emonTx_3Phase_PLL.ino

This sketch is a development of the 3-phase ‘discrete sample’ sketch and MartinR’s PLL energy diverter. It is intended for use on a 3-phase, 4-wire system. It utilises advanced features of the Atmel328P microprocessor to provide continuous monitoring of voltage of one phase and the currents in all three phases, thereby allowing a good estimate of real power to be calculated. The physical quantities are measured continuously, the average values are calculated and transmitted at user-defined intervals.

Pulse counting and temperature monitoring using a single DS18B20 sensor is supported.

This document has the following main sections:

Key Properties – important points about this sketch
Limitations
Initial configuration
Calibration
Installation
Explanation of operation of the sketch
List of required supporting libraries

Key Properties

- Continuous monitoring of one voltage channel and up 4 current channels.
- Gives an accurate measure of rapidly varying loads.
- 1800 sample sets per second – using 4 channels of an emonTx V3.4 @ 50 Hz
- Calculates rms voltage, rms current, real & apparent power & power factor.
- Pulse input for supply meter monitoring.
- Integrated temperature measurement (one DS18B20 sensor).
- User-defined reporting interval.
- Suitable for operation on a three-phase, 4-wire supply at 50 or 60 Hz.
- Can be calibrated for any voltage and current (default calibration is for emonTx with 100 A CTs & UK a.c. adapter).

Limitations

Because the voltage of only one phase can be measured, the sketch must assume that the voltages of the other two phases are the same. This will, in most cases, not be true, therefore the powers calculated and recorded will be inaccurate. However, this error should normally be limited to a few percent. Voltage imbalance might be the result of unbalanced loads within your installation, or it might result from the actions of other consumers on the same supply.

If you find that one or other phase voltage is consistently wrong, you might want to consider a small adjustment to the *current* calibration of the affected phase.

Because of the additional power required for continuous operation, a 5 V USB power supply is likely to be required, even if only the on-board RFM69CW radio is used. The 5 V power will always be required when the ESP8266 WiFi module is added.

The sketch is not compatible with the RFM12B radio module, nor the Arduino Due.

Initial Configuration

The following parameters must be set in the sketch for correct operation. This is done using both *pre-processor directives* and normal variable definitions. There are three ways to change the setting. For example:

1. `#define USEPULSECOUNT`
   As it stands, pulse counting is enabled. To disable it, make this line a comment.
2. `#define PULSEINT 1`
   This defines Interrupt 1 as the interrupt for pulse counting. Change the '1' to '0' to make the sketch suitable for the emonTx V2, which counts pulses using Interrupt 0.
3. `int nodeID = 11;`
   This declares the variable `nodeID` and defines the initial value (11). Change the number as required.

EEPROM Memory

The internal EEPROM memory can be used to retain some of the system settings and calibration constants. When the settings have been saved to EEPROM memory, those values are read at `each power-up thereafter and override the values in sketch. You can however choose to restore the default values and erase the EEPROM settings. How to store, change and revert the settings is explained later.

System Settings

`EMONTX_V34`
Defines the emonTx model for the I/O pin mapping. Permissible values are:

`EMONTX_V2`	for the emonTx V2
`EMONTX_V32`	for the emonTx V3.2
`EMONTX_V34`	for the emonTx V3.4
`EMONTX_SHIELD`	for the emonTx Shield

Default: EMONTX_V34

`SERIALPRINT`
Turns on 'human-friendly' print statements for calibration and commissioning - comment this line to exclude. You should probably comment this when the installation is working satisfactorily. This output format is automatically turned off if either of the other serial output formats is selected.

`USEPULSECOUNT`
Turns on the ability to count pulses. Comment this line if pulse counting is not required.

`PULSEINT`
Defines the interrupt number for pulse counting:
EmonTx V2 = 0,
EmonTx V3 = 1,
EmonTx Shield – selectable, see the Wiki.

