

Detailed energy monitor system design

This part details the system design of the measurement part of a mains AC: non-invasive energy monitor built upon an Arduino. The system can be divided into 3 main parts:

- 1.Current sensors + current sensor electronics
- 2.Voltage sensor + voltage sensor electronics
- 3.Arduino (the microcontroller platform)

The sensors produce signals proportional to voltage and current. The analog electronics convert these signals in to a form ready for the Arduino which in turn calculates useful values in the digital world.

Sensing current



Image 1 – Clip-on CT sensor.

UK: Whole house energy use is measured with 1 CT sensor.

US: Whole house energy use is measured with 2 CT sensors.

Current is measured using a sensor called a current transformer (CT). A CT sensor works by induction. The current in the mains wire produces a magnetic field in the ferrite core of the CT. A secondary coil is wrapped around the ferrite core. When a resistor is connected across the terminals of the coil a current flows that is proportional to the current in the mains wire.

The sensor just clips around the wire to be measured which means that it can be easily used to measure the electrical energy used by a whole building.

The CT sensor produces a current that is proportional to the current flowing in the mains wire by:

$$I_{\text{sensor}} = \text{CTturnsRatio} * I_{\text{mains}}$$

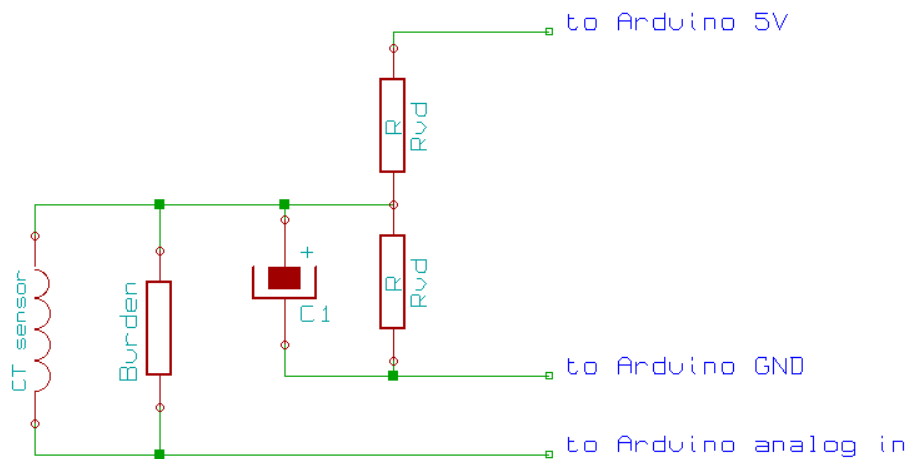
The number of secondary turns on a typical home energy monitor CT is around 1500 and so the current in the secondary is 1500 less than the current in the mains wire. The current in the secondary is also electrically isolated from the primary current. This makes household CT's a safe way of measuring mains current.

Current sensor electronics

The current sensor electronics is divided into two main parts:

- 1.Current sensor and burden resistor
- 2.Biasing voltage divider

Here's the circuit diagram:



Schematic 1 – current measurement circuit

The CT sensor produces a current that is proportional to the instantaneous current flowing in the mains wire by:

$$I_{sens} = CT_{turnsRatio} \times I_{inst}$$

The resistor in parallel with the CT sensor is called a burden resistor and converts the current I_{sens} into a voltage:

$$V_{sens1} = Burden\ Resistance \times I_{sens}$$

The two R_{vd} resistors form a voltage divider that outputs a voltage at half the Arduino supply voltage of 5V. This voltage biases the AC voltage produced by the CT sensor and burden resistor by 2.5V, needed because the Arduino analog input channel requires a positive voltage.

$$Voltage\ at\ analog\ input = Bias\ Voltage + V_{sens1}$$

The capacitor $C1$ stabilizes the DC bias as this can often be a source of considerable noise.

Suitable sizes for resistors R_{vd} are 10 to 100k. Higher resistance lowers energy consumption but also increases noise.

A suitable value for $C1$ is 10uF.

Choosing the size of the burden resistor

1. Choose the power range you wish to measure.
2. Divide by the mains voltage to give mains current.
3. Convert the mains current from an RMS value to a Peak value by multiplying by $\sqrt{2}$.
4. Divide this peak value by the $CT_{turnsRatio}$ to give the current in the secondary coil.
5. The Burden resistor that gives the specified range is equal to 2.5V divided by the current in the secondary coil.

For quick reference:

A 100Ohm burden resistor with an efergy CT gives a current measurement range of 0 to 26.5Amps.

A 56Ohm burden resistor with an efergy CT give a current measurement range of 0 to 47.4Amps.

