

# AC Watt Meter Project

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2013-08-13



## **Danger**

**Important Warning! Safety issue: All electrical parts of the meter are connected to the live mains supply. Do NOT touch any of those parts when the power meter is connected to the mains outlet. Danger for Electrocution!**

**Also do NOT connect the circuit to e.g. a PC (via Rs232 or USB or...) because it will lead to a short circuit<sup>5</sup>.**

See also section 3.2.1 for details.

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## 1 Introduction

This meter is built with as less as components possible. It is of course a little limited in range, accuracy and stability.

It is made for **230V**~ (rms), max **2.5A**~ (rms) and **50Hz**, but is rather easily adaptable to other voltages, currents and frequencies. It can handle both sinusoidal and non sinusoidal voltages and currents, both with and without DC component.

It measures:

- the Rms **voltage** (unit: **V**olt)
- the Rms **current** (unit: **A**mpère)
- the **apparent power** consumption (unit: **V**olt**A**mpère: **VA**, the product of both the rms Voltage and the Rms current). This value is also called "Complex power".
- the **real power** consumption (unit: **W**att) (= the one that you are going to pay for)
- the **power factor** (no unit, ratio of real power to the apparent power), is the same as " $\cos\Phi$ " (cos phi) for sinusoidal voltages and currents.

All values are shown on an LCD, except for the Apparent (Complex) power. The meter measures once per second. Additionally there is one push button to set the "zero" point for the AD convertors. The values of these zero points are stored in Eeprom and recalled after startup of the PIC.

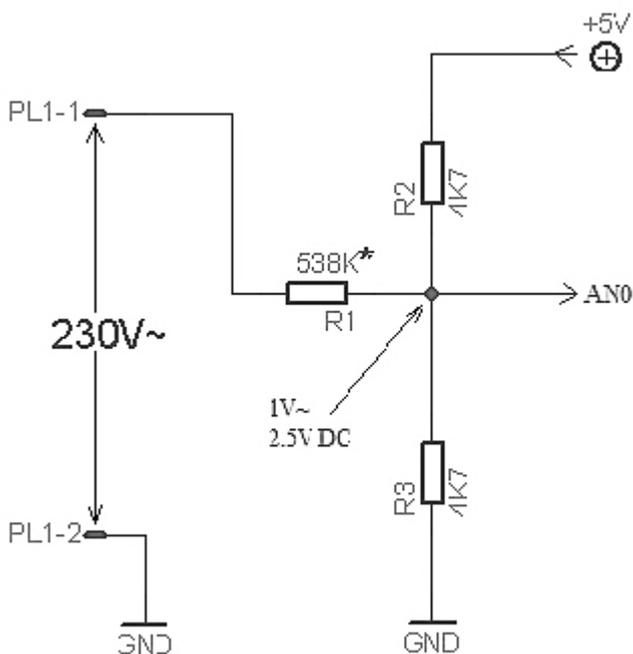
## 2 Principle of working

The project is built around an P18F2550, but any pic with an ADC will do, provided it is fast enough and has enough rom/ram (8988 bytes<sup>1</sup> / 548 bytes).

### 2.1 The voltage measuring circuit

The mains voltage (the one across the load) is divided by a factor 230 and shifted to a DC level of 2.5 V. This voltage is then fed to an ADC input (AN0) of the PIC. The level shifting enables to measure positive and negative voltages.

The circuit:



**Keep in mind that “GND” is no earth potential, it is only the GND for the PIC. It carries live mains voltages!**

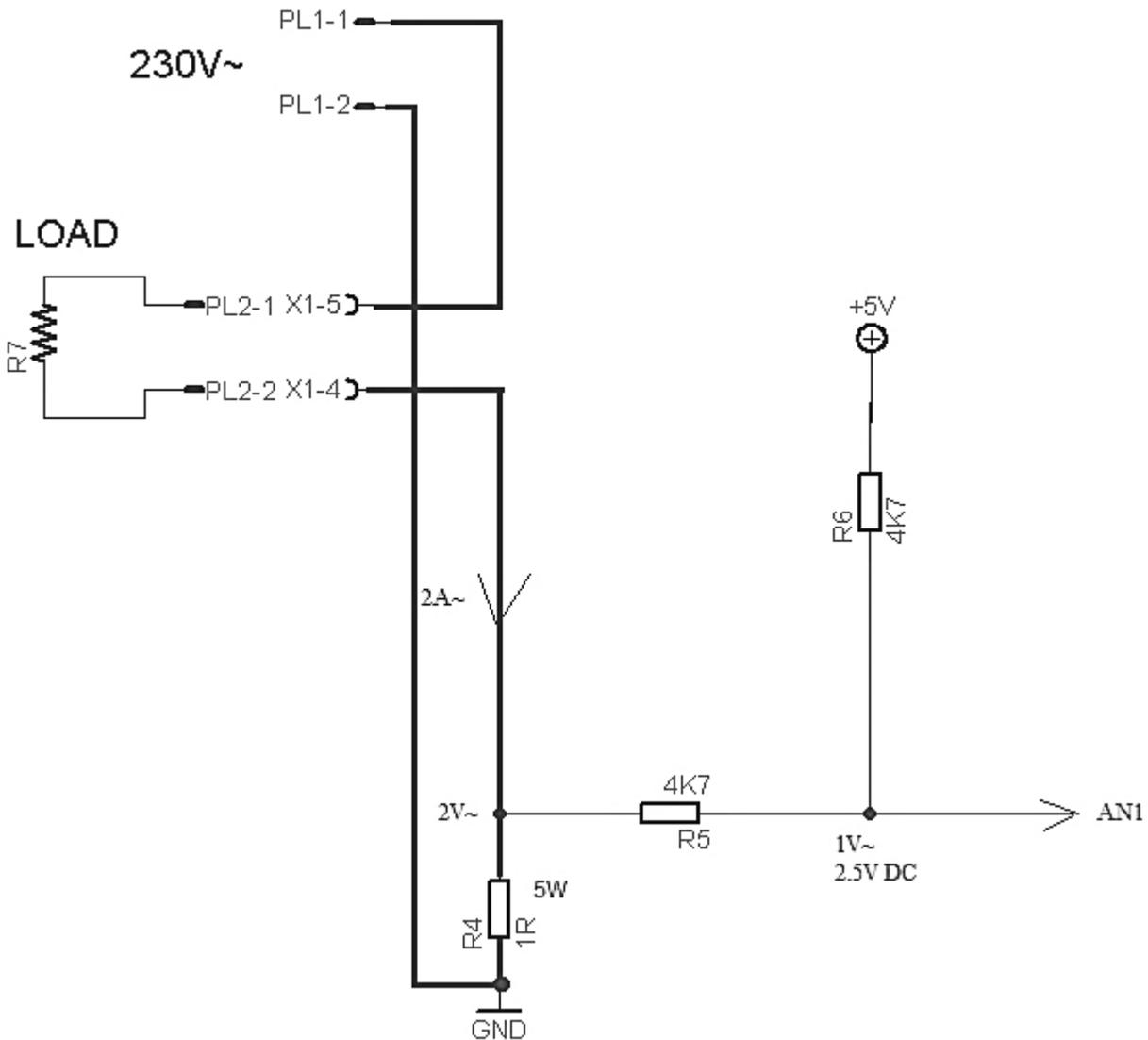
See also section 3.4.1 to change the wattmeter to another nominal mains voltage.

<sup>1</sup> when using Janni's replacement libraries: 5784 bytes romcode.

## 2.2 The current measuring circuit

The current through the load is translated to a voltage of 1V per A via a series resistor, this means that the series resistor has a value of 1 Ohm. The level shifter to 2.5V DC is also there, but it also halves the sensitivity of the circuit, it becomes 0.5V per A, or **2A per Volt**.

The circuit:



Keep in mind that “GND” is no earth potential, it is only the GND for the PIC. It carries live mains voltages!

See also section 3.4.2 to change the nominal current of the wattmeter.

## 2.3 The sampling

Of both analog inputs (AN0 for the voltage, AN1 for the current) **100 samples** are taken, one every 400 microseconds. This means a total measuring time of 40 milliseconds, which is 2 full 50Hz cycles. 2 full AC cycles is the minimum suitable for this type of measurement. In this project voltage and current sampling can not be taken simultaneously (as it should be), they are taken in sequence. This gives a little phase error between voltage and current measurement, which can normally be neglected.

These raw measurements are stored in 2 word arrays for further processing.

## 2.4 The calculations

### 2.4.1 Scaling

First the samples taken are translated (scaled) to actual volts and amperes, which are no “words” but “reals”. This means the 2.5V offset has to be subtracted (value = nominal 511, the middle of the ADC range), and multiplied with a constant value to get the correct Volt and Current values out of the samples.

For the voltage the multiplication factor is **230.0**, for the current the factor is 2/R4 (in our case: the value is **2.0**). Furthermore both have to be multiplied with the voltage per ADC step, in both cases the value 5/1024 (5V, 1024 steps).

So, the multiplier formulas here become:

```
const Vdd = 5.0; // the PIC supply voltage is 5V nominal
    VMultiplier = Vdd / 1024.0 * 230.0;
    AMultiplier = Vdd / 1024.0 * 2.0; // I nominal = 2/R4 = 2.0
```

The final formulas to become Volts and Amperes are:

```
VReal := VMultiplier * real(integer(VRaw[I] - VOffset));
AReal := AMultiplier * real(integer(ARaw[I] - AOffset));
```

Now we have the translated ADC values into real Volt and Ampère values.

