Design and Development of a Microcontroller Based Digital Wattmeter (MIDIWAT).

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ABSTRACT

This paper presents a design to produce a microcontroller based digital wattmeter that measures the magnitude of power consumption of various loads (electronic devices) connected through it. To measure the power consumption under a sine wave signal (AC supply), the root mean square (rms) of both voltage and current is multiplied. The design is implemented using the techniques of digital signal processing and transformation. By this approach, both voltage and current are sampled a number of times during a cycle, the rms of the signals, real power, apparent power and the power factor are computed on the discrete signals. Finally, the magnitude of the power consumption is computed by integrating the power usage over a period of time.

Product of this effort is a MIDIWAT that can measure rms voltage and current and power consumption over a period of time up to 1 kVA of loads (± 2%) with an overload protection.

(Keywords: microcontroller, sensors, operational amplifier, LCD)

INTRODUCTION

Generally, a wattmeter is used for checking the power supply of a given power-outlet in a house and for estimating the electricity costs of different appliances. The power company uses a basic wattmeter to measure the amount of power that a house or an apartment is consuming from the general power supply. The wattmeter measures both the amount of energy consumed and records the time when it was consumed. This wattmeter is located somewhere outside a building so that a representative of the power company can come by in person to see the readings of the device.

The digital wattmeter that will be designed and constructed during the course of this project provides users with information that is far superior to that which an analogue wattmeter provides. Instead of a very imprecise needle display, the digital wattmeter will measure the current passing through its cables at a thousand times a second, measuring every small change and providing an average which is the true power supplied whereas an analogue wattmeter measures the apparent power which far exceeds the real power, thereby charging the user more than the actual consumption rate.

LITERATURE REVIEW

The major goal for designing any measuring instrument is to obtain a device that can measure with high precision the quantity with which it was design to measure and obtaining a minimal error. Over the years, different wattmeters have been designed to measure power. These have been classified as analogue and digital wattmeters.

There are wattmeters that can measure sinusoidal and non-sinusoidal waves with frequency between the range of 50hz and 60hz.
In 1995, S. Svensson described an instrument that utilizes digital sampling techniques which has been built and evaluated at the Swedish National Testing and Research Institute (SP). The Digital Sampling Watt Meter (DSWM) is based on standard laboratory equipment: digital multimeters, voltage dividers, shunt resistors and a PC. The DSWM is versatile and can be used for calibrations of many quantities. The most basic ones are the (total) active power and the amplitude and phase angle of individual

harmonics of non-sinusoidal voltages and currents.

The DSWM was first verified for sinusoidal signals. At 120 V and 5 A and power factor one, the DSWM has an estimated uncertainty (2σ) of 60 ppm at 50 Hz and 600 ppm at 20 kHz. The wattmeter has also participated in three international comparisons with satisfactory results. The most important additional feature, the input distortion, has been verified to be less than 800 ppm for all harmonics and lower than 100 ppm for most harmonics [1].

In July 1988, Don Kirk designed an analog-based talking wattmeter which he called the orator for the impaired people. The design included a single chip microcomputer and an analog-to-digital converter. The orator was designed to be used in conjunction with an analog wattmeter. A voltage sample derived from the wattmeter drives the orator. One of two modes of operation, voice or tone, is selected by the toggle switch at the left of the control unit. In the voice mode, synthesized speech announces the power output in watts measured by the wattmeter. The Orator range steps from 0-190 watts. When the talk button is pushed, the orator will voice the power level in digits followed by the word watts. If the power level is above 190W, the orator says out of range [2].

In October 2002, Thomas Scherrer designed a Digital RF Wattmeter with LC Display for 1 kHz to 1 GHz This RF wattmeter uses an AD8307 to measure the power level. The AD8307 front end circuit is both frequency-compensated and optimized for return loss to give optimum input SWR over a wide frequency range. A pre-programmed microcontroller type PIC16F876 with built-in 10-bit analogue to digital converters is used to convert the analogue voltage output from the AD8307 into digital values. Next, a set of lookup tables are used to convert the dBm values into RF voltage and RF power (watts). The readout of all values including a bar-graph appears on a large 20×2 LCD display with back light. There is also a DC voltmeter with minimum and maximum peak storage [3].

