

Two-phase Rogowski coil based electricity meter analog front-end circuit

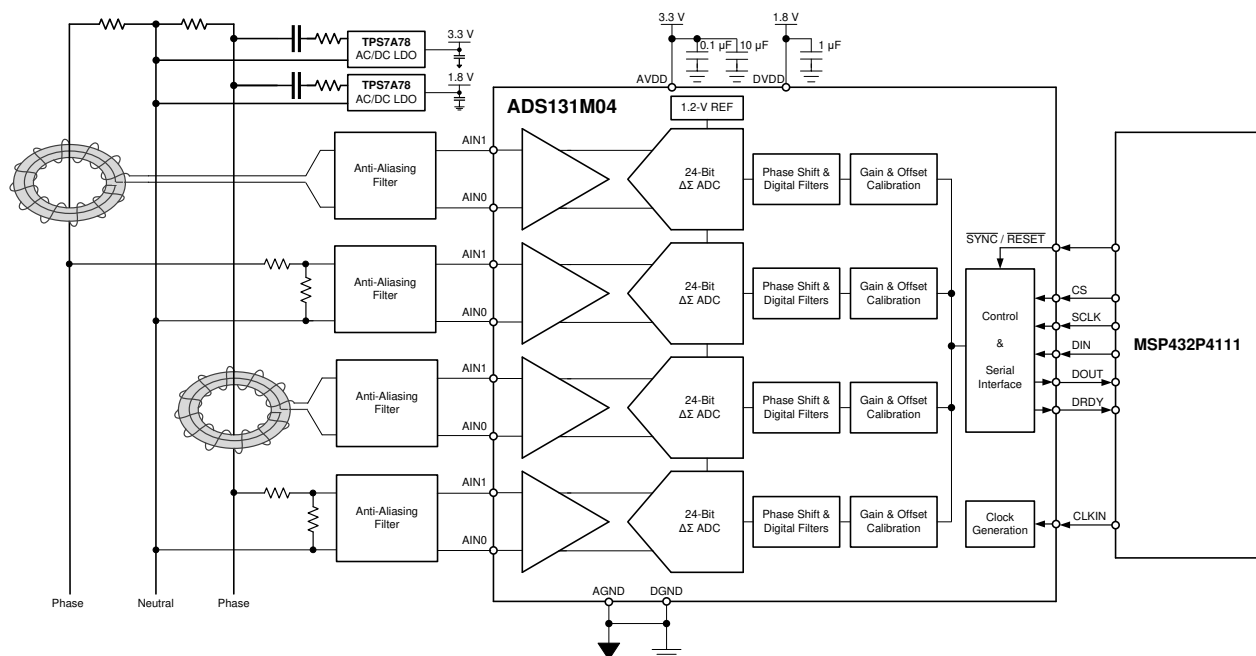
Victor Salomon

Features	Description
Number of Phases	1 phase (split-phase with two voltages measured)
E-Meter Accuracy	Class 0.1
Current Sensor	Rogowski Coil
Current Range	0.05A – 100A
System Nominal Frequency	50Hz
Measured Parameters	- AC Voltage Input - AC Current Input (using voltage output, di/dt sensor)

Design Description

This circuit document describes a class 0.1 split-phase energy measurement front-end using the ADS131M04. The ADC samples the outputs of a Rogowski coil and voltage dividers to measure the current and voltage (respectively) of each leg of the AC mains. The design can achieve high accuracy across a wide input current range (0.05A–100A) and supports high sampling frequencies necessary for advanced power quality features such as individual harmonic analysis.

Since output of the Rogowski coil is proportional to the derivative of the instantaneous primary current, an integrator is required to retrieve the original current signal, this circuit assumes the Rogowski integrator is implemented in the digital domain.