### 2.4.2 Calculating Voltage and Current RMS values ( $V_{rms}$ and $A_{rms}$ )

For both holds:

The RMS value (or the “effective” value) is the square Root of the Mean of all samples Squared.

This means:

- the square of all scaled samples is calculated
- their average (mean) is calculated from those squared samples
- the square root is taken from that average.

In formula form:

$$x_{rms} = \sqrt{\frac{1}{n} (x_1^2 + x_2^2 + \dots + x_n^2)}.$$

wherein  $x_1, x_2, \dots, x_n$  are the scaled sample values,  $n$  is the number of samples and  $x_{rms}$  is the RMS value calculated from those samples.  $x$  stands for voltage or current (amperes).

### 2.4.3 Calculation of the Apparent Power, Real Power (Watts) and PowerFactor

#### 2.4.3.1 The apparent power (Volt Ampères, VA)

This is the easy one: the product of the RMS voltage and the RMS current.

In formula form:

$$S(\text{in VA}) = V_{\text{rms}} * A_{\text{rms}}$$

### 2.4.3.2 The real power (watts, W)

The real power is The average (mean) of all products of V and A scaled samples.

In formula form:

$$P(\text{in W}) = \frac{1}{n} (v1.a1 + v2.a2 + \dots + vn.an)$$

wherein **v1, v2, ..., vn** are the scaled voltage samples, **a1, a2, ..., an** are the scaled current samples and **n** is the number of samples.

### 2.4.3.3 The PowerFactor

The PowerFactor is The Real Power divided by the Apparent Power.

In formula form:

$$PF = P(\text{in W}) / S(\text{in VA})$$

## 3 Appendixes

### 3.1 Electrical units

Electrical entity	Unit	Unit Abbrev	Symbol
Tension or voltage	Volt	V	UorV
current	Ampère	A	I
Real (active power)	Watt	W	P
Apparent Power <sup>2</sup>	Volt-Ampère	VA	S
Resistance	Ohm	Ω	R
Power Factor	-	-	PF <sup>3</sup> or $\cos\Phi$ <sup>4</sup>

### 3.2 Considerations

#### 3.2.1 Safety (push button, trafo, batteries, output...)



**Make sure no metal parts connected to the circuit can be touched while the meter is connected to the mains. Take especially care for the LCD, the push button and the battery pack (if any). Danger for electrocution! Build the whole wattmeter in a properly insulating cabinet.**

**Also do NOT connect the circuit to e.g. a PC (via Rs232 or USB or...) to read out the measurements because it will lead to a short circuit<sup>5</sup>.**

<sup>2</sup> or "Complex" power

<sup>3</sup> "F" on the LCD

<sup>4</sup> the cosine of "phi", the angle between voltage and current. This notation can only be used with sinusoidal voltages and currents.

<sup>5</sup> unless the mains used to feed the load is completely isolated from the actual mains power, e.g. via an isolating safety transformer.

Make also sure that R1 in the circuit diagram can withstand 400V<sub>top</sub>, and that R4 can dissipate 5Watt without any problems. Do not use the power meter in the configuration described above with currents more than 2.5A rms.

### 3.2.2 Power supply

The power supply is not drawn in the schematic diagram. It can be a battery, a transformer with rectifier and buffer capacitor or even an (capacitive) bleeder from the mains, all followed by a 5V stabilizer.

Additions submitted by [Larry Reisinger](#):

- *Users should be warned not to try this with a cheap transformerless power supply. The really cheap 5v 'wall wart' power supplies aren't isolated. You need to be sure that the PS is a transformer type. They're getting hard to find.*
- *One other possible way to power a meter like this is with a series capacitor type DC power supply. You run that directly off of the mains power, and don't worry about external power. They're limited in current, but for 50 mA, they can be reasonable.*

### 3.2.3 LCD

Also the LCD connections are not drawn in the circuit diagram. In the code PortB is used to drive the LCD.

### 3.2.4 Accuracy

The accuracy of the meter depends on:

- the 5V supply: if it deviates from 5V then it is probably wise to change the "V<sub>dd</sub>" value used in the "multiplier" formulas (see section [Scaling](#)).
- the accuracy of the level shifting resistors (R2, R3, R5 and R6). Choose 1% or 2% types for these.
- the accuracy of the "measuring" resistors (R1 and R4). Also choose an 1% or 2% type for R1 (make sure it can handle 400V<sub>top</sub>!) and for R4 (which probably does not exist in a 1% accuracy) one can take e.g. 1.2 ohm and place some parallel resistors until 1 ohm is reached.
- The "zeroing" of the AD convertors. Make sure the zeroing (with the push button) is done regularly **while no mains is connected!** (no load is not sufficient, also the 230V~ has to be disconnected).
- The number of samples (the more the better)
- The total measurement period, currently 2 full cycles of a 50Hz AC mains (the more the better). Make sure always a number of full cycles is measured. The actual start point of the measurement is of no importance.
- The simultaneously measuring of voltage and current. This is only possible with a PIC with at least 2 AD convertors, which can be started together.