In 2012, *Freescale Semiconductor Inc* in its work titled "LH60 Single Phase Power Meter Reference Design" described a reference design on the construction and features of a static single phase power meter with direct measurement. Static means that the power meter does not contain any mechanical parts. Static meters are microcontroller based. Current flowing to the load is sensed on a shunt resistor, this is called direct measurement. Voltage and current are measured using a high precision AD converter. Power is then calculated from the measured values. Finally, the power is summed in time to get the total active energy (Wh) [4].

DESIGN PROCEDURE / METHODOLOGY

This section focuses on the design of the microcontroller based digital wattmeter and analyzes how each section on the circuit diagram in the block diagram are connected and their various functions as it contributes to the overall design of the project.

The design incorporated both hardware and software.

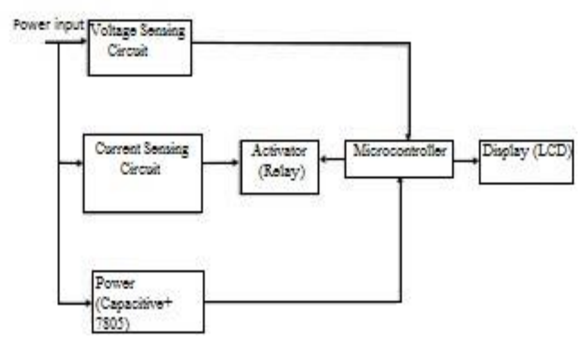


Figure 1: Block Diagram of the Digital Wattmeter.

Capacitive Power Supply Section

220-to-240 volts AC voltage comes into the system from a source. The voltage is first stepped down by the ceramic capacitor connected in series to one of the voltage line. The signal then flows into the bridge rectifier and is filtered. A 12 volt voltage regulator is then introduced to further reduce the input voltage to a regulated 12 volts supply. The output voltage is then taken into a variable voltage regulator and varied to supply 5 volts DC for points requiring that microcontroller, the LCD, voltage comparator and the resistor divider networks.

This circuit made use of a capacitive transformerless power supply. This is the latest kind of power supply that is both cost effective and saves space in comparison with linear mode power supply and switch power supply. Capacitor does not dissipate power rather it merely absorbs and releases it alternately. The capacitive power supply is like a linear mode power supply except instead of a transformer, it uses a capacitor.

The capacitor does the function of the transformer. Current passing through a resistor is directly proportional to the voltage across it but the current through a capacitor is directly proportional to the change in voltage across the capacitor as proven by the equation below:

$$I = C\frac{dv}{dt} \quad \textbf{(1)}$$

Where I is the current passing through the capacitor and $\frac{dv}{dt}$ is the change in voltage with time.

Since the voltage and current passing through a capacitor are 90 degree phase angle apart, the power supplied to the capacitor is alternating which means that the capacitor does not dissipate power and thus can be used to step down the input voltage.

Analyzing the Power Supply

The flow of current through a capacitor produces a reactance in opposition to voltage change. This capacitive reactance can be calculated as follows:

$$X_c = \frac{1}{2\pi f C} \quad \textbf{(2)}$$

Where *Xc* is the capacitive reactance in ohms, *f is* the frequency of the AC signal in hertz and C is the capacitance of the capacitor in farads.

The **input current** is obtained using:

$$I_{in} = \frac{V_{hfrms}}{Xc+R} \geq I_{out} \quad \textbf{(3)}$$

Where I_{in} is the input voltage in amperes, V_{hfrms} is the RMS voltage of the half-wave AC sine wave in volts, *Xc* is the capacitive reactance in ohms and R is the current limiting resistor in ohms and *Iout* is the output current.

Where:

$$V_{hfrms} = \frac{V_{peak}-V_z}{2} = \frac{\sqrt{2}V_{rms}-V_z}{2} \quad \textbf{(4)}$$

Where V_{peak} is the peak voltage of the wall power, V_{rms} is the rms voltage of the wall power whose value is 220V AC in Nigeria and 115V AC in Europe.

Comparing (i), (ii) and (iii),

$$I_{in} = \frac{\sqrt{2}V_{rms}-V_z}{2(\frac{1}{2\pi f C}+R)} \quad \textbf{(5)}$$

Where the value of f=50Hz for AC sine wave in Nigeria and 60Hz in United States.

These equations are used to determine:

1. The minimum input current that would be applied to the circuit.

2. The maximum input current to determine the power requirements of individual components.

Calculating for minimum possible value of *i*$_{in}$:
Assume minimum values of all components except *Vz* and R1. Assume maximum value of *Vz* and R1.