`PULSEPIN`
Defines the interrupt input pin:
EmonTx V2 = 2,
EmonTx V3 = 3,
EmonTx Shield – selectable, see the Wiki.

`PULSEMINPERIOD`

Defines the minimum period between pulses, in milliseconds. This should be made smaller than the minimum time between switch operations where a mechanical switch is used (e.g. a magnetic reed switch). Set this to 0 for an electronic sensor with a solid-state output, where there is no risk of contact bounce.
Default value: 110

`RFM69CW`

Defines the mode of transmitting the output data. Permissible settings are:

RFM69CW Hope RFM69CW radio module
SERIALOUT Wired serial connection via the FTDI port (suitable for direct connection to the emonBase or emonPi (see https://github.com/openenergymonitor/emonTxFirmware/blob/master/emonTxV3/noRF/emonTxV3_DirectSerial/emonTxV3_DirectSerial.ino)
EMONESP ESP8266 WiFi module (see https://github.com/openenergymonitor/EmonESP)

If neither radio nor serial connection is required, do not define anything - in which case, the serial output will be ‘human readable’ for information and debugging only.
NOTE: The sketch will hang if the wrong radio module is specified, or if one is specified and not fitted.

`RF12_433MHZ`

Defines the frequency of RFM module. This can be

RF12_433MHZ
RF12_868MHZ
RF12_915MHZ

You should use the one matching the module you have.
NOTE: This is different from the normal OEM definition.

`RFPWR 0x99`

Sets the transmitter power (RFM69CW only).
The control range for transmitter power is 0x80 to 0x9F = -18 dBm to +13 dBm.
NOTE: Ensure a correctly matched antenna is used when operating at or near maximum power, otherwise the module may be damaged. The RFM12B equivalent power is: 0x99 (+7 dBm).
Default: 0x99 = +7 dBm
A 5 V d.c. USB supply is likely to be required if the transmitter is operated above minimum power.

`nodeID`

Sets the node ID for this emonTx. If DIP switch 1 was ON at power-up, then the nodeID is one more than the number specified. This value can be changed at power-up and the new value stored in EEPROM memory.
Default: 11

networkGroup

Sets the wireless network group. This must be same as the emonBase / emonPi and the emonGLCD. The OEM default is 210. This value can be changed at power-up and the new value stored in EEPROM memory.
Default: 210

Sensor Calibration Constants

These values can be changed at run time and the new value stored in EEPROM memory. Thereafter, the stored value is used instead of the values in the sketch.

VCAL

The voltage at the sensor input that gives 1 V rms as measured by the ADC input. It is a function of the a.c. adapter / transformer voltage ratio and the resistor divider network. For the emonTx V3 using the 'standard' UK a.c. adapter, the calculated value is 240:11.6 x 13:1 = 268.97

For the emonTx Shield, the calculated value is 234.2

This value depends on component tolerances and should be adjusted for best accuracy.

If DIP switch 2 is ON at power-up, then the calibration constant for the EU a.c. adapter is used.

Default: 268.97

I1CAL - I4CAL

The current at the sensor input that gives 1 V rms as measured by the ADC input. It is a function of the current transformer ratio and the burden resistor value (or the current transformer's current:voltage ratio for c.t's with an internal burden resistor).

For the emonTx V3 inputs 1-3 and the 'standard' current transformer, the calculated value is 100A:0.05A for current transformer ÷ 22 Ω for resistor = 90.91

For the emonTx Shield, the calculated values are 60.6 & 16.67

This value depends on component tolerances and should be adjusted for best accuracy.

Default: 90.91 for inputs 1 – 3, 16.67 for input 4.

CT4Phase

Attaches c.t.4 to one of the phases to allow the correct voltage reference to be used for real power calculations. Permissible values are:

PHASE1
PHASE2
PHASE3

Comment this line if c.t.4 is not used. This permits a faster sampling rate to be selected – see NUMSAMPLES below.