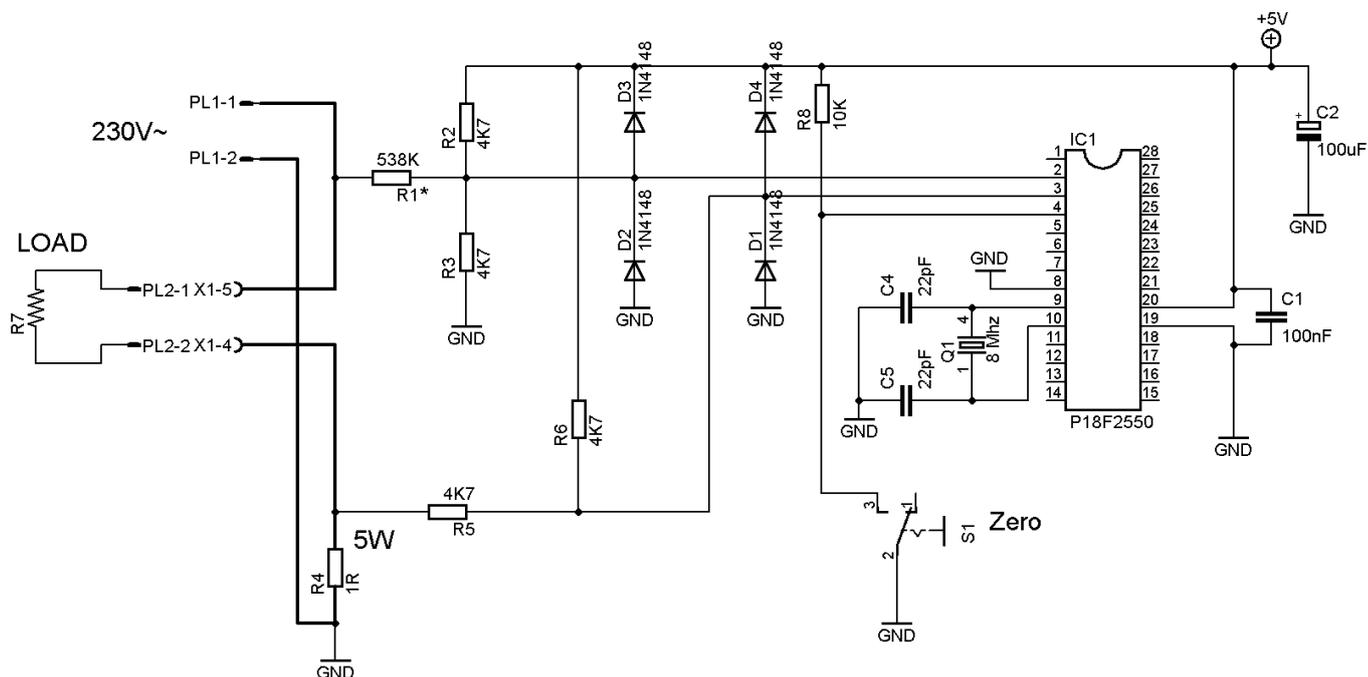
### 3.2.5 Stability

The stability of the output values depend on:

- The averaging of the measurements. Currently the only averaging that is done is the measuring over 2 AC periods instead of one.
- The stability of the 5V supply.

### 3.3 Circuit Diagram

This is the circuit diagram of the original design: not mains isolated, using a current sensing series resistor.



R1, R2, R3, R4, R5 and R6 are precision resistors (1%)  
 R1 must be capable to withstand 400V (splitted up if necessary)  
 \* e.g. (820K parallel with 1.5M) in series with 8K2  
 R4 must be capable of handling 5W of dissipation  
 LCD and its connections not drawn.

Author: Dany  
 Date: 2013-07-27

### 3.4 Adaptations to other circumstances

#### 3.4.1 To another mains voltage

##### **Hardware:**

The values in the above [Circuit Diagram](#) are those for 230V~. The only value that has to change is the one of R1:

$R1 = (V - 1) * 2.35K\Omega$  wherein "V" is the working voltage wanted.

So, for 230V, R1 is  $229 * 2.35K = 538.15 K\Omega$ .

For e.g. 120V, R1 is  $119 * 2.35K\Omega = 279.65 K\Omega$ .

The value of R1 may be very possible not a "standard" value. Either one chooses the closest standard value and accepts the accuracy error or one can build with more resistors an R1 with a value close to the wanted one.

e.g.  $538K\Omega = (820K \text{ parallel with } 1M5) \text{ in series with } 8K2$ .

Make sure that R1 (as a whole) can withstand 400Vtop.

