EE 318 Electronic Design Lab, EE Dept, IIT Bombay
Submitted: Aril 10, 2006

Power and Energy Measurement using MSP430, implementing Rogowski coils for Current sensing.

Group B7
Shreyas Nagdawane – 03007010 shreyas@ee.iitb.ac.in
Parikshit Shahani – 03007013 parikshit@ee.iitb.ac.in
Gaurav Mittal – 03007019 gmittal@e.iitb.ac.in

Supervisors: Prof. Mukul C. Chandorkar & Prof. L.R.Subramanian

Abstract

It is very important to monitor the voltage and current since it gives an idea of the quality of power being delivered. The given project involves the monitoring of 3-phase power and energy using the MSP430 micro-controller. The basic steps involve programming the MSP430 micro-controller to sample the different voltages and currents, using these sampled values to calculate the required values of power and energy, displaying these values on a LCD display and interfacing the MSP430 with a computer using a RS232 interface. A more detailed description of the individual blocks which will execute these functions along with the block diagram is given below. We implement Rogowski coils for sensing current since it converts the current to voltage.

1. Introduction

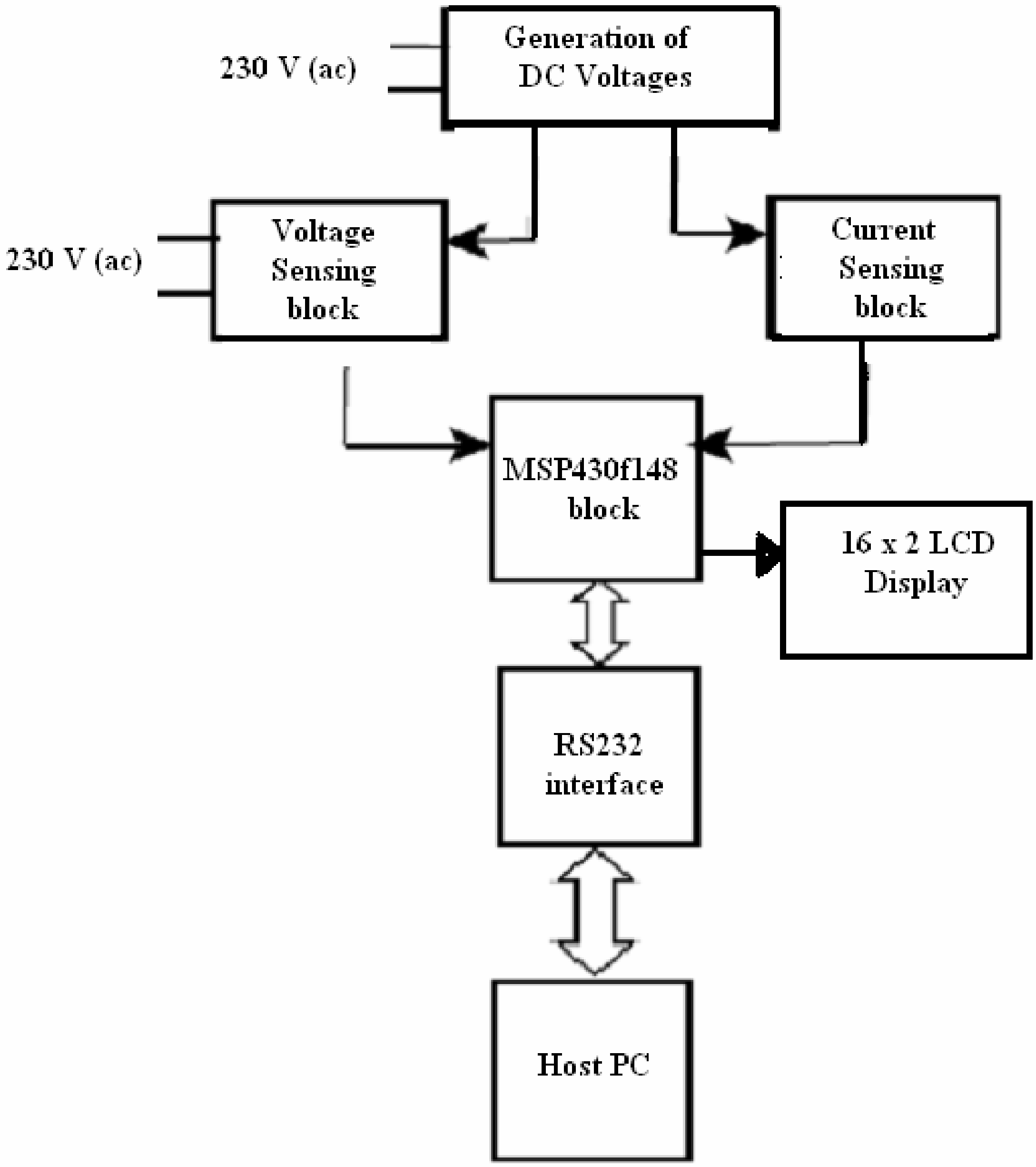
This Electrical Design Project involves monitoring of 3 phase current and voltage and then calculating the Power and rms values of voltage and current. The voltage is taken from the mains and is attenuated down to an AC value of 1.6 V, so that it can be passed to the Analog to Digital Converter of the MSP430f148 after level shifting it by a DC voltage of 1.6 V. This ensures that the ADC does not get a negative input and that the maximum instantaneous value does not exceed 3.3 V as the range for the analog signal given to the ADC lies between 0 V to 3.3 V. The current sensing is done using a Rogowski coil. Three such coils are used for the three phases. The Rogowski coil is essentially very similar to a toroid, where one gets an induced voltage at the terminals when a changing current (and hence changing flux) that is passed through the coil. This flux links with the coil and hence induces a voltage proportional to the derivative of flux with respect to time. This voltage being small (of the order of μV) is greatly amplified, flowed by a filter and integrator so that is less than 1.6 V AC. After DC shifting its value by 1.6 V, we can now pass this sample to the micro-controller through the ADC. Power calculations are performed and the result is displayed on a 16 x 2 LCD screen. We also include 2-way communication between the host PC and the MSP430 controller, through the RS232 interface.