Design Notes

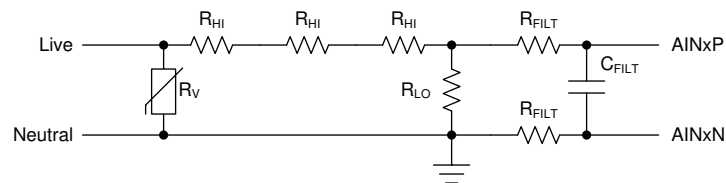
1. Use supply decoupling capacitors for both the analog and digital supplies. AVDD and DVDD must be decoupled with at least a 100- μ F capacitor to AGND. See the [ADS131M04 4-Channel, Simultaneously-Sampling, 24-Bit, Delta-Sigma ADC Data Sheet](#) for additional details on power supply recommendations.
2. The core digital voltage of 1.8V is created from an internal LDO from DVDD. The CAP pin outputs the LDO voltage created from the DVDD supply and requires an external bypass capacitor. When operating from DVDD > 2.7V, place a 220-nF capacitor on the CAP pin to DGND. If DVDD \leq 2V, tie the CAP pin directly to the DVDD pin and decouple the star-connected pins using a 100-nF capacitor to DGND.
3. When possible, use C0G (NPO) ceramic capacitors for input filtering. The dielectric used in these capacitors provides the most stable electrical properties over voltage, frequency, and temperature changes.
4. Input filtering for the ADC inputs and the reference inputs are selected using standard capacitor values and 1% resistor values. An example design and analysis of these filters is found in [RTD Ratiometric Measurements and Filtering Using the ADS1148 and ADS1248 Family of Devices](#).
5. Certain signal chain errors can be corrected through a single room temperature calibration. The ADS131M04 device has the capability to store calibration values and use the values to correct the results in real time. Among those errors that can be corrected in real time with the ADS131M04 are offset error, gain error, and phase error.

Component Selection

Voltage Measurements Front-End

The nominal voltage from the mains is from 100V–240V so this voltage must be scaled down to be sensed by an ADC. shows the analog front-end used for this voltage scaling.

Voltage Measurement Front End



1. The analog front-end for voltage consists of a spike protection varistor (R_v), a voltage divider network (R_{HI} and R_{LO}), and an RC low-pass filter (R_{FILT} and C_{FILT}). At lower currents, voltage-to-current crosstalk affects active energy accuracy much more than voltage accuracy if a power offset calibration is not performed. To maximize the accuracy at these lower currents, this design does not use the entire ADC range for the voltage channels. Because the ADCs of the ADS131M04 are high-accuracy ADCs, using the reduced ADC range for the voltage channels in this design still provides more than enough accuracy for measuring voltage. PGA gain for the voltage measurements was selected to have a gain of 1 on this design.
2. The following equation shows how to calculate the range of differential voltages fed to the voltage ADC channel for a given mains voltage and the selected voltage divider resistor values.

$$V_{ADC} = \pm V_{RMS} \times \sqrt{2} \times \frac{R_{LO}}{3R_{HI} + R_{LO}}$$

3. R_{HI} is 330k Ω and R_{LO} is 750 Ω in this design. For a mains voltage of 120V (as measured between the line and neutral), the input signal to the voltage ADC has a voltage swing of $V_{ADC} = \pm 128\text{mV}$ (91mV_{RMS}) which is well within the $\pm 1.2\text{-V}$ input voltage range that can be sensed by the ADS131M04 for the selected PGA gain value of 1.

Current Measurement Front-End

In this design a Rogowski coil or di/dt sensor is used for the current sensing input. A Rogowski coil is created by encircling the primary conductor with air-cored (non-magnetic) toroidal coiled wiring. An alternating magnetic field produced by the current in the primary conductor (I_p) induces a voltage (V_s) in the coil. Due to its non-magnetic core, the output of the coil does not saturate for a large primary current.

