

ELECTRICITY METER**FIELD**

5 The present disclosure relates to an electricity meter for measuring one or more properties of an alternating electrical signal. More particularly, but not exclusively, the present invention relates to an electricity meter for accurately measuring low-amplitude alternating currents. Also disclosed is a method of measuring low-amplitude alternating electrical signals in an electricity meter.

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BACKGROUND

 It is known to use an electricity meter (also known in the art as an electric meter) for measuring one or more properties of an electrical input associated with a power supply such as an alternating input voltage, an alternating input current or an alternating input power.

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 However, for low-amplitude inputs (e.g. low-amplitude current inputs) the accuracy of the measurement of such inputs may be degraded due to quantization noise when using a low-resolution analogue-to-digital converter (ADC). Typically, in order to mitigate such inaccuracies in electricity meters more expensive higher resolution ADC's are required. Improved apparatus and methods of measuring low-amplitude alternating electrical signals in electricity meters are therefore desirable.

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 It is therefore desirable to implement a low-cost and low-complexity electricity meter capable of relatively high-accuracy measurements of low-amplitude input signals.

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 It is an object of at least one embodiment of at least one aspect of the present disclosure to obviate or at least mitigate at least one of the above identified problems, disadvantages and/or shortcomings of the prior art.

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SUMMARY

Various aspects of the present invention are defined in the independent claims. Some preferred features are defined in the dependent claims.

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According to a first aspect of the present disclosure there is provided an electricity meter for measuring one or more properties of an alternating electrical signal, the electricity meter comprising:

10 signal injection circuitry configured to inject a conditioning signal onto the alternating electrical signal to generate a conditioned electrical signal;

an analogue-to-digital converter (ADC) coupled to the signal injection circuitry and configured to generate an ADC output data sequence based on the conditioned electrical signal;

15 a filter coupled to the ADC and configured to filter out the conditioning signal from the ADC output data sequence to generate a filtered ADC output data sequence; and

a processing resource coupled to the ADC and configured to determine one or more properties of the alternating electrical signal based on the filtered ADC output data sequence.

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Advantageously, by injecting a conditioning signal onto the alternating electrical signal to be measured, the quantization error present in the resulting ADC output data sequence may be significantly reduced, in particular for low-amplitude alternating electrical signals supplied to low resolution ADCs. If the resulting quantized signal is filtered to remove the injected conditioning signal component from the ADC output data sequence, the filtered ADC output data sequence may be more representative of the alternating electrical signal (i.e. more accurate) than an electricity meter without signal injection which is otherwise the same. Increasing the accuracy of the ADC output data sequence also increases the accuracy of the resulting property determination by the processing resource. This is particularly effective for low-amplitude alternating electrical signals e.g. low-amplitude alternating currents or voltage inputs or outputs to or from the electricity meter. Alternatively, by injecting a signal onto the alternating electrical signal a lower bit ADC may be used in the electricity meter without reducing the low current registration performance, providing for a reduction in material cost of the electricity meter.

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It will be appreciated that the expression “to inject a conditioning signal onto the alternating electrical signal” may be referred to in the art as ‘dithering’ or to add or inject ‘dither’ onto the alternating electrical signal. The term “dither” may refer to the act of injecting a random noise, pseudo random noise, periodic or other suitable signal onto another signal or alternatively may refer to the injected signal itself. This term may be used interchangeably with this expression throughout the present disclosure.

The conditioning signal may comprise or may be based on a periodic signal.

The use of a periodic signal may allow the conditioning signal to be more readily removed post quantization using a simpler filter circuit than would otherwise be required, for example, to filter out randomized noise.

The conditioning signal may comprise or be based on a sinusoidal waveform. The conditioning signal may comprise or be based on a square waveform. The conditioning signal may comprise or be based on a saw tooth waveform. The conditioning signal may comprise or be based on a triangle waveform. The conditioning signal may comprise or be based on random noise. The conditioning signal may comprise or be based on pseudorandom noise.

The electricity meter may further comprise a digital-to-analogue converter (DAC) which may be configured to generate the periodic signal. The processing resource may comprise the DAC.