2. Design

Below is the block diagram of the whole project. The basic modules are:

- Power module – Generation of DC voltages for the functioning of various IC's.
- Voltage sensing block – Consists of an amplifier stage and a level shift stage. There are 3 such blocks for the three phases. The voltage signals are then passed on to the ADC.
- Current sensing block – Consists of a Rogowski coil that converts the current to the voltage. This is passed to an amplifier stage, followed by a filter. An integrator converts the voltage back to the current preserving the phase of the current. Finally, a DC level shifter converts the voltage into a suitable range and is then passed to the ADC. There are three such blocks for the three phases.
- MSP430 block – Here 6 channels of the ADC are used. (3 for voltage and 3 for current). The converted digital samples are stored in memory and appropriate calculations are performed to get the power used, along with the rms values of the voltage and current. This data is then sent to a 16 x 2 LCD screen which

updates itself at regular time intervals. The MSP430 is interfaced to a computer which supports two way communication through the RS232 protocol. A switch on the board allows for change of the LCD display from displaying power and energy to displaying voltage and current.



3. Power Module:

Voltage Requirement:

- 12 V for the positive supply to the Operational Amplifiers and for the 5 V regulator
- -12 V for negative supply to the Operational Amplifiers
- 5 V for generating a DC value of 1.6 V employed in the level shifter stage. Also used to power the 16 x 2 LCD. The 3.3 V regulator also takes it input from the output of the 5 V regulator
- 3.3 V for MSP430F148 (micro-controller), MAX3243 (for interfacing with the computer)

Components and sub modules

- 9-0-9 Transformer that converts the 230 V AC mains down to 9 V rms
- Diode Bridge with capacitor - used for rectifying the AC voltage. The ripple is reduced by using a high value capacitor, and we get a constant DC value of 12.7 V at its output.
- Voltage Regulators: 7812, 7912, 7805, TPS 7333

Circuit Description

The only voltage source available to the module is the AC line voltage of any phase which is approximately 230 Volts. All DC voltages required for the functioning of the various chips should be generated from this supply. A DC of 12 V is required for the operation of the Operational Amplifiers. A 3.3 V supply is required for the MSP430 and MAX3243.

The 9-0-9 transformer followed by a diode bridge and capacitor gives a DC voltage of approximately 12.7 V. The reference voltage for the whole circuit is taken as the center tap of the transformer. The positive rectified voltage (with respect to ground) is given to the 7812 regulator. We can generate negative rectified voltage in the same way as we generate positive rectified voltage. (See the circuit Diagram). This is passed to the 7912 Regulator. The input to regulator 7805 is taken from the output of the 12 V regulator. Similarly, the input to the 3.3 V regulator is taken from the output of the 5 V regulator.
The detailed circuit diagram (schematic) is given below.

Circuit Diagram