The Rogowski coil has an associated sensitivity (k) measured in $\mu\text{V}/\text{A}$ for a given frequency, these are some of the key parameters to consider when choosing a Rogowski coil:

- **Dynamic Range:** Minimum to maximum current range that is required for the application
- **Linearity:** Linear output voltage for a specified range of current
- **Accuracy:** Output voltage accuracy for a specified range of current
- **Secondary Output Voltage:** Sensitivity of the coil specified as $\mu\text{V}/\text{A}$ for a given frequency (for example: PA3209NL Rogowski coil from Pulse specifies $463\mu\text{V}/\text{A}$ at 50Hz, $556\mu\text{V}/\text{A}$ at 60Hz)
- **Phase Shift Error:** Specifies the phase difference between the output voltage and input current
- **Primary-Secondary Isolation:** Specifies the isolation barrier potential that the Rogowski coil can handle
- **Inner Diameter:** Specified in mm depending on the current

The output voltage of a Rogowski coil is proportional to the rate of change of the current in the primary conductor, and is not impacted by the DC current.

$$v_s(t) = -M \times \frac{di_p(t)}{dt}$$

For a given frequency the output voltage of a Rogowski coil, V_{OUT} , can be simplified to:

$$V_{\text{OUT}} = k \times I_{\text{RMS}}$$

where

- k = sensitivity constant at a given frequency

This circuit document assumes a Rogowski coil with a sensitivity (k), of $1.2\text{mV}/\text{A}$ at 50Hz. The following equation shows how to calculate the range of differential voltages fed to the current ADC channel for a given maximum current, CT turns ratio, and burden resistor value.

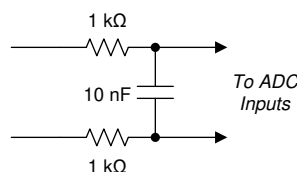
$$V_{\text{ADC}} = k \times \pm I_{\text{RMS}} \times \text{Gain}_{\text{PGA}}$$

Based on the maximum RMS current of 100A, a Rogowski coil sensitivity k of $1.2\text{mV}/\text{A}$ at 50Hz, and PGA gain of $8\text{V}/\text{V}$, the input signal to the current ADC has a voltage swing of $\pm 960\text{mV}$ maximum ($679\text{mV}_{\text{RMS}}$) when the maximum current rating of the meter (100A) is applied. This $\pm 960\text{-mV}$ maximum input voltage is well within the $\pm 1.2\text{-V}$ input range of the device for the selected PGA gain of 8 that is used for the current channels.

Anti-Aliasing

An analog low-pass filter is required in front of each of the channel inputs to prevent out-of-band noise and interferers from coupling into the band of interest. Because the ADS131M04 is a delta-sigma ADC, the integrated digital filter provides substantial attenuation for frequencies outside of the band of interest up to the frequencies adjacent to f_{MOD} . Therefore, a single-order RC filter with a relatively low cutoff frequency, such as the values recommended in [Recommended Anti-Aliasing Filter](#), should provide enough attenuation for f_{MOD} frequencies between 1MHz and 4.1MHz.

Recommended Anti-Aliasing Filter



Digital Integration

The output voltage of the Rogowski coil is the differentiation of the primary current. To get the actual waveform of the primary current, the output voltage needs to be integrated in either an analog or digital domain. Integrating in a digital domain is simple and advantageous over analog due to the configurability and repeatability of the magnitude and phase response compared with discrete analog components.

Integrating in the digital domain can be implemented using a simple first-order IIR function such as:

$$y(n) = y(n-1) + (T \times x(n))$$

ADS131M04 uses a delta-sigma ($\Delta\Sigma$) modulator to convert the analog input voltage to a ones density modulated digital bit-stream which feeds into a digital filter. The digital filter is a linear phase, finite impulse response (FIR), low-pass sinc-type filter that attenuates the out-of-band quantization noise of the $\Delta\Sigma$ modulator.

The data passing through the filter is decimated and downsampled, to reduce the rate at which data come out of the modulator (f_{MOD}) to the output data rate (f_{DATA}). The decimation factor is defined as the ratio of f_{MOD} and f_{DATA} and is called "oversampling ratio" (OSR) - the OSR determines the amount of averaging of the modulator output in the digital filter and therefore also the filter bandwidth.