##### **Software:**

Do not forget to adapt the “230.0” in the “VMultiplier” constant in the code:

```
const Vdd = 5.0;
    VMultiplier = Vdd / 1024.0 * 230.0;
```

### 3.4.2 To another maximum current

The component values in the above [Circuit Diagram](#) are those for nominal value of 2A~ (up to 2.5A~ rms max). This maximum current can only be made lower *in this design*. For higher currents the dissipation in R4 would become unacceptably high using a simple series resistor. In the latter case 2 other solutions can be used, see sections 3.4.2.2 and 3.4.2.3.

#### 3.4.2.1 With the current design

The current design uses a series resistor (R4) to measure the current, and two resistors (R5 and R6) to shift the DC level to  $\frac{1}{2} V_{cc}$ .

##### **Hardware:**

The only value that has to change is the one of **R4**.

The nominal value of the current should generate **2V~ across R4**. This means that:

**$R4 = 2/I$**  wherein “I” is the nominal current wanted.

so, for 2A~ nominal (as in the [Circuit Diagram](#)) R4 is  $2/2 = 1\Omega$

For 1A~, R4 should be  $2/1 = 2\Omega$ .

For 0.5A~ (100mA~) R4 should be  $2/0.5 = 4\Omega$  etc...

Make sure R4 is capable of dissipating the heat generated by the measured current. This dissipation is:

$P = \frac{I^2}{R4}$  wherein I is the nominal current and adapted R4.

So, for 2A~ nominal the max dissipation  $4/1 = 4$  Watt (rounded to 5W)

For 1A~, the dissipation is  $1/2 = 0.5$  Watt

For 0.5A~ the dissipation is  $0.25/4 = 0.0625$  Watt.

##### **Software:**

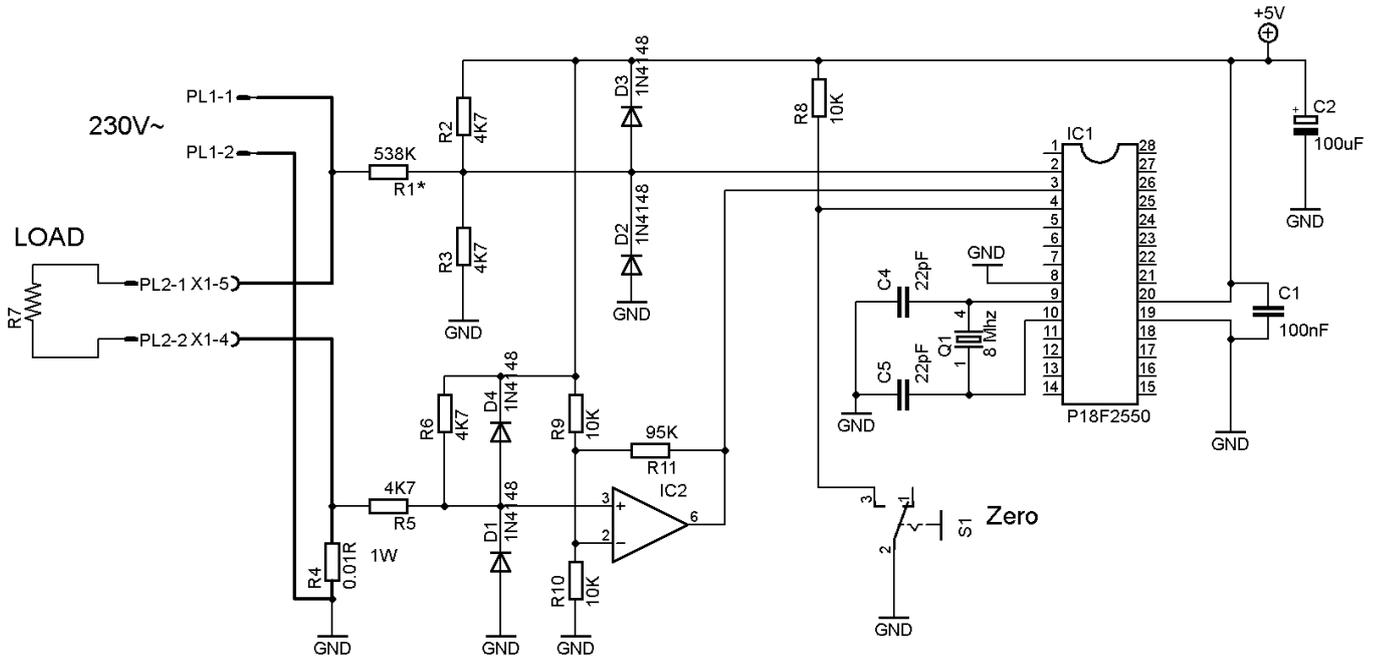
Do not forget to adapt the “2.0” in the “AMultiplier” constant in the code:

```
AMultiplier = Vdd / 1024.0 * 2.0; // for 2A nominal (R4 = 1Ω)
AMultiplier = Vdd / 1024.0 * 1.0; // for 1A nominal (R4 = 2Ω)
AMultiplier = Vdd / 1024.0 * 0.5; // for 0.5A nominal (R4 = 4Ω)
```

etc...