Vrms = 220V AC

Vz = 12V

f = 49.5Hz

C = C1 = 1μF x 0.8 = 0.8µF (Assuming $\pm$20% capacitor)

R = R1 = 470 x 1.1 = 517Ω (Assuming $\pm 10\%$ resistor)

Using Equation (iv):

Iin = 33mA (This is the minimum input current applied to the circuit.)

Calculating for maximum possible value of *i*$_{in}$:
Assume maximum values of all components except Vz and R1. Assume minimum value of Vz and R1.

Vrms = 230V AC

Vz = 11.9V

f = 50Hz

C = C1 = 1µF x 1.2 = 1.2µF (Assuming $\pm 20\%$ capacitor)

R = R1 = 471 x 0.9 = 424Ω (Assuming $\pm 10\%$ resistor)

Using (iv),

Iin = 51mA (This is the relatively maximum value of input current)

Careful analysis of the circuit shows that the maximum current capacity of the circuit is 100mA exceeding this range will damage the circuit.

To obtain the voltage output:

$$V_{out} = V_z \tag{6}$$

Where Vz is the Zener voltage across the Zener diode.

Vout = 12V

The output voltage to the voltage regulator is 12V.

Voltage Regulation

The remaining part of the power supply is the filter and regulation sections. The filtration is accomplished with a 1000µF electrolytic capacitor (C4). The regulation of the various voltage outputs are achieved with the use of fixed voltage regulator in the case of 8V and 12V DC, the variable voltage regulation is accomplished with a variable regulator IC. The IC LM7808, LM7812 and variable regulator, LM317 were used. The zener diode is used to set the reference voltage for the variable voltage regulator (LM317). The variable resistor is for the adjustment of its output voltage to the desired voltage. R2 is used as a current limiting resistor for the zener diode.

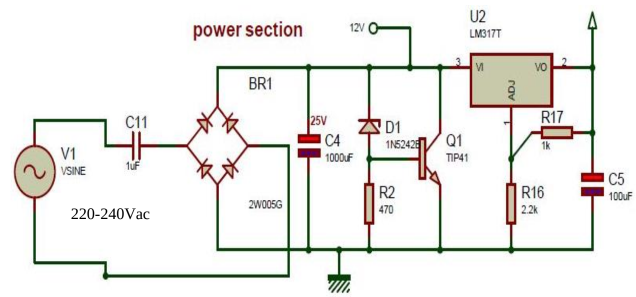


Figure 2: Power Supply Section of the Circuit Diagram.

Voltage Sensing Circuit

This circuit measures the incoming voltage on the AC circuit. The circuit is necessary to alert the wattmeter of voltage change due to power fluctuations. When the voltage is lower, appliances will need to draw more current to get the same amount of power. If the wattmeter doesn't know that the voltage has changed, it will think that the appliance is more power hungry, which isn't actually the case.

The voltage sensing circuit is a voltage divider circuit that references the AC signal about to enter the ADC of the microcontroller. That means that it feeds a reduced voltage of 5V to the ADC of the microcontroller. The electrolytic capacitors in the network decouple the signal before feeding the signal to the ADC thereby allowing only AC properties into the controller. The mains voltage (the one across the load) is divided by a factor 220 and shifted to a DC level of 2.5 V. This voltage is then fed to an ADC (AN0) of the PIC. The level shifting enables the measurement of positive and negative voltages.

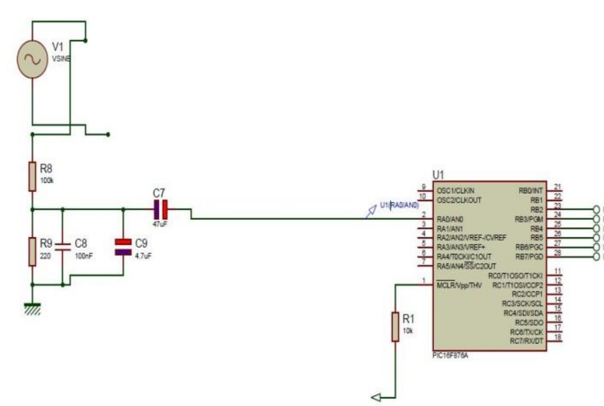


Figure 3: Voltage Section of the Circuit Diagram.

Current Sensing Circuit

The current sensing circuit takes measure of the current flowing through it and the current is then amplified in order to be fed to the ADC (AN1) of the PIC as shown in Figure 4.

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.

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 cannot 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.