ADS131M04 offers the following digital filter options integrated:

- **Fast-Settling Filter:** allows for settled output data generation with minimal latency. The fast-settling filter has the characteristic of a first-order sinc filter (SINC¹)
- **SINC³ and SINC³ + SINC¹ Filter:** SINC³ filter path two conversion after power-up or device reset. For OSR settings of 128 to 1024 the SINC3 filter output directly feeds into the global chop and calibration logic. For OSR settings of 2048 and higher the SINC³ filter is followed by a SINC¹ filter.
- **DC Block Filter:** includes an optional high-pass filter to eliminate any systematic offset or low-frequency noise.

A post-processing digital filter could be used as another option instead of, or in addition to the ADS131M04 integrated digital filters. In the case where a post-processing filter might be considered an IIR Butterworth implementation could be favored, due to maximally flat response in the passband, but it has a pretty smooth and large transition with minimal MIPS expense. An example implemented in a software like MATLAB® follows:

```
% Design an IIR Butterworth DC Block
dcblock = fdesign.highpass('N,F3dB', params.Order, params.F3dB);
dcButter = design(dcblock, 'IIR', 'butter');
h = fvtool( dcButter );
```

Where:

- "*params.Order*" is the order of the filter. In this case, *params.Order* = 1
- "*params.F3dB*" is the frequency of the -3-dB point expressed as a normalized frequency in a fraction of the sampling rate/2, which should be set to 0.004 for filter 3-dB point of 0.002 × *fs*.

In the case of 0.002 × *fs* the equation would be as follows:

$$y(n) = 0.9937 \times y(n-1) + x(n) - x(n-1)$$

The following resources can be used as reference for implementations of digital filters in Rogowski coil applications:

- [High Accuracy AC Current Measurement Reference Design Using PCB Rogowski Coil Sensor](#) shows how to design the digital filter for a Rogowski.
- [Implementation of a 3-Phase Rogowski Coil Based Watt Hour Meter Reference Design](#) shows a software implementation using an MSP430F67791A as the MCU, and provides the [software design files](#).

Calibration Options

Calibration allows for the automatic computation of calibrated ADC conversion results from preprogrammed values. The host can rely on the device to automatically correct for system gain and offset after the error correction terms are programmed into the corresponding device registers. The measured calibration coefficients must be stored in external nonvolatile memory and programmed into the registers each time the ADS131M04 powers up. The ADS131M04 offers the following types of calibration options:

1. Offset calibration: used to correct for system offset error, otherwise known as zero error. Offset error corresponds to the ADC output when the input to the system is zero.
2. Gain Calibration: used to correct for system gain error. Gain error corresponds to the deviation of gain of the system from the ideal gain.
3. Channel phase calibration: allows fine adjustment of the sample phase between channels through the use of channel phase calibration, this feature is helpful in power metrology applications, voltage can be measured by a voltage divider, whereas current is measured using a current transformer that exhibits a phase difference between its input and output signals. The differences in phase between the voltage and current measurement must be compensated to measure the power and related parameters accurately.

Register Settings

The ADS131M04 receives its clock from the MCU in this design. The ADS131M04 is configured in HR mode and the MCU provides an 8.192-MHz master clock, which is within the allowable clock frequency range for HR mode. The MCU SPI port that is used to communicate with the ADS131M04 is configured to CPOL = 0 and CPHA = 1. The SPI clock frequency is configured to be 8.192MHz so that all conversion data can be shifted out of the device successfully within the sample period. When powered on, the MCU configures the ADS131M04 registers with the following settings using SPI register writes.