Default: PHASE1

I1LEAD - I4LEAD

The number of degrees by which the a.c. adapter / v.t. phase error leads the c.t. phase error. This can be obtained from the manufacturers' or from test data, or can be established by trial and error during calibration.

NOTE: Input 4 will probably be significantly different, even with the same c.t., due to the different burden resistor.

Default: 2.00 for c.t's 1 – 3, 0.2 for c.t. 4.

PLL & ADC Constants and Settings

LEDISLOCK

The on-board LED lights to indicate that phase lock has been obtained, and flickers very briefly to indicate a data transmission (this might not be readily visible). Comment this line for the 'standard' LED behaviour where a flash indicates data transmission.

SUPPLY_V0LTS
Specifies the reference voltage for the ADC. This will normally be 3.3 for any emonTx but 5.0 for an Arduino (including the emonTx Shield). If the accurate voltage is known, it may be specified. This value affects the calibration of every analogue input.
Default: 3.3

SUPPLY_FREQUENCY
The nominal supply frequency, either 50 or 60.
Default: 50

NUMSAMPLES
The number of times to sample each 50/60Hz cycle. The number chosen must be a multiple of 3. Permissible maximum values are:

	3 c.t's	4 c.t's
50 Hz	45	36
60 Hz	36	33

Lower values are permissible, but in general should not be used without good reason. (E.g. if phase lock is lost.)
Default: 36

ADC_BITS
Defines the resolution of the ADC. 10 for the Atmel 328P (emonTx, many Arduino boards).
Default: 10

ADC_RATE
The time between successive ADC conversions in microseconds. This is calculated from the clock frequency and the divider setting. Do not change this unless either of these is changed.
Default: 64

LOOPTIME
Sets the time between data transmissions in milliseconds.
Default: 5000

PLLTIMERRANGE
Sets the limits for the PLL timer. 100 = ~ +/-0.5Hz. This should not normally be changed.
Default: 100

PLLLOCKRANGE
The allowable ADC range to enter locked state. This should not normally be changed.
Default: 40

PLLUNLOCKRANGE
The allowable ADC range to remain locked. This should not normally be changed.
Default: 80

PLLLOCKCOUNT
The number of cycles to determine if PLL is locked. This should not normally be changed.
Default: 100

Calibration

Calibration might not be necessary provided that the ‘standard’ components are used. However, if there is any deviation from this, and especially if the optimum accuracy is desired, then the unit must be carefully calibrated using known good test instruments.
If test instruments are not available, then by adjusting the various calibration constants by small amounts, over a period of time, it should be possible to obtain agreement with the energy supplier’s meter.

Before calibrating the sketch, read (but do not do) the calibration instructions in Learn > Electricity Monitoring > Current & Voltage. Those instructions contain the general procedure and safety warnings, which you must be familiar with. The detailed instructions that follow apply only to this sketch. Follow *these* instructions for the order in which to make the adjustments and how to apply the values in the sketch, but follow the *general instructions* for how to proceed with the measurements.

1. Obtain a resistive load that will draw a current that is close to but less than the maximum that your multimeter can read and less than the rating of your c.t. Steps 2 – 5 that follow can be done on the test bench.
2. Plug in the a.c. adapter. Set the output to use SERIALPRINT, i.e. if you have enabled SERIALOUT or EMONESP, temporarily disable those. Using your multimeter (or a reliable voltage measurement), adjust VCAL so that the voltage measured is the same as your meter indicates.
3. Set all three main c.t’s (inputs 1 – 3) on the cable to your test load, and all facing the same way. Label the c.t’s, because the calibration is for the combination of c.t. and input. From now on, each c.t. must stay with the same input.
Insert your multimeter in series with the test load, to measure current. The power factor for c.t.1 should be nearly +1.0 If it is close to -1.0, reverse all three c.t’s on the cable. Adjust the three current calibration factors I1CAL, I2CAL & I3CAL to read the same current as your meter. Ignore the power values. When done, take the meter out of circuit. If you are using (say) an inverter’s power meter to calibrate, set I1CAL to give the correct c.t.1 power, but set I2CAL and I3CAL to give the same currents as c.t.1.
4. Adjust I1LEAD so that power factor 1 is as close to 1.000 as possible. Adjust I2LEAD and I3LEAD so that each is as close to -0.5 as possible.
5. If you are using c.t. 4, put this on the cable too and adjust I4CAL and I4LEAD to read the same current and power factor as c.t.1, 2 or 3 as appropriate.