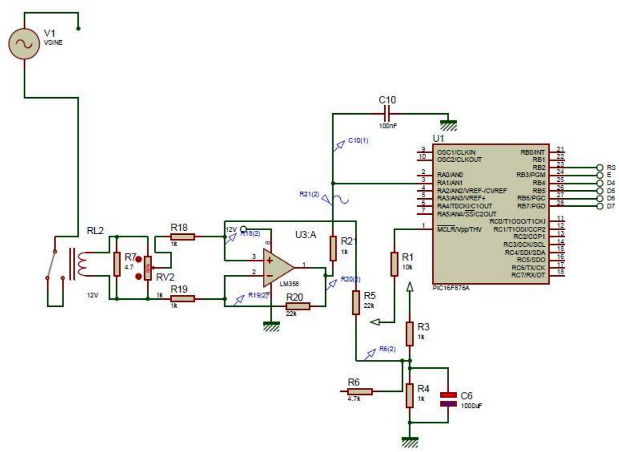


Figure 4: Current Section of the Circuit Diagram.

Determining Magnitude of Various Parameters Scaling

This is the process of deciding the tolerable range of voltage that the device can adjust to work with. One approach might be to accept any rms voltages from 190 to 240 volts. This 50volt window (190-240 volts) is then converted to a microcontroller safe value of, for example, 0 to 5.0 volts. Assuming proportionality, using this scheme, the microcontroller would read a value on the ADC of about 2.29 when the original AC input was 220 volts. The microcontroller would then register this as 469 (in a 10 bit system).

Calculating Voltage and Current RMS Values (VRMS and ARMS)

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:

$$x_{\mathrm{rms}} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}. \qquad \mathbf{(7)}$$

Wherein x_1, x_2, ... 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).

Calculating the Apparent Power (Volt Amperes, VA)

This is the product of the rms voltage and the rms current.

In formula form:

S(in VA) = V_{rms} x A_{rms} **(8)**

Calculating the Real Power (Watts, W)

The real power is the average (mean) of all products of V and A scaled samples.
In formula form:

$$P\ (in\ watt) = \frac{1}{n}(V_1.a_1 + V_2.a_2 + \ ... + V_n.a_n) \quad \textbf{(9)}$$

Wherein V_1, V_2, ..., V_n are the scaled voltage samples, a_1, a_2 ,..., a_n are the scaled current samples and **n** is the number of samples.

To Obtain the Power Factor

The Power Factor is The Real Power divided by the Apparent Power. In formula form:

PF = P(in W) / S(in VA) **(10)**

THE CORE MICROCONTROLLER

The microcontroller performs the logical steps to convert amps and volts to power and displays it on an LCD. The operational amplifier multiplies the small voltage present on the resistor and sends it to an ADC (analog to digital converter) on a microcontroller for reading. The microcontroller takes a voltage from 0-Vdd and converts it to a digital value between 0 and 255 (for an 8 bit conversion) or 0-1023 (for a 10 bit conversion). For this reason, to get a full scale reading requires some sort of scaling circuit as discussed in section 3.6.

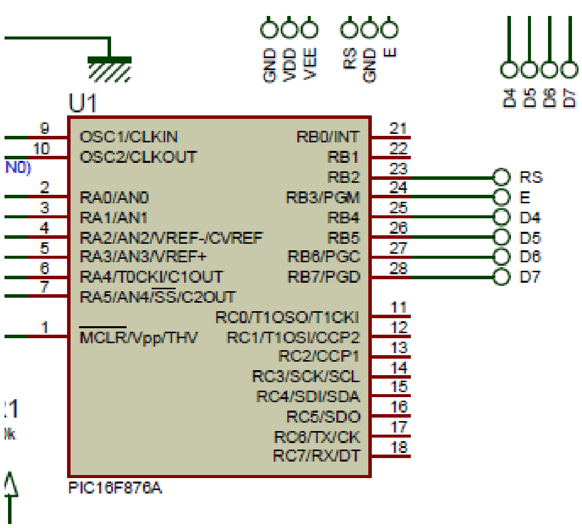


Figure 5: The PIC 16F876A.

The point of scaling is to determine beforehand what range of operation the wattmeter must accept. For this wattmeter, it is rated up to 15 amps.

5 volt supply must be applied to the vdd and mclr point, a crystal oscillator coupled with a ceramic capacitor between 22 to 33pf are necessary to set the controller ready for use, other details are the setting up of the tris register for every port's pin that might be made use of to either input or output.