Register Configuration Settings for Two-phase Rogoski Coil Based Electricity Meter Analog Front-end Circuit for Live Current With Voltages Measured to Neutral

Register Address	Register Name	Setting	Description
04h	GAIN1	3030h	PGAGAIN1 = PGAGAIN3 = 1, for the voltage measurement inputs. PGAGAIN0 = PGAGAIN2 = 8 for the current measurement inputs
09h, 0Eh, 13h, 18h	CHx_CFG	0000h	Register settings (where x is the channel number): All four ADC channel inputs are connected to the external ADC pins and the channel phase delay set to 0 for each channel. DC Block controlled by DCBLOCK[3:0]
03h	CLOCK	0F0Fh	512 OSR, all channels enabled, and HR mode
08h	THRSHLD_LSB	0008h	ADS131M04 includes an optional high-pass filter to eliminate any systematic offset or low-frequency noise. The filter is set to a corner frequency of 4.99 Hz

Code Example

The following shows a code example with the required steps to set up the device and the microcontroller that interfaces to the ADC to take subsequent readings from the ADS131M0x device .

```

numFrameWords = 6; // Number of words in a full ADS131M04 SPI frame
unsigned long spiDummyWord[numFrameWords] =
    {
        0x00000000,
        0x00000000,
        0x00000000,
        0x00000000,
        0x00000000,
        0x00000000}; // Dummy word frame to write ADC during ADC data reads
bool firstRead = true; // Flag to tell us if we are reading ADC data for the
// first time
signed long adcData; // Location where DMA will store ADC data in memory,
// length defined elsewhere
/*
Interrupt the MCU each time DRDY asserts when collecting data
*/
DRDYinterrupt(){
    if(firstRead){ // Clear the ADC's 2-deep FIFO on the first read
        for(i=0; i<numFrameWords; i++){
            SPI.write(spiDummyWord + i);
        }
        for(i=0; i<numFrameWords; i++){
            SPI.read();
        }
        firstRead = false; // Clear the flag
        DMA.enable(); // Let the DMA start sending ADC data to memory
    }
    for (i=0; i<numFrameWords; i++){
        SPI.write(spiDummyWord + i);
    }
}

// Send the dummy data to the ADC to get the ADC data
/*
adcRegisterWrite
Short function that writes one ADC register at a time. Blocks return until SPI
is idle. Returns false if the word length is wrong.
param
addrMask: 16-bit register address mask
data: data to write
adcWordLength: word length which ADC expects. Either 16, 24 or 32.
return
true if word length was valid
false if not
*/
bool adcRegisterWrite(unsigned short addrMask, unsigned short data,
    unsigned char adcWordLength){ // Stores the amount of bit shift based on
    unsigned char shiftValue; // ADC word length
    if(adcWordLength==16){ // If length is 16, no shift
        shiftValue = 0;
    }else if(adcWordLength==24){ // If length is 24, shift left by 8
        shiftValue = 8;
    }else if(adcWordLength==32){ // If length is 32, shift left by 16
        shiftValue = 16;
    }else{
        return false; // If not, invalid length
    }
    SPI.write((WREG_OPCODE | // Write address and opcode
        addrMask) << shiftValue); // Shift to accommodate ADC word length
    SPI.write(data << shiftValue); // Write register data
    while(SPI.isBusy());
    return true;
}