No calibration is required for the temperature sensor.
Temperature Sensor Error values:

300.00	:	Faulty sensor, sensor broken or disconnected.
301.00	:	Sensor has never been detected since power-up/reset.
302.00	:	Sensor returned an out-of-range value.
85.00	:	Although within the valid range, if it is not close to the expected value, this could represent an error, and might indicate that the sensor has been powered but not commanded to measure (‘convert’) the temperature. It might be a symptom of an intermittent power supply to the sensor.

Pulse sensor.
If multiple pulses are counted where only one is expected, and a mechanical reed switch is in use, then it might be necessary to increase the value in `PULSEMINPERIOD`.

Installation

It is possible that there will be exposed live metal parts where you install the current transformers. If you think this might be the case, take the greatest possible care and ensure that you, or nothing that conducts electricity, touches a live part.

At the place where you will install the c.t's, identify the phase sequence and the phase on which the a.c. adapter will be installed. This is most important. If you cannot identify the phase sequence from the wire colours or the labelling, you will need to do this by trial and error:
Plug in the a.c. adapter. This will define phase 1 as far as the sketch is concerned, even though that might not be phase 1 as indicated by the phase colours or labels or terminal numbers on the meter or main circuit breaker.

Use your test load, and check its power rating. Switch off all other loads. Put the c.t. for phase 1 (c.t. input 1) onto one of the main phase conductors. Plug the test load into each phase in turn. If, at some point, the test load reads the correct power, c.t.1 is on the correct phase. If it reads half the correct power, the c.t. is not on the correct phase, so try another.

When you have identified phase 1, repeat with c.t.2 and the remaining two phase conductors.

Finally, put c.t.3 on the remaining phase and check that it reads the test load correctly.

Our convention is consumed power is positive. Reverse the c.t. on its cable if the power is negative. If you use an a.c. adapter that is reversible, that may be reversed if all three c.t's indicate the wrong polarity. Take care not to reverse the a.c. adapter subsequently.

On-line calibration & configuration of RF Module

On-line calibration & configuration is not available when the serial output is being used for machine-read data (i.e. when `SERIALOUT or EMONESP` has been set).

The user has the opportunity during the Power-On-Self-Test (POST) procedure to change the Network Group and the Node ID, and to adjust the sensor calibration when running.

To enter configuration mode at start-up, using the serial monitor part of the Arduino IDE, enter "+++" followed by the [Enter] key when prompted. You must respond within 10 seconds. If you do nothing, the start-up procedure continues normally after the timeout has expired.

You will then see a short menu:

```
Available commands for RF config during start-up:
<nn>i      - set node ID (standard node ids are 1..30)
             (i - reports the node ID)
<nnn>g     - set network group (1-250, RFM12 only allows 210)
             (g - reports the network group)
r          - restore sketch defaults
s          - save config to EEPROM
v          - Show firmware version
x          - exit and continue

Available commands when running:
k<x> <yy.y> <zz.z>
           - x = a single numeral: 0 = voltage calibration,
                 1 = ct1 calibration, 2 = ct2 calibration, etc
           - yy.y = a floating point number for the voltage/current
                 calibration constant
           - zz.z = a floating point number for the phase calibration
                 for this c.t.
                 (z is not needed, or ignored if supplied, when x = 0)
                 e.g. k0 256.8
                      k1 90.9 2.00
l          - list the config values
s          - save config to EEPROM
```

When running, you will not normally see any response to a 'k' command, but you will see the displayed values change. You will see confirmation when you save the changes. If you change one or more of the settings, the change will take effect immediately, or when you continue (option 'x') for the RF configuration commands. But if you do not save ('s') the changes, the settings will revert to the previous values at the next restart. After you save ('s') the settings, the new setting will be used forever, or until changed again.