#### 3.4.2.2 With the use of an extra amplifier

This design also uses a series resistor to measure the current, but an amplifier is used between the resistor and the current sensing analog input of the PIC. Doing this the series resistor can have a lower value and dissipates much less. If the amplification of the amplifier is e.g. 10 then R4 can have a 10 times lower value than the normal one, resulting in a 10 times lower dissipation.

**Hardware:**

R1, R2, R3, R4, R5, R6, R9, R10 and R11 are precision resistors  
 R1 must be capable to withstand 400V (splitted up if necessary)  
 \* e.g. (820K parallel with 1.5M) in series with 8K2  
 R4 must be capable of dissipating 1 Watt  
 LCD and its connections not drawn.

10A version  
 Author: Dany  
 Date: 2013-08-13

**Important:** Ic2 is an “output rail to rail” or “input/output rail to rail” linear amplifier, as e.g. the MCP601 of Microchip.

The circuit diagram above shows a 10A version of the wattmeter. The 2 values that have to be changed to obtain another nominal current are those of R4 and R11.

*Steps to calculate R4 and R11:*

- **R4** (the series resistor) can be defined with the following formula:  $R4 = \frac{P}{I^2}$  wherein “I” is the nominal current (10A in above diagram), “P” is the nominal dissipation R4 can handle, e.g. 1 Watt. So, here  $R4 = 1W/(10A * 10A) = 0.01\Omega$ .
- The required **Gain** of Ic2 can be calculated with the formula:  $Gain = \frac{1}{R4 * I}$ , wherein “I” is the nominal current trough the load. In our case it is  $1/(0.01\Omega * 10A) = 10x$ .

*Note: The gain of the amplifier IC2 and its surrounding components should be such that 1V~ rms is obtained at the current sense input of the PIC with the nominal load current. In the example above the nominal load current is 10A, so the voltage across R4 is  $10A * 0.01\Omega = 0.1V$ . So, to obtain the required 1V, the gain has to be  $1V/0.1V$  is 10x.*

- To obtain the value of **R11** (which ultimately defines the amplifier gain if all other resistors have the value as in the diagram), the formula is:  **$R11 = (10 * Gain) - 5$** , so R11 becomes 95KΩ in our example.

Note: The gain of IC2 and its surrounding components is defined by the formula:  **$Gain = 1/2 + \frac{R11 \text{ in } K\Omega}{10K}$** .

**Software:**

The formula “AMultiplier” should be adapted as follows:

$$AMultiplier = Vdd / 1024.0 * I;$$

where **I** is the nominal current, so in our example above (the 10A example), the formula becomes:

$$AMultiplier = Vdd / 1024.0 * 10.0;$$

This method only works provided R4 and Gain are calculated as above.

**3.4.2.3 With the use of a dedicated current sensor IC.**

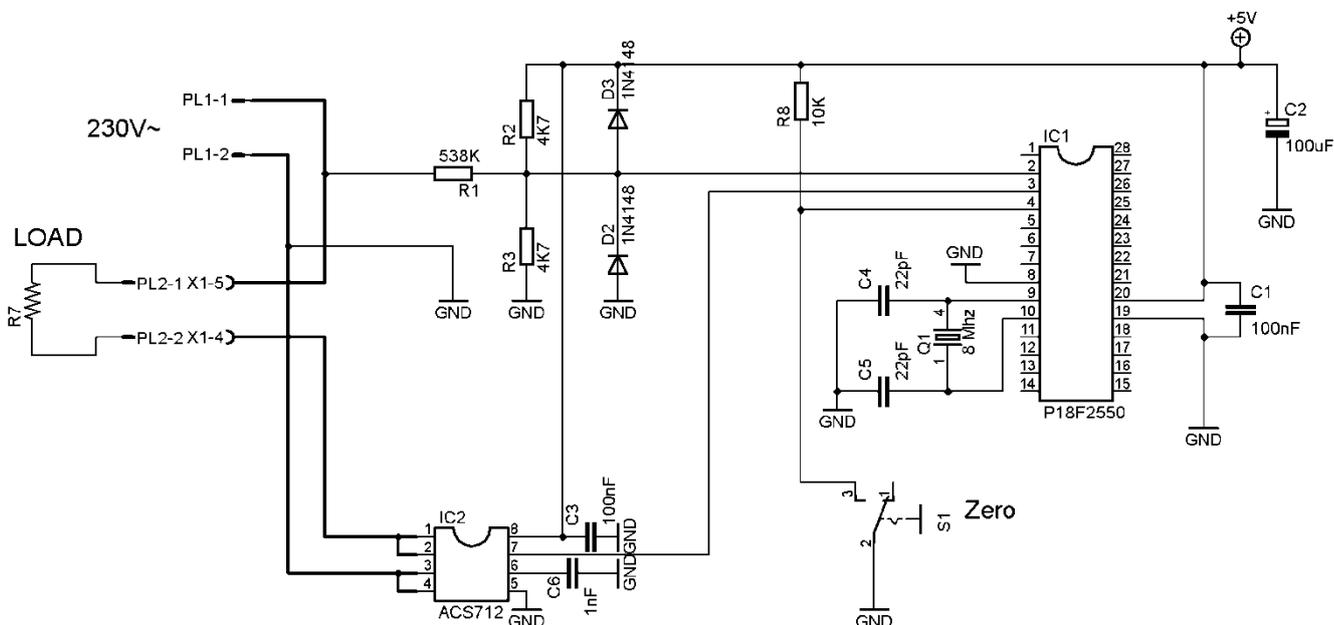
A number of dedicated current IC’s exist that translate the current sensed into a voltage directly suitable for the current sensing analog input of the PIC. The most suitable devices are the devices