By using a DAC within the processing resource to generate the periodic signal from which the conditioning signal is derived, no additional signal generation circuitry may be required to retrofit existing electricity meters or electricity meter designs, reducing the cost and complexity of doing so. Furthermore, the output from the DAC may also more easily be adjusted e.g. in real time to generate a conditioning signal with the optimum amplitude and frequency for the specific alternating electrical signal.

The conditioning signal (e.g. a periodic signal, pulse train or the like) may be generated using one or more Digital Input/Output (DIO) signals. The DIO signal(s) may be electrically coupled to one or more filters configured to condition the DIO signal(s) to produce the required conditioning signal. The DIO signal(s) may be derived or derivable

from a DIO pin, pad or the like which may be comprised in a microcontroller. The microcontroller may be, comprise or be comprised in the processing resource. Using a DIO signal (which may be available from the existing processing resource) may further reduce the cost and/or complexity of the generation of the conditioning signal, whilst still
5 allowing the conditioning signal to be adjusted e.g. in real time by adjusting the characteristics of the DIO signal.

The electricity meter may further comprise one or more input terminals. The one or more input terminals may be coupled to the signal injection circuitry. The one or more
10 input terminals may be configured to receive the alternating electrical signal.

Advantageously, input terminals may enable the electricity meter to be connected to one or more alternating electrical signal sources and/or loads (e.g. a grid, electric or hybrid electric vehicle or vehicle charger, solar generation system or the like) which may
15 selectively supply and/or consume electrical power.

An amplitude of the conditioning signal may be configured to be substantially equal to an amplitude of a least significant bit (LSB) of the ADC. An amplitude of the conditioning signal may be configured to correspond to a magnitude of a least significant
20 bit (LSB) of the ADC. A voltage-range of the conditioning signal may be configured to correspond to an equivalent voltage of a least significant bit (LSB) of the ADC.

Advantageously by injecting a conditioning signal onto the alternating electrical signal which has an amplitude close to or equal to the amplitude of the LSB the threshold
25 levels for each quantization level of the ADC will be crossed more often as the amplitude of the alternating electrical signal rises and/or falls between quantization levels resulting in a higher resolution representation of the alternating electrical signal after filtering.

It will be appreciated that the expression “amplitude of a least significant bit (LSB) of the ADC”, refers to the voltage difference between two quantization steps of the ADC
30 i.e. the ADC input signal range defined by the reference inputs of the ADC divided by the total number of quantization levels (2^N for an N bit ADC).

The filter may have a cut-off frequency lower than the frequency of the
35 conditioning signal.

In this way the conditioning signal can more effectively be filtered out of the ADC output data sequence.

5 The processing resource may comprise the filter.

By using a filter within the processing resource to remove the conditioning signal component from the ADC output data sequence, no additional filtering circuitry may be required to retrofit existing electricity meters or electricity meter designs, reducing the cost and complexity of doing so. Furthermore, the filter may be selected and/or adjusted more easily e.g. in real time, in response to a change in the injected signal.

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The frequency of the conditioning signal may be configured to be less than the Nyquist frequency of the ADC and greater than the cut-off frequency of the filter.

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When using a filter within the processing resource of an existing electricity meter or electricity meter design the cut-off frequency of the available filter(s) may be fixed. To allow the conditioning signal to be effectively removed from the ADC output data sequence, the frequency of the conditioning signal may be selected such that it is above the cut-off frequency of the available filter(s). In this way no additional filtering circuitry may be required to retrofit existing electricity meters or electricity meter designs, reducing the cost and complexity of doing so.

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The alternating electrical signal may comprise an input voltage. The alternating electrical signal may comprise an input current. The alternating electrical signal may comprise an input power;

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The alternating electrical signal may comprise an alternating voltage. The alternating electrical signal may comprise an alternating current. The alternating electrical signal may comprise an alternating power. The alternating electrical signal may be associated with a phase of a multiple phase power supply.

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The signal injection circuitry may be configured to inject a further conditioning signal onto the alternating electrical signal to generate a further conditioned electrical signal. The further conditioning signal may be out of phase from the conditioning signal.

