    0.01505 kW
I2       0.4382  Arms | P3 ⤓  0.01163 kW
U2     142.86   Vrms | P  ⤒  0.03794 kW
I3       0.4469  Arms | λ  ⤒  0.20468  ind
U3 ⤓   142.63   Vrms | fI3     72.972  Hz
general set: average A
```

Fig. 9a Three phase voltage, current and power measurement at the output of a frequency inverter.



```
16:14:36   sampling ADAPTIVE AUTO  CH 2   RUN
range  MANUAL  average  AUTO              ∫-OFF  adr
mode   AC+DC                326ms         M-OFF       P:1
CH1:I1  CH2:U1  CH3:I2  CH4:U2  CH5:I3  CH6:U3
I1 ⤓     0.0000  Arms | P1 ⤓  0.00000  W
U1     142.44   Vrms | P2 ⤓  0.00000  W
I2 ⤓     0.0000  Arms | P3 ⤓  0.00000  W
U2     142.81   Vrms | P  ⤓  0.00000  W
I3 ⤓     0.0000  Arms | λ      _._____  cap
U3     142.62   Vrms | fU2     72.957  Hz
general set: average A
```

Fig. 9b Measurement of the same load but with the high lead of the shunt connected to the low lead. The results for current and power are zero. The common mode rejection is absolutely sufficient for this application.

Measurement of mechanical values for the calculation of the motor efficiency in EMC polluted environment of a frequency inverter

The necessity of absolutely precise power measurements for the calculation of the losses by differential measurements has been discussed previously in this article. Electric motors are typical loads with a very high efficiency up to 95 %. The losses of the motors can be calculated only by measuring electrical input power and mechanical output power and calculating their difference. The main characteristics of an instrument for electric power have been described previously. The measurement of the mechanical values of torque and speed cause additional challenges. Normally a torque-speed-shaft delivers an analog voltage for torque and a pulsed signal for the speed of the motor. In the environment of an inverter, the disturbances could cause an offset of the analog signal. In this case the result of the mechanic power and the motor losses is not useable. Some torque-speed-shaft manufacturers offer shafts with frequency output for the torque as well as for the speed. These signals are not so easy to disturb and can be measured with an accuracy of about 0.025 %. Torque-speed-shafts are available up to a precision of about 0.5 %. With the right shaft sensors and the right power meter, electrical and mechanical power can be measured with an accuracy of 0.1 %, independent of the environment. That means that loss calculation of inverter motors is possible.

Conclusion

The article above should be helpful for all power electronics engineers who are interested in acquiring a wide band power meter. It describes the challenges when measuring power at higher frequencies, calculating losses of high efficiency devices, and acquiring mechanical power data with sufficient accuracy. It also discusses the most important characteristics of wide band meters and describes their proof in a laboratory.

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Publication No. A 21305 E (03.01 • 2.5 • GKD)