- ACS712: 5A, 20A and 30A versions
- ACS757: 50A and 100A versions

**Hardware:**

R4, R5, R6, D1 and D4 are removed, the ACS’s current sense pins are connected in series with the load and the output pin of the device is connected to AN1 (the PIC’s current sensing analog input).

Example for the ACS712:



R1, R2 and R3 are precision resistors (e.g. 1%)  
LCD and its connections not drawn.

**Software:**

The only formula to be adapted in the code is the “AMultiplier” formula:

Device	Formula
ACS712, 5A	AMultiplier = Vdd / 1024.0 * <b>5.4054</b> ;
ACS712, 20A	AMultiplier = Vdd / 1024.0 * <b>10.0</b> ;
ACS712, 30A	AMultiplier = Vdd / 1024.0 * <b>15.1515</b> ;
ACS757, 50A	AMultiplier = Vdd / 1024.0 * <b>25.0</b> ;
ACS757, 100A	AMultiplier = Vdd / 1024.0 * <b>50.0</b> ;

The calculation method for the factor in the above formula is  $\frac{1}{\text{DeviceSensitivity}}$

e.g. for the ACS712, 5A version the *device sensitivity* is 185mV per A, or 0.185V per A. We need the reciprocal value (the A per V value), so here this becomes  $1/0.185 = 5.4054$ .

**3.4.3 Adding Mains Isolation**

The current design is such that there is a galvanic connection between the wattmeter circuit and live main supply. This means the wattmeter components

- can not be touched without danger, and
- can not be connected to other devices (e.g. a PC via uart or USB) without risk of a short circuit.

The solution for this is a complete galvanic isolation of both voltage and current sensing circuits from the live mains.

- The isolation of the current sensing is easy: use one of the dedicated current sensing IC’s as presented in section 3.4.2.3. The current sensing devices presented in that section all provide galvanic isolation from its output from its input.

Make sure the formula “AMultiplier” is adapted to the type of Ic2 according section 3.4.2.3.

- The galvanic isolation of the voltage sensor can be achieved by adding a very small mains transformer from e.g. 230V~ to 24V~, see TR1 in the diagram below for the connections.

R1 has to be adapted to the **actual**<sup>6</sup> secondary voltage (as defined in section 3.4.1).

The formula “VMultiplier” is the software stays however the one for 230V.



**Important:** Do NOT make the secondary voltage of TR1 too low, otherwise the zero point of the voltage will “shift” downwards too much due to the fact that R1 would become too low in value (R1 must be “much higher” than 2.35K). Any secondary voltage equal to or above 12V~ is acceptable. Any lower voltage will make the voltage sensor too much asymmetrical.