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The ADC may comprise a differential ADC. The ADC may be configured to generate an ADC output data sequence based on the conditioned electrical signal and the further conditioned electrical signal. The filter may be further configured to filter out the further conditioning signal from the ADC output data sequence.

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The further conditioning signal may be 180 degrees out of phase from the conditioning signal.

Advantageously, by using a differential ADC and injecting an out of phase conditioning signal into electrical signals supplied to the ADC, any common mode noise on the ADC inputs may be more readily rejected, further increasing the performance of the ADC, in particular for low-amplitude alternating inputs. By having one conditioning signal out of phase from the other (for example 180 degrees out of phase) the conditioning signals may not be rejected as common mode noise.

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According to a second aspect of the present invention there is provided a method for measuring one or more properties of an alternating electrical signal, the method comprising:

using signal injection circuitry to inject a conditioning signal onto the alternating electrical signal to generate a conditioned electrical signal;
using an ADC to generate an ADC output data sequence based on the conditioned electrical signal;
using a filter to generate a filtered ADC output data sequence based on the ADC output data sequence;
determining one or more properties of the alternating electrical signal based on the filtered ADC output data sequence.

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According to a third aspect of the present invention there is provided a use of the electricity meter of the first aspect to carry out the method of the second aspect.

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The above summary is intended to be merely exemplary and non-limiting. The disclosure includes one or more corresponding aspects, embodiments or features in isolation or in various combinations whether or not specifically stated (including claimed) in that combination or in isolation. It should be understood that features defined above in accordance with any aspect of the present disclosure or below relating to any specific

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embodiment of the disclosure may be utilized, either alone or in combination with any other defined feature, in any other aspect or embodiment or to form a further aspect or embodiment of the disclosure.

5 **BRIEF DESCRIPTION OF THE DRAWINGS**

 These and other aspects of the present disclosure will now be described, by way of example only, with reference to the accompanying Figures, in which:

- 10 **Figure 1** depicts an illustration of ADC quantization error as is known in the art;
- Figure 2** depicts an illustration of the effect of dither on quantization as is known in the art;
- 15 **Figure 3** depicts a schematic illustration of an electricity meter in accordance with an example embodiment of the present disclosure;
- Figure 4** is a schematic illustration of the dither injection circuit of figure 3;
- 20 **Figures 5a-f** depict a series of plots of simulated signals from an example electricity meter with and without dither;
- Figure 6** depicts a table showing the improvement in signal-to-noise ratio of the ADC of figure 3 when dither is applied; and
- 25 **Figure 7** depicts a flowchart of a method for measuring properties of an electrical signal in accordance with an example embodiment of the present disclosure.

30 In the Figures, like parts are denoted by like reference numerals.

 It will be appreciated that the drawings are for illustration purposes only and are not drawn to scale.

DETAILED DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates the effect of quantization error on the performance of an ADC 2 and, in particular for low-amplitude alternating input signals. Figure 1 shows a low level sinusoidal input signal 1 having a peak to peak amplitude just larger than 1 LSB of the ADC 2 and centered on a quantization step of the ADC 2. When this signal 1 is input to the ADC 2, it will be represented by only two 'codes'. If the sinusoidal signal level is centered on the threshold between the two codes, the digital output 3 from the ADC 2 will represent a square wave represented by digitized signal 3. Any offset will change the duty cycle, but the digitized signal 3 will always take the form of a series of pulses at the same frequency as the input. This is a very poor representation of a sinusoidal signal i.e. there is significant error in the output signal 3 from the ADC 2 when compared to the input signal 1.

Figure 2 illustrates how, by adding dither (in the form of a sinusoidal signal) to the input signal 1 of Figure 1 (to produce input signal 1a), the harmonic distortion is reduced and the resolution of the conversion is improved. The addition of dither will cause the output 3a of the ADC 2 to toggle between two or more states more frequently for the same low level sinusoidal input. Sub-LSB information is preserved in the percentage of time spent between these levels or codes. With time averaging and/or filtering the resolution of the conversion can be increased significantly beyond an LSB. A power spectrum of the output 3a would show that the harmonic distortion arising from the quantization process has been significantly reduced, as compared to the case with no dither as shown in Figure 1.