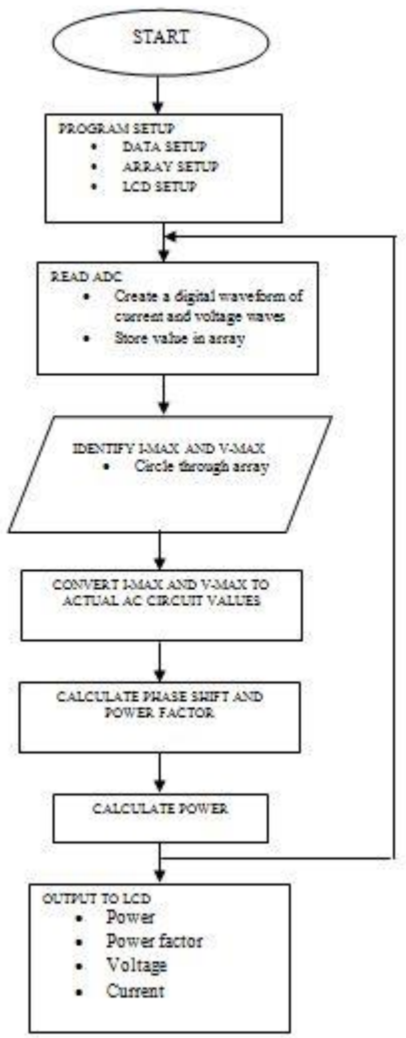
Before the AC voltage can be worked with, it must be converted to a lower DC form. Since DC cannot take on multiple ambiguous values, the AC measurement must be decided before converting to DC.

If the RMS is to be used, then the DC value converted from the AC will have to be proportional to the 220 volts RMS value. Of course, 220 volts is too high for the microcontroller to handle, so it will need to be scaled down to an appropriately low level.

The microcontroller has to have at least two ADCs to make the current and voltage measurements. Internally, the microcontroller represents these readings as a digital value from 0 and 1023 (for the 10 bit ADC).

It is important to remember the converting factors to convert these digital seemingly arbitrary values back to the voltages and amperages they represent. The current measurement would have a different factor, but the same process would be used, and when the values are demystified, they would be multiplied together, at run time, by the microcontroller, and the result would be the power (in watts) that the particular external appliance was consuming.

Flowchart of the Microcontroller



The Display Section

This section displays the final piece of the information in a human usable form. This section is completely taken care of by c-complier using its inbuilt libraries.

The liquid crystal display (LCD) used here is a 20 by 4 display unit and already provided for in a library called" LCD420.C" Driver for common 4x20 LCD modules. Its duties are to send to the display libraries a series of words to display while the library handles the rest. The display set up and use is illustrated below.

```
lcd_init();
lcd_putc('\f');
delay_ms(10);
lcd_gotoxy(1, 16);
lcd_putc("    STEVTECH    ");
delay_ms(1000);
lcd_gotoxy(1, 2);
lcd_putc("  MICROTRONICS  ");
delay_ms(1000);
lcd_gotoxy(1, 3);
lcd_putc("  REAL - POWER  ");
delay_ms(1000);
lcd_gotoxy(1, 4);
lcd_putc("   WATTMETER    ");
```