Efergy CT turns ratio: 1:1500

CT's also have an intrinsic phase shift of 0.1 to 0.3 degrees

Sensing Voltage



Image 2 – AC to AC power adaptor

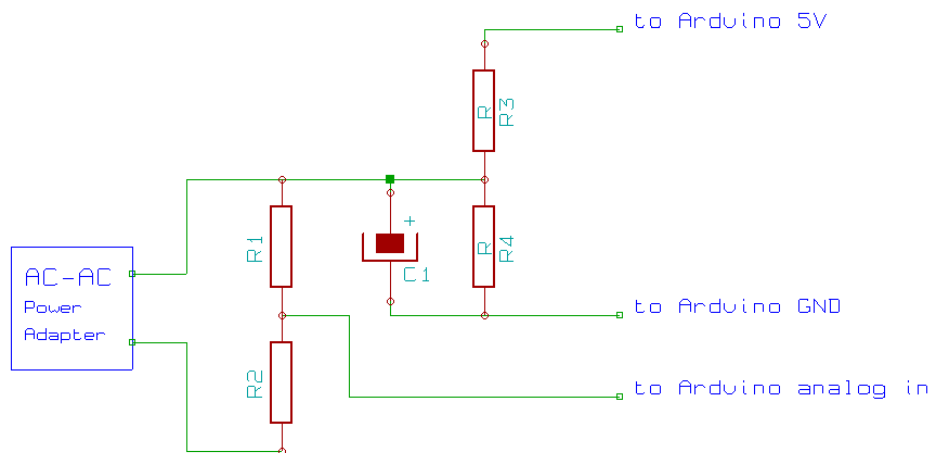
Voltage can be measured using an AC to AC step down power adaptor. Using the power adapter method rather than making a direct measurement on the high voltage side maximizes safety as no high voltage work is needed.

Sensor Electronics

The current sensor electronics is divided into two main parts:

1. Step down voltage divider
2. Biasing voltage divider

Here's the circuit diagram:



Schematic 2 – voltage measurement circuit

The step down voltage divider scales the AC voltage coming from the voltage adapter down from 9V down further to around 1V peak-peak.

The resistors R3 and R4 form a voltage divider that outputs a voltage at half the Arduino supply voltage of 5V. This voltage biases the AC voltage produced by the CT sensor and burden resistor by 2.5V, needed because the Arduino analog input channel requires a positive voltage.

$$\text{Voltage at analog input} = \text{Bias Voltage} + V_{\text{sens}}V$$

The capacitor C1 stabilizes the DC bias as this can often be a source of considerable noise.

R1 and R2 need to be chosen to give a peak to peak voltage of around 1V.

Suitable sizes for resistors R3 and R4 are 10 to 100k. Higher resistance lowers energy consumption but also increases noise.

A suitable value for C1 is 10uF.

The Arduino

The arduino is the heart of the system and also the bridge in-between the analog world of electronics and the digital world of software. The arduino makes it possible to graph energy consumption on a computer, upload information to the internet and display information on lcd's with ease.

For the basic energy monitor setup the Arduino takes the input from the sensors and sensor electronics, calculates values for real power, apparent power, power factor, rms voltage and rms current and outputs these values to the USB port where we can access them on the computer.

The interface between the analog and the digital world, the ADC

The Arduino turns the analog input signals into digital information with an on-board Analog to Digital converter.

The Arduino ADC has a resolution of 10bits this along with the sample rate determines the detail of the digital representation of the input analog signal. The Arduino analog input has a default input range of 0 to 5V (this can be changed). 10 bits means we can divide that range in to 2^{10} or 1024 divisions. The ADC therefore has a $5V / 1024 = 4.8mV$ sensitivity (It can detect changes in the input voltage of 4.8mV).

An analog input is read by the command: `sample = analogRead(pinNumber)`.

sample is an integer. If the voltage at the pin is 0 sample = 0. If the voltage is 5V, sample = 1024. If the voltage is equal to 2.5V, sample = 512 and so forth.

Arduino Sketch Structure

The Arduino sketch is structured as follows:

variable deceleration and setup

```
void loop()
{
```

```
  for n=0 to numberOfSamples
```

```
  {
    read in voltage and current sample
```

```
    remove voltage and current sample offset with digital high pass filter
```

```
    correct current phase displacement with linear interpolation caused by: ADC multiplexing,
    inherent CT and power adapter phase displacements.
```

```
    accumulate squares of voltage and current for rms calculation
    accumulate product of voltage and current for real power calculation
```

```
  }
  calculate values for real power, apparent power, power factor, rms voltage, rms current from accumulators
  apply voltage and current calibration coefficients.
```

```
  print values to USB serial
```

```
  reset accumulators.
```

```
}
```

For a more detailed treatment of calculating values for real power, apparent power, power factor, rms voltage, rms current, have a look at AC Power Theory 1 and 2.