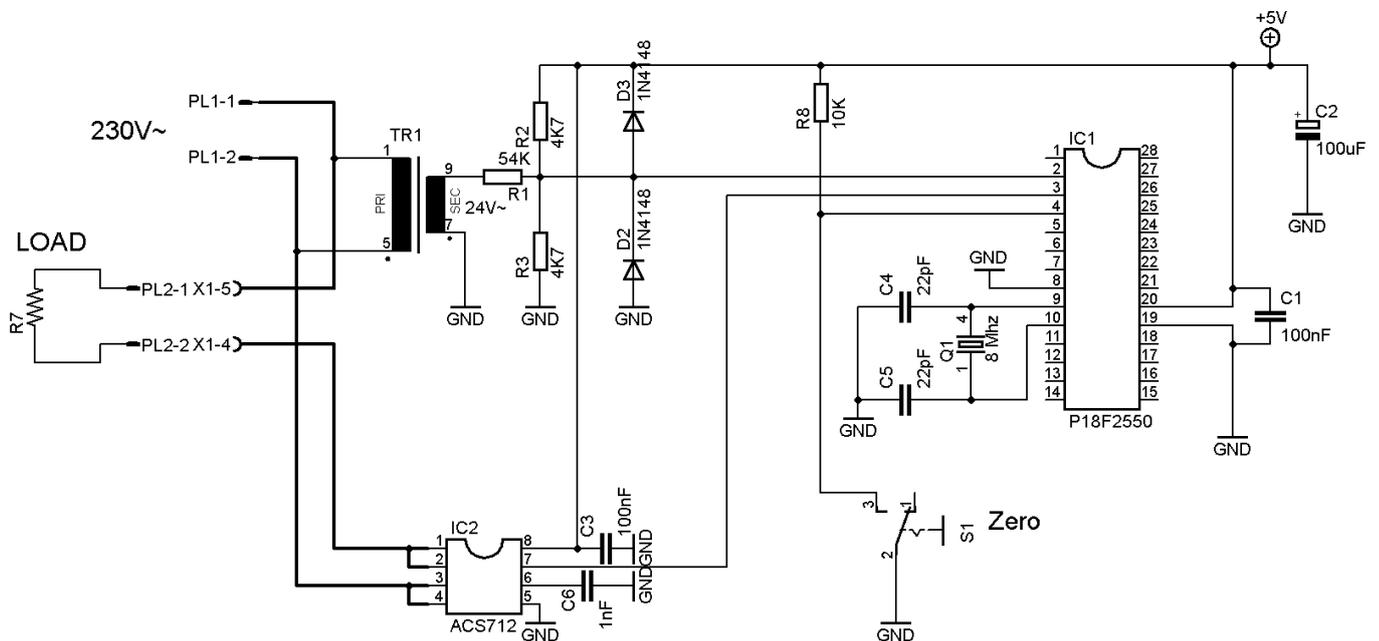


**Important:** You can NOT use TR1 to feed the wattmeter’s circuit, it would lead to a distortion of the secondary voltage of TR1, resulting in faulty power measurements.

Note: adding a transformer in the voltage sensing circuit blocks any DC component that is present in the mains voltage. But: it is not very likely that a large (noticeable) DC component is present in it, since the

<sup>6</sup> this voltage will be probably much higher than the one specified, since the transformer will have no power to deliver.

mains outlet has a very low internal resistance (for DC and AC). It is much more likely that the current drawn by specific loads carries DC components, which are correctly detected by the dedicated current sensing devices as e.g. the ACS712.



R1, R2 and R3 are precision resistors (e.g. 1%)  
LCD and its connections not drawn.

Isolated Version  
Author: Dany  
Date: 2013-08-08

### 3.4.4 Adaptations for other measuring frequencies

**Hardware:** none.

**Software:**

The only adaptation is the time of 1 V and A measurement. It is defined in this piece of code:

```
// measurement

for I := 0 to (NR_OF_MEASUREMENTS - 1) do
begin
  VRaw[I] := ADC_Read(0); // takes 37 us
  ARaw[I] := ADC_Read(1); // takes 37 us
  delay_us(326); // makes a total of 400 us (= 40 ms total for all measurements
                // = 2 full 50Hz cycles)
end;
```

For 50Hz the time for one measurement is 400us, the total measuring time thus is 100 \* 400us is 40 ms, which is twice the time of one AC cycle. That is the aim. The 400us is composed of the measuring time (ADC sample and conversion), and a delay to make the time full.

The ADC sample and conversion time depends on the type of PIC used and its clock frequency. It is rather difficult to calculate, so it is better to measure it.

For 60Hz to total time of 2 full cycles is 33.33 ms, or 333us per measurement.

### 3.4.5 Adaptations for other PICs or clock speeds.

#### **Hardware:**

If a 3.3V PIC is used then the nominal ADC input values of nominal 1V<sub>rms</sub> should be scaled down to 0.7V<sub>rms</sub>. This is done by enlarging R1 and lowering R4.

#### **Software:**

If a 3.3V pic is used then “Vdd” value used formulas VMultiplier and AMultiplier has to be adapted to 3.3V.

```
const Vdd = 3.3;
    VMultiplier = Vdd / 1024.0 * 230.0;
    AMultiplier = Vdd / 1024.0 * 2.0;
```

If the number of ADC steps is different than in this project (1024) then the formulas “VMultiplier” and “AMultiplier” have to be adapted.

```
const Vdd = 3.3;
const VMultiplier = Vdd / 2048.0 * 230.0;
    AMultiplier = Vdd / 2048.0 * 2.0;
```

If the clock speed is different then the one in this project (48Mhz), or the ADC sample and conversion time is different than in this project (P18F2550 at 48MHz gives an ADC time of 2x37us), then the “measurement” loop as described in section [Adaptations for other measuring frequencies](#) has to change.

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