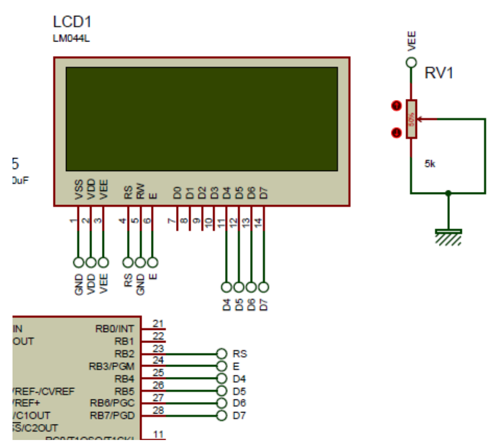
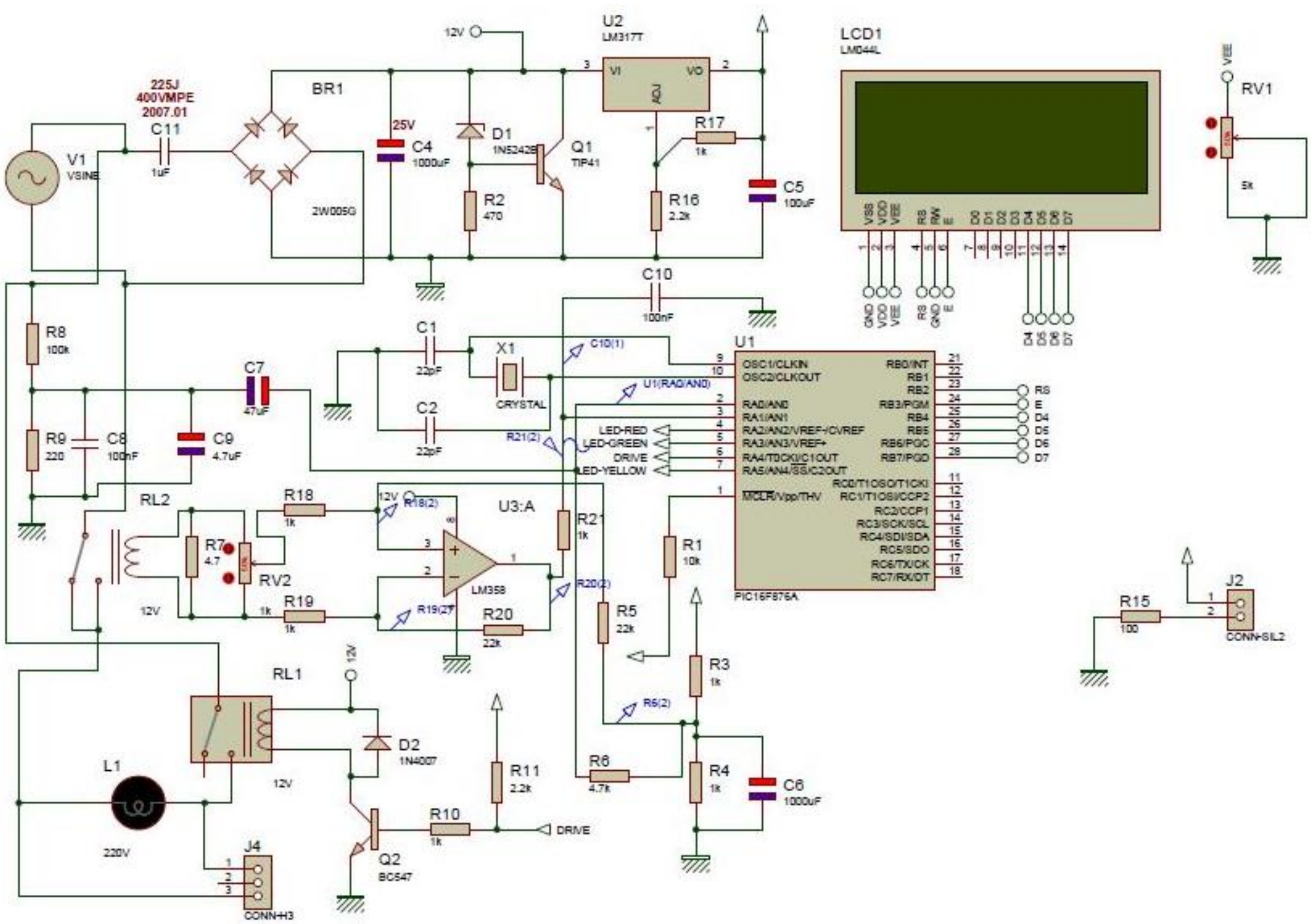


Figure 7: 20 x 4 LMO44L Liquid Crystal Display.

Principle of Operation

Electricity of 220-240V AC is passed from the wall outlet through a fuse and stepped down using a capacitive power circuit and then rectified by a bridge rectifier to supply 12V DC to the voltage regulator which in turn supplies 5V to the microcontroller and also the signal passed through a current sense circuit. Attached to the current sense circuit is an operational amplifier which amplifies the very small current coming from the sense circuit into a voltage which can be read by the microcontroller. The microcontroller converts this voltage using an analog to digital converter (ADC) and also takes into consideration the voltage which is roughly 220volts, and ultimately computes the power consumption of the load across it.

CIRCUIT DIAGRAM



TEST AND OBSERVATIONS

Initial Setup

To make the device ready for the first time, there is need for calibration. This is the setting of the synchronization of the reading of the display unit with the actual output of the power supply. The synchronization is achieved with the use of a standard digital voltmeter. The standard voltmeter used is the MY64 model made by MASTECH. The power supply was connected to an AC mains rated 220V. The voltage selector switch was set to 12V.