Figure 3 schematically illustrates an electricity meter 100 for measuring one or more properties of an alternating electrical signal in the form of an analog input signal 110. The electricity meter 100 comprises a signal injection circuit in the form of a dither injection circuit 120 electrically coupled to the analog input signal 110 e.g. via a pair of input terminals (not shown). The electricity meter further comprises an ADC 130 electrically coupled to the output of the dither injection circuit 120, and a processing resource in the form of a microprocessor 140. The microprocessor 140 comprises a low pass filter 142 electrically coupled to the output of the ADC 130 and further processing resource 144 to provide energy metric calculations based on the output of the low pass filter 142. The microprocessor 140 further comprises a DAC (not shown) which provides

a pulse train which is passed through an RC filter 150 to generate the dither which is electrically coupled to the dither injection circuit 120.

5 In use, the analog input signal 110 (e.g. a low-amplitude alternating current) is received at the dither injection circuit 120 via a pair of input terminals (not shown). The dither injection circuit 120 generates a conditioned electrical signal by injecting dither onto the analog input signal 110. The conditioned electrical signal is received by the ADC 130. The ADC 130 then generates an ADC output data sequence based on the conditioned electrical signal by quantizing the conditioned electrical signal. The ADC
10 output sequence is then received by a low pass filter 142 comprised in a microprocessor 140 within the electricity meter 100. The low pass filter 142 generates a filtered ADC output data sequence by removing (i.e. filtering out) the dither injected by the dither injection circuit 120. The filtered ADC output data sequence is then analyzed by the further processing resource 144 to provide the required energy metric calculations of the
15 analog input signal 110.

In this example, the injected dither has a predetermined frequency and amplitude and is based on a pulse train supplied from a DAC comprised in the microprocessor 140 which is conditioned by RC filter 150 to produce a periodic triangle waveform.
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The dither frequency and amplitude is determined by first identifying the full-scale range (FSR) of the ADC 130 i.e. the ADC input signal range defined by the reference inputs of the ADC. The 'size' (i.e. amplitude) of the least significant bit (LSB) of the N bit ADC 130 can then be calculated by:
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$$\text{LSB} = \text{FSR} / 2^N$$

The amplitude of the dither to be injected can then be determined based on the LSB. In general, the amplitude should be ~ 1 LSB. However, as will be appreciated by
30 those skilled in the art some experimentation may be necessary to find the optimal amplitude (and/or frequency) value for the specific application and/or specific electricity meter. The frequency of dither to be injected is determined based on the sampling frequency of the ADC 130. The dither frequency should be less than the Nyquist frequency (where the Nyquist frequency = 0.5 times the sampling frequency) and greater
35 than the frequency cut-off of the digital filter 142 in the microprocessor 140. As will also

be appreciated by those skilled in the art, in order to avoid aliasing, the frequency of the dither should not be an integer multiple of the sampling frequency.

Once the dither frequency and amplitude has been determined, by modelling,
5 experimentation, calculation or otherwise, the DAC of the microprocessor 140 can be 'coded' to output a pulse train with the desired characteristics. This pulse train is conditioned using an RC filter to generate the desired periodic triangle dither waveform.

Figure 4 shows an example of circuit 200 which could be used as a signal
10 injection circuit (such as the dither injection circuit 120 of figure 3) to inject a conditioning signal onto a differential ADC input 232, such as the input of the ADC 130 of figure 3. This utilizes an RC filter 250 to generate a triangle waveform from a pulse train, and injects it into the alternating current input to the ADC represented in figure 4 by AC source 234. The sources 260 are representative of pulse trains generated by two DAC output
15 pins from a microprocessor such as the microprocessor 140 of figure 3. As the circuit 200 is designed for a differential input ADC, the two conditioning signals are out of phase from one another (e.g. 180 degrees out of phase from one another) to prevent cancellation of the noise in the difference amplifier of the ADC. As will be appreciated by those skilled in the art, the value of the RC filter(s) 250 will need to be modified
20 appropriately for the specific application depending on the frequency of the pulse train required to achieve the desired triangular (or otherwise) dither waveform.