If you restore the sketch default values ('r'), the EEPROM data is erased and the sketch restarts immediately, using the values set in the sketch. There is then no means of recovering the EEPROM data.

Explanation of operation of the sketch

General Principle

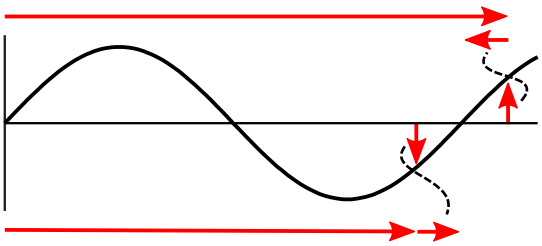
The sketch measures samples of voltage and current many times in each cycle of mains electricity. To be able to measure real power and energy, which is the quantity that energy suppliers generally charge for, the relationship between voltage and current must be known. The emonTx has only one voltage input, and as this sketch is designed for 3-phase use, it is necessary to use artificial methods to obtain a voltage reference for two of the three phases. This is done by ensuring that the number of voltage readings in one mains cycle is a multiple of three, and by storing the voltage readings for one third and two thirds of a cycle, they can be made to coincide with the second and third phases of the mains supply. The sketch uses a Phase-Locked Loop (PLL) to ensure that the readings always happen at the same place on each phase on each mains cycle, even though the mains frequency can change.

Pairs of readings (voltage and current) are multiplied together and added in an accumulator. At the end of the 'reporting period', the average power is calculated and transmitted. The rms averages for the voltage and current are calculated in a similar way.

What is a PLL – operating principle

A Phase Locked Loop (PLL) is a particular form of a closed loop control system. It is often used, as here, to follow the changes in frequency of some incoming signal. In our case, that is the mains electricity supply.
If we set up our emonTx to measure the mains voltage and current 1800 times per second, (that's 36 times per cycle in the UK) then as long as the mains frequency remains at 50 Hz, and as long as the clock in our emonTx is accurate and doesn't drift, then we will indeed take exactly 36 measurements in each cycle, and on successive cycles each measurement will be at exactly the same place on the wave. Clearly, in practice even if we can start out like this, it won't stay like it for long. Both the mains frequency and our clock can drift, and so the measurements will slide backwards and forwards along the wave as the two frequencies change relative to each other.
To stop this from happening, we must control the frequency at which we make the measurements so that they happen at exactly the same place on the wave each time. If we say we start measuring when the mains voltage crosses zero going positively, then the 37th measurement should again be zero. If our clock is running fast, we will get there early and the voltage will be negative and we need to slow our clock; on the other hand, if we are late the voltage will be positive and we need to speed our clock up. So we are not only locking our clock and the frequency of our measurements to the mains, we are also locking every 36th measurement to the positive-going zero crossing of the voltage. We have a phase locked loop.

36th sample late: Positive voltage at crossing is subtracted from the count, shortening the time period.



36th sample early: Negative voltage at crossing is subtracted from the count, extending the time period.