The output was read with the digital voltmeter and compared with that of the display unit. Adjustment was made by turning the scale variable resistor till the readings were the same (12V). After this setting was done, further readings produced harmonized results. This means the power supply meter has been well calibrated.

Data Observation

The Digital Wattmeter functions well with purely resistive loads. The average error obtained during power calculation when compared to the lab wattmeter is 3.1%. The current calculation of the wattmeter had an average error of 1.9% on purely resistive loads. The voltage reading error was consistently less than 0.5%. Power factor calculated relative accurate to 0.98 and error of 2%.

Inductive and capacitive loads had unexpected effect on the current signal path. Below 300 millivolts, the current waveform is tracked fairly accurately with an average error of less than 4%. The power factor was also derived relatively accurately; power factor has more significant error than any other component of the system. The estimated power factor comparison is observed on an oscilloscope displaying the current and voltage waveforms as seen in Figure 9.

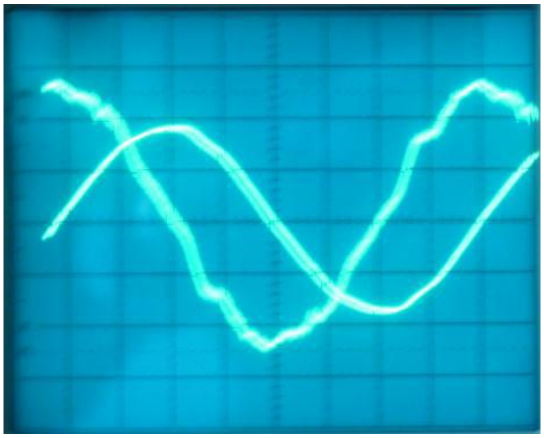


Figure 9: Voltage and Current Waveform Observation on Oscilloscope.

TEST DATA

Table 1: AC Testing of the Digital Wattmeter.

DIGITAL WATTMETER TEST ON RESISTIVE LOAD							ERROR %				
VOLTAGE (VOLTS)		CURRENT (AMPERES)		POWER FACTOR	POWER (WATTS)		LAB VS DIGITAL WATTMETER			LOAD	
V-ANALOG	V-DIG	I-METER	I-DIG	DIGITAL METER	DIG (w)	ANALOG (w)	I	V	P	R-SWITCHES	R-VAL (OHMS)
120	120.2	0.35	0.348	0.98	41.6	44	0.6	0.2	5.8	3	341
160	160.2	0.46	0.474	0.98	74.8	76	3.0	0.1	1.6	3	341
200	200.6	0.58	0.592	0.98	120	116	2.0	0.3	3.3	3	341
221.2	221	0.69	0.718	0.98	168	160	3.9	0.1	4.8	3	341
120	120.2	0.35	0.348	0.98	41.6	44	0.6	0.6	5.8	3	341
160	160.2	0.46	0.474	0.98	74.8	76	3.0	0.1	1.6	3	341
200.6	200.0	0.99	1.012	0.98	196.8	196	2.2	0.3	0.4	3	341
220	219.6	1.20	1.20	0.98	284	276	0.0	0.2	2.8	3	341
120	120.2	0.35	0.348	0.98	41.6	44	0.6	0.6	5.8	3	341
160	160.2	0.46	0.474	0.98	74.8	76	3.0	0.1	1.6	3	341
200	200.6	0.58	0.592	0.98	120	116	2.0	0.3	3.3	3	341
220	219	2.14	2.082	0.98	496	488	2.8	0.5	1.6	3	341

Comparison of the Measurement of Resistive Load by Analog and Digital Wattmeter

The following graphs plotted below illustrate the measurement of a resistive load by both analog and the digital wattmeter designed during the course of this project. The reading is obtained as shown in Table 1. The first graph represents the result obtained by using analog wattmeter and the later represent result obtained using the digital wattmeter.

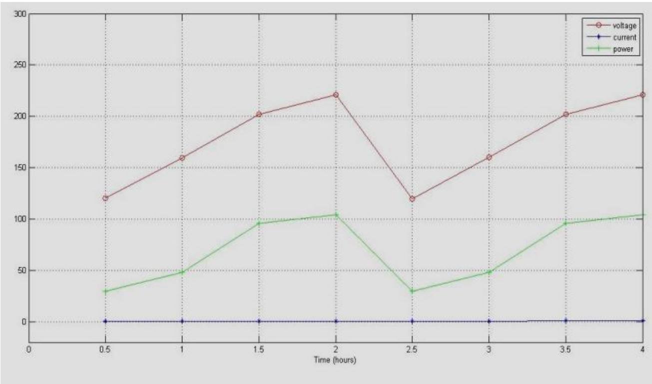


Figure 10a: Graph Representing Measurement of Resistive Load by Analog Wattmeter.