Figures 5a to 5f show a series of plots of simulated signals from an example
25 electricity meter with (figures 5d, 5e and 5f) and without (figures 5a, 5b and 5c) a conditioning signal injected onto the analog input signal of an ADC comprised within said electricity meter. In the example simulation the amplitude of the input analog reference signal is 100ma RMS (~1.414mA peak), the sampling rate of the ADC is ~15kHz with an oversampling ratio of 256, the dither (of figures 5d, 5e and 5f) is a high frequency triangular waveform and the filter is a 100 order FIR filter with a cut-off frequency of 1kHz.

30 Figure 5a shows a plot of a sinusoidal analog reference signal which may be the analog input signal 110 of figure 3. Figure 5d shows a plot of the same signal as shown in figure 5a with a conditioning signal injected (for example using the dither injection circuit 200 of figure 4) to generate a conditioned electrical signal.

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Figure 5b shows a plot of an output ADC sequence generated at the output of an ADC (for example the ADC 130 of figure 3) based on the analog reference signal as shown in figure 5a. Figure 5e shows a plot of an output ADC sequence generated at the output of an ADC (for example the ADC 130 of figure 3) based on the conditioned electrical signal as shown in figure 5d.

Figure 5c shows a plot of the output ADC sequence shown in figure 5b after filtering by a low pass filter (for example the filter 142 of figure 3). Figure 5f shows a plot of the output ADC sequence shown in figure 5e after filtering by a low pass filter (for example the filter 142 of figure 3).

In the plots of the filtered and quantized signal (Figures 5c and 5f) it can be seen that the signal shown in figure 5f, in which the conditioning signal was initially injected, is a significantly better representation of the analog reference signal shown in Figure 5a than the signal shown in figure 5c, to which no conditioning signal was applied.

Figure 6 shows a table which illustrates the improvement in signal-to-noise ratio (SNR) with 12, 16 and 24 bit ADCs when conditioned and unconditioned analog reference signals of various RMS amplitudes are supplied at their input. The injected conditioning signal is a triangular waveform with the amplitude and frequency as shown in the table. For this example, the performance gained would allow a 12-bit ADC with a conditioning signal injected into the analog input signal to achieve similar results to a 16-bit ADC with no conditioning signal injected. Similarly, a 16-bit ADC with a conditioning signal injected achieved similar results to a 24-bit ADC with no conditioning signal injected.

Therefore, it can be seen that by injecting a conditioning signal into an alternating electrical signal of an electricity meter, the energy registration performance for low-amplitude inputs in electricity meters that use lower resolution ADCs can be improved. Additionally/alternatively the resolution of the ADC (and therefore the cost of the ADC) used within an electricity meter can be reduced without reducing the low current input registration performance.

Figure 7 is a flowchart summarizing a method 1000 for measuring one or more properties of an alternating electrical signal in an electricity meter, as described

throughout this disclosure. The method comprises at step S1100 receiving an alternating electrical signal. At step S1200 a conditioning signal is injected onto the alternating electrical signal to generate a conditioned electrical signal using signal injection circuitry. At step S1300 the conditioned electrical signal is received by an ADC which generates
5 an ADC output based on the conditioned electrical signal. At step S1400 the signal is filtered to remove the conditioning signal component in order to generate a filtered ADC output. At step S1500 the filtered ADC output is analyzed to determine one or more properties of the alternating electrical signal.

10 Although the disclosure has been described in terms of preferred embodiments as set forth above, it should be understood that these embodiments are illustrative only and that the claims are not limited to those embodiments. Those skilled in the art will be able to make modifications and alternatives in view of the disclosure which are contemplated as falling within the scope of the appended claims.

15 For example, instead of a triangular waveform, the conditioning signal may comprise a sinusoidal waveform, a square waveform, a saw tooth waveform, random noise, white noise, pseudo randomized noise, a combination thereof or the like. Instead of being generated by a DAC within the processing resource, the periodic (or otherwise)
20 pulse train which is conditioned by a filter to produce the conditioning signal may be generated by one or more DIO pins or pads comprised in or on the processing resource. Methods and circuits suitable for generating such signals, in addition to the configuration of a filter to filter out the injected conditioning signal after quantization, would be apparent to those skilled in the art.

25 Instead of a predetermined noise signal, the amplitude, frequency and/or waveform characteristics of the conditioning signal may be automatically determined in real time based on the characteristics of the alternating electrical signal, and the filter and DAC (or other source of periodic pulse train or otherwise) may be selected or coded
30 in real time to provide the required conditioning signal to optimize the electricity meter performance.

The filter and/or the DAC (or other source of periodic pulse train or otherwise) may alternatively be external to the processing resource for determining one or more
35 properties of the alternating electrical signal.

Each feature disclosed or illustrated in the present specification may be incorporated in the disclosure, whether alone or in any appropriate combination with any other feature disclosed or illustrated herein.

CLAIMS:

1. An electricity meter for measuring one or more properties of an alternating electrical signal, the electricity meter comprising:
 - 5 signal injection circuitry configured to inject a conditioning signal onto the alternating electrical signal to generate a conditioned electrical signal;
an analogue-to-digital converter (ADC) coupled to the signal injection circuitry and configured to generate an ADC output data sequence based on the conditioned electrical signal;
 - 10 a filter coupled to the ADC and configured to filter out the conditioning signal from the ADC output data sequence to generate a filtered ADC output data sequence; and
a processing resource coupled to the ADC and configured to determine one or more properties of the alternating electrical signal based on the filtered
 - 15 ADC output data sequence.
2. The electricity meter of claim 1 wherein the conditioning signal comprises or is based on a periodic signal.
- 20 3. The electricity meter of claim 1 wherein the conditioning signal comprises or is based on at least one of:
 - a sinusoidal waveform;
 - a square waveform;
 - a saw tooth waveform;
 - 25 a triangle waveform;
 - random noise; or
 - pseudorandom noise.
4. The electricity meter of claim 2 further comprising a digital-to-analogue converter (DAC) configured to generate the periodic signal.
- 30 5. The electricity meter of claim 4 wherein the processing resource comprises the DAC.

6. The electricity meter of any preceding claim further comprising one or more input terminals coupled to the signal injection circuitry configured to receive the alternating electrical signal.
- 5 7. The electricity meter of any preceding claim wherein an amplitude of the conditioning signal is configured to be substantially equal to an amplitude of a least significant bit (LSB) of the ADC.
8. The electricity meter of any preceding claim wherein the filter has a cut-off
10 frequency lower than the frequency of the conditioning signal.
9. The electricity meter of any preceding claim wherein the processing resource comprises the filter.
- 15 10. The electricity meter of claim 9 wherein the frequency of the conditioning signal is configured to be less than a Nyquist frequency of the ADC and greater than the cut-off frequency of the filter.
11. The electricity meter of any preceding claim, wherein at least one of:
20 the alternating electrical signal comprises an input voltage, an input current or an input power;
the alternating electrical signal comprises an alternating voltage, an alternating current, or an alternating power; or
the alternating electrical signal is associated with a phase of a multiple phase
25 power supply.
12. The electricity meter of any preceding claim wherein:
the signal injection circuitry is configured to inject a further conditioning
signal onto the alternating electrical signal to generate a further conditioned
30 electrical signal, the further conditioning signal being out of phase from the conditioning signal;
the ADC comprises a differential ADC configured to generate an ADC output data sequence based on the conditioned electrical signal and the further conditioned electrical signal; and

the filter is further configured to filter out the further conditioning signal from the ADC output data sequence.

13. The electricity meter of claim 12 wherein the further conditioning signal is 180
5 degrees out of phase from the conditioning signal.

14. A method for measuring one or more properties of an alternating electrical signal,
the method comprising:
10 using signal injection circuitry to inject a conditioning signal onto the alternating
electrical signal to generate a conditioned electrical signal;
using an ADC to generate an ADC output data sequence based on the
conditioned electrical signal;
using a filter to generate a filtered ADC output data sequence based on the ADC
output data sequence;
15 determining one or more properties of the alternating electrical signal based on
the filtered ADC output data sequence.

15. A use of the electricity meter of any one of claims 1 to 13 to carry out the method
of claim 14.
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