The ADC and interrupts

The analogue to digital converter (ADC) in the Atmel processor can run in one of two modes. The data sheet lists features that are key to how we use the ADC:

- Free Running or Single Conversion Mode
- Interrupt on ADC Conversion Complete

This sketch uses the "Single Conversion Mode". The first conversion is started by an interrupt from Timer 1, which is the timer that controls the PLL. This "interrupts" the main program, and a special function, the "interrupt handler" or "Interrupt Service Routine" (ISR) then runs. It is from here that the instruction to start the first conversion is sent. When that conversion completes, we tell the ADC which conversion to perform next. While the ADC is converting, the main program is free to carry on with whatever it was doing.
When the ADC finishes the first conversion, it puts the result in a special place. It also generates an "Interrupt on ADC Conversion Complete". This again interrupts the main program, and a second ISR then runs to pick up the result and do something useful with it (and it's this function that tells the ADC which conversion to do next).

This second ISR is at the heart of the sketch. In addition to directing the operation of the input multiplexer and the ADC, it performs the initial calculations on each sample to remove the initial offset, multiplies or squares the samples and accumulates them over the measuring period.

The maths – removing the bias offset

The way that the ADC input works means that we must 'bias' the input signal to mid-way between the power supply rails in order to measure an alternating voltage. But that means we must then remove the effect of that bias in order to read the correct value. That can be done by measuring the average input over a long time (a whole number of mains cycles) and then subtracting that average from the readings. This has the advantage that we do not need to do complicated maths using decimal numbers on each reading – we can simply multiply voltage and current (for the power) or multiply the current or voltage by itself for the rms value – and add the result to an accumulator. This inherently uses integer mathematics, which is a simpler and faster operation than calculating decimal fractions in a software filter.

Purely to reduce the size of the numbers, we actually subtract the nominal offset – 512 for a 10-bit ADC – first, then perform the multiplication and accumulation, finally removing the remaining offset at the end of the measurement period. For the real power, we simply subtract the "offset power", which is the product of the voltage and current offsets. For the rms current and voltage, we make use of a simplified version of the formula for the rms value of a wave with many components:

$$[rms\ of\ signal + offset] = \sqrt{(signal^2 + offset^2)}.$$

The maths – removing the effect of timing and transformer phase errors

The physical properties of all transformers means that there will be a phase error between input and output. Careful design and choice of materials can minimise this, but there will always be some error. We also introduce a timing error because, having only one ADC, it is necessary to measure voltage and current one after the other. Fortunately, we can use the same software to compensate for these two effects together. The first step is to read the current first, because generally, the current transformer has the smaller error – which is

almost always a ‘phase lead’ – meaning the current appears to have been measured before it actually was. The voltage transformer (a.c. adapter) has a much greater phase lead, so by measuring it later, we have already partly compensated for its phase lead. But we have no control over the time between readings, that is decided by the ADC. However, it is possible to interpolate between voltage samples to generate a new voltage wave that we can move about in time at will.
The formula used by emonLib, which does this calculation for each voltage sample and then multiplies the ‘shifted’ voltage sample by the current sample to give the instantaneous power, which is then averaged over the sampling period, is

$$average\ power = \frac{k}{n}\sum_{0}^{n-1}[(lastSampleV + PHASECAL * (sampleV - lastSampleV)) * sampleI]$$

where *k* is a calibration constant depending on the voltage and current calibration constants, the ADC reference voltage and the ADC resolution, and *n* is the sample count.

Because `PHASECAL` is a constant, the equation can be rearranged as

$$average\ power = \frac{k}{n}.(PHASECAL.\sum_{0}^{n-1}[sampleV \times sampleI] + (1 - PHASECAL).\sum_{0}^{n-1}[lastSampleV \times sampleI])$$

This implies that the two multiplications can still be done with integer arithmetic, it follows that the summation is integer arithmetic, and the only calculation that requires decimal precision is multiplication by `PHASECAL` or `(1-PHASECAL)` and the final scaling by *k/n*. And that is done after summation, in the main program where time is not critical.
One final refinement is to adjust the values of `PHASECAL` and `(1-PHASECAL)` to compensate for the amplitude change that interpolation creates. For a pure sine wave, the coefficients are modified thus:

$$average\ power = \frac{k}{n}.(X \times \sum_{0}^{n-1}[sampleV \times sampleI] + Y \times \sum_{0}^{n-1}[lastSampleV \times sampleI])$$

where

$\Delta = sampling\ interval$
$\Phi = phase\ error\ difference\ between\ two\ transformers$
$Y = \sin\Phi / \sin\Delta$
$X = \cos\Phi - Y \times \cos\Delta$

While interpolation still introduces some more distortion to already distorted waves, such as the ‘flat-topped’ mains wave shape commonly encountered, it is much less than when extrapolation is used.