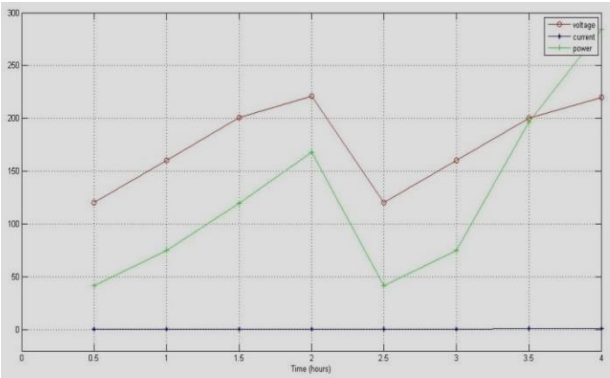


Figure 10b: Graph Representing Measurement of Resistive Load by Digital Wattmeter.

Snap Shot of the Digital Wattmeter

Figures 11 and 12 show the completed constructed digital wattmeter.

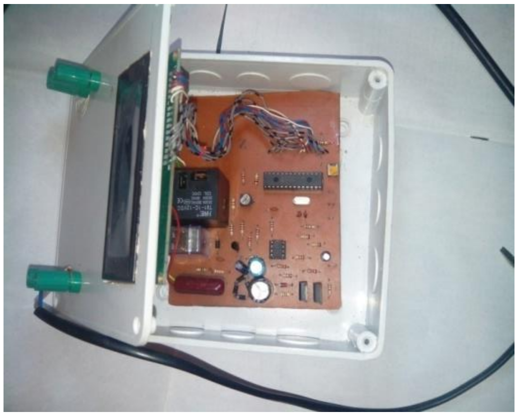


Figure 11: Internal View of the Digital Wattmeter.

Figure 12: External View of the Digital Wattmeter.

ACCURACY

The accuracy of the meter depends on:

- The 5V supply: if it deviates from 5V then it is probably wise to change the "Vdd" value used in the "multiplier" formulas.
- 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 (it should be to able handle 400Vtop) and for R4 (which probably does not exists 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. 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.

STABILITY

The stability of the output values depends 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.

CONCLUSION

This project has demonstrated how to design and construct a microcontroller-based digital wattmeter that measures RMS voltage and current, the power consumption in kilowatt-hour of various loads passing through the device. This design has proven the reliability of digital-based wattmeter over conventional electromechanical wattmeter. The wattmeter has the capacity of measuring energy consumption for all loads conditions i.e. power factor and non-sinusoidal voltage and current waveforms. The wattmeter has no rotating parts thus helps in the prevention of meter tempering, which is an attractive feature for the utilities. The digital wattmeter includes a "no load threshold" feature that will eliminate any creeping effects in the meter. In addition, the process of reading the power consumption is facilitated by the LCD display which is way easier to use than the imprecise analog counterpart.

Using a capacitive transformerless power supply, the design of the digital wattmeter was cost effective and very light in weight from not using a transformer. This is one tremendous improvement that has been achieved in the development of a user friendly, cost effective and flexible device. Transformerless power supplies are instrumental in keeping costs low in microcontroller-based applications powered from a wall receptacle. Both resistive and capacitive power supplies offer substantial cost and space savings over transformer-based and switch-based supplies. Capacitive power supplies offer an energy efficient solution, while resistive power supplies offer increased cost savings. Incorporating a transformerless power supply as done in this project is very innovative and economical.

RECOMMENDATION

Additional energy savings can be achieved if energy saving techniques were used in our designs. More portable electronic products could also be integrated into our design eliminating the need for large components as much as possible. This will, in turn, make these products less expensive, and more energy efficient.

The authors also recommend that for future modification of this device, a time differentiation ($\frac{dI}{dt}$) sensor be used as the current sensing circuit for the reason stated below:

Electrical isolation –The ($\frac{dI}{dt}$) sensor detects current without any contact to the conductor

- Capable of handling very high current

($\frac{dI}{dt}$) sensor is capable of handling very high current

- Low power consumption-No significant power consumption needed for current sensing.

- Low temperature shift-The output varies very little with changes in temperature.

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