```

```
/*
main routine
*/
main(){
    enableSupplies();
    GPIO.inputEnable('input'); // Enable GPIO connected to DRDY
    clkout.enable(8192000);
    SPI.enable();
    SPI.wordLengthSet(24);
    SPI.configCS(STAY_ASSERTED);

    while(!GPIO.read()){ // Wait for DRDY to go high indicating it is ok
// to talk to ADC

    adcRegisterWrite(CLOCK_ADDR,
        ALL_CH_DISABLE_MASK |
        OSR_1024_MASK | PWR_HR_MASK, 24);
    adcRegisterWrite(MODE_ADDR,
        RESET_MASK | DRDY_FMT_PULSE_MASK |
        WLENGTH_24_MASK |
        SPI_TIMEOUT_MASK, 24);
    adcRegisterWrite(GAIN1_ADDR,
        PGAGAIN3_32_MASK |
        PGAGAIN1_32_MASK, 24);
    adcRegisterWrite(THRSHLD_LSB_ADDR,
        0x09, 24);

    DMA.triggerSet(SPI); // Configure DMA to trigger when data comes in
// on the MCU SPI port
    DMA.txAddrSet(SPI.rxAddr()); // Set the DMA to take from the incoming SPI
// port
    DMA.rxAddrSet(&adcData); // Set the DMA to send ADC data to a predefined

    adcRegisterWrite(MODE_ADDR,
        WLENGTH_32_SIGN_EXTEND_MASK |
        DRDY_FMT_PULSE_MASK |
        SPI_TIMEOUT_MASK, 24);
    SPI.wordLengthSet(32);
    adcRegisterWrite(CLOCK_ADDR,
        ALL_CH_ENABLE_MASK |
        OSR_1024_MASK | PWR_HR_MASK, 32);
    GPIO.interuptEnable();
}
}
```


Comparison Between Rogowski Coil and CT Based Current Measurement Systems

Circuit Topology	Advantages	Disadvantages
1 phase (split-phase with two voltages and two currents measured) using a Rogowski coil	<ul style="list-style-type: none"> • Provides galvanic isolation from the primary circuit • Does not saturate (wide dynamic range) and no magnetizing current error because of nonmagnetic core • Linear and not affected by DC • Electrically safe when open • Very low primary burden • Potential for lower cost • Smaller in size and weighs less in comparison to CT 	<ul style="list-style-type: none"> • Has lower sensitivity • Lower temperature stability • Needs integrator (hardware or software) • Low frequency noise is magnified • Sensitive to position of the primary current conductor carrying • Limited external magnetic field immunity • Manufacturing tolerance is high
1 phase (split-phase with two voltages and two currents measured) using a CT	<ul style="list-style-type: none"> • Provides galvanic isolation from the primary circuit • Accurate over defined range of current input • Low power loss • Not affected by common-mode noise input 	<ul style="list-style-type: none"> • Tend to be bulky and expensive (depends on accuracy and current level requirements) • Requires more board area • External magnetic fields and frequent overloads affect the performance and reduce the usable life of CTs

Design Featured Devices

Device	Key Features	Link	Other Possible Devices
ADS131M04	24-bit 32-kSPS 4-channel simultaneous-sampling delta-sigma ADC	ti.com/product/ADS131M04	Link to similar devices
ADS131M06	24-bit 32-kSPS 6-channel simultaneous-sampling delta-sigma ADC	ti.com/product/ADS131M06	Link to similar devices
ADS131M08	24-bit 32-kSPS 8-channel simultaneous-sampling delta-sigma ADC	ti.com/product/ADS131M08	Link to similar devices

Design References

See [Analog Engineer's Circuit Cookbooks](#) for TI's comprehensive circuit library.

Additional Resources

- L. Kojovic and others, [Practical Aspects of Rogowski Coil Applications to Relaying](#), IEEE PSRC Special Report, September 2010.
- Texas Instruments, [High Accuracy AC Current Measurement Reference Design Using PCB Rogowski Coil Sensor](#)
- Texas Instruments, [Wide Input Current Using Shunts and Voltage Measurement for Protection Relays Reference Design](#)
- Texas Instruments, [Implementation of a Three-Phase Electronic Watt-Hour Meter Using the MSP430F677x\(A\) Application Report](#)
- Texas Instruments, [Active Integrator for Rogowski Coil Reference Design With Improved Accuracy for Relays and Breakers Design Guide](#)
- Texas Instruments, [Reference Design to Measure AC Voltage and Current in Protection Relay With Delta-Sigma Chip Diagnostics](#)
- Texas Instruments, [Implementation of a 3-Phase Rogowski Coil Based Watt Hour Meter Reference Design](#)
- Texas Instruments, [Multi-Phase Rogowski-Based E-Meter Design Guide](#)

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