Detailed description of the sketch

1. emonTx_3Phase_PLL.ino

The first part, lines 1 – 135, contain comments and the normal settings that the user might need to change. There should be no need to change anything below line 130.

Debugging pins – lines 143 – 148
These are pin allocations for attaching an oscilloscope, to monitor timing etc. Due to the limited availability of accessible output pins, it might be necessary to re-use pins already allocated. This will create a conflict, proceed with care.

Line 151 - Arduino pin use.
Definitions of I/O pins for various hardware.

Line 213 - constants calculated at compile time.
Values substituted by the pre-processor, placed here primarily to reduce clutter in the code.

Line 231 - Temperature sensor definitions.

Line 246 - Pulse counting definitions and variables.

Line 266 - Include the required libraries.

Line 271 - Data structure for RFM transmitted data.

Line 275 – Variables for rarely changed intermediate calculations.

Line 281 - Values accumulated over 1 mains cycle. These are shared between the ISR and the main program.

Line 287 - Values accumulated over the reporting period. These are of necessity 64-bit values, and used exclusively in the main program.

Line 293 - Function and variable declarations used in final stages of calculation.

Line 316 - setup( ). Set I/O pins, serial comms, initialise RF module. The first temperature measurement is started, the ADC is set up (but not started) and the phase correction coefficients calculated. Finally, the timer is started.

Line 460 – loop( ). The main loop processes no time-critical operations. As each mains cycle completes, it add the cycle accumulated values to the period accumulators, and at the end of the reporting period - ‘nextTransmitTime’, it calculates the average values, fetches the temperature reading, and transmits the data. It then starts the next temperature conversion. (Note: temperature readings may therefore be “old” by nearly the full reporting interval. Normally, temperature will change only slowly so this is of little consequence.)

Line 462 – getCalibration( ). If user input is present (via the IDE serial monitor), then this allows sensor calibration to be achieved without reloading the sketch.

Line 496 - Timer 1 interrupt handler. Timer 1 is the main timer for the PLL. It runs at a frequency that is nominally the mains frequency times the number of samples per cycle (i.e. between 1440 and 2250 per second), and each time starts the ADC with the conversion of the first (c.t.1) current.

Line 509 - ADC interrupt handler. This is the heart of the sketch. It executes when the ADC has completed a conversion. First (lines 502-503) it fetches the result of the conversion just completed and removes the nominal offset of half the ADC range. Then, depending on which conversion has just completed, it starts the next one.
For the current samples, it stores the I value and the I^2 value in their respective accumulators.
For the voltage sample, it stores the V value and the V^2 value in their respective accumulators, then it goes on to accumulate the 'partial' power values (which will eventually give the totals for using in the phase & timing correction formula) for each of the three or four c.t's.
Finally, it calls the function that updates and corrects the PLL timing so that synchronism is maintained.

Line 589 - PLL update function. This is called from and is therefore part of the ISR. It looks for the end of a cycle, and checks the voltage that was measured. If it is rising, then the Timer 1 count is adjusted as described earlier. If lock has been lost, then the timer is set so that lock can be regained as quickly as possible. The 'locked' flag is controlled from here.

Line 642 - addsumCycle( ) This function is called by the main loop when a mains cycle ends, and transfers the cycle totals into the 'period' accumulators.

Line 694 - removeRMSOffset( ). Applies the formula to remove the residual offset from the rms value that includes the offset.

Line 700 - removePowerOffset( ). Subtracts the "offset power" from the average power that includes the offset.

Line 705 - Converts degrees to radians for the trigonometric functions.

Line 710 - applyPhaseShift( ). This function calculates the real power from the two 'partial' power values.

Line 719 - Calculate voltage, current, power and frequency.
This is the final calculation to produce the result of the measurement in engineering units. First, the frequency is calculated, then the residual offsets are removed and the true value of real power, apparent power and power factor calculated for each c.t.
The data structure for the RFM module is filled (line 767?) and the period averages are zeroed.

Line 816 – calculateConstants( ). Calculate the internal, rarely changed, ratios used in the calculations.

Line 839 – calculateTiming( ). Calculate the coefficients for applying the phase error correction by interpolation.

Line 855 - Send the results. The results are formatted according to the eventual destination (screen display, ESP8266 or emonBase/emonPi) and sent to the serial output.

Line 950 - convertTemperature( ) Issues the command to the DS18B20 to measure the temperature.

Line 957 - readTemperature( ) This commands the DS18B20 to send the temperature reading on the OneWire bus, processes and converts the data to a temperature. An error value is returned if a fault is detected.

Line 990 - onPulse( ). This is the ISR triggered by a pulse from a reed switch, Hall effect or optical detector. Pulses occurring sooner than PulseMinPeriod after the previous one are ignored, this effectively removes contact bounce. PulseMinPeriod may be set to zero if the input device does not exhibit contact bounce.

2. config.ino

This handles the ‘on-line’ configuration commands.

Line 21 – loads the EEPROM standard library and sets up a structure ‘eeprom’ to facilitate the interface between the sketch variables and EEPROM memory.

Line 53 – load_config(bool verbose) Reads data from EEPROM and assigns it to the relevant variables. If the first byte of EEPROM is 0xFF (255), it is assumed that the EEPROM memory is either unused or erased, and no action is taken, therefore the values set in the sketch are used. If ‘verbose’ is true, the values are printed to the serial user interface. The values should not be printed when using SERIALOUT or EMONESP.

Line 89 – list_calibration( ) Prints the calibration constants.

Line 103 – save_config( ) Transfers the configuration variables into EEPROM.

Line 135 – wipe_eeprom( ) Writes the value 0xFF (255) to the area of EEPROM in use. (This is the default value before first use of the EEPROM memory.)

Line 150 – readInput( ) This handles user input via the IDE Serial Monitor during the start-up phase. Interpretation of the commands is handled by config( ).

Line 182 – config( ) Here the incoming characters are processed. Numeric input is built into an integer value, and the alpha character that follows determines the action taken. The present RF configuration is printed.

Line 273 – getCalibration( ) This handles user input via the IDE Serial Monitor at run time. If no serial input is available, no further time is wasted and the function returns immediately. If a character is present, then, if it is ‘k’, the following 2 or 3 values are read and the values are loaded into the appropriate constants, and the necessary follow-up actions (calculation of other variables, including the phase calibration) is done. If the first character was ‘l’, then the calibration values are listed; if the first character was ‘s’, then the configuration is saved.

Line 370 – showString( ) Prints the help text.

3. rfm.ino

The interface to the Radio Module.

The data format is fully compatible with JeeLib. The function names match those used in JeeLib (from which the major part of the RFM69 code is derived), but the rfm_send( ) function has been modified to accept the node ID and network group, thus allowing these to be changed without requiring rfm_init( ) to be used again. The code is heavily commented and requires no further description.

REQUIRED LIBRARIES

These libraries are required to support the sketch:

Wire	[Arduino standard library]
OneWire	(Paul Stoffregen)
SPI	[Arduino standard library]
CRC16	[Arduino standard library]
EEPROM	[Arduino standard library]

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@Bill.Thomson (Bill Thomson) for testing at 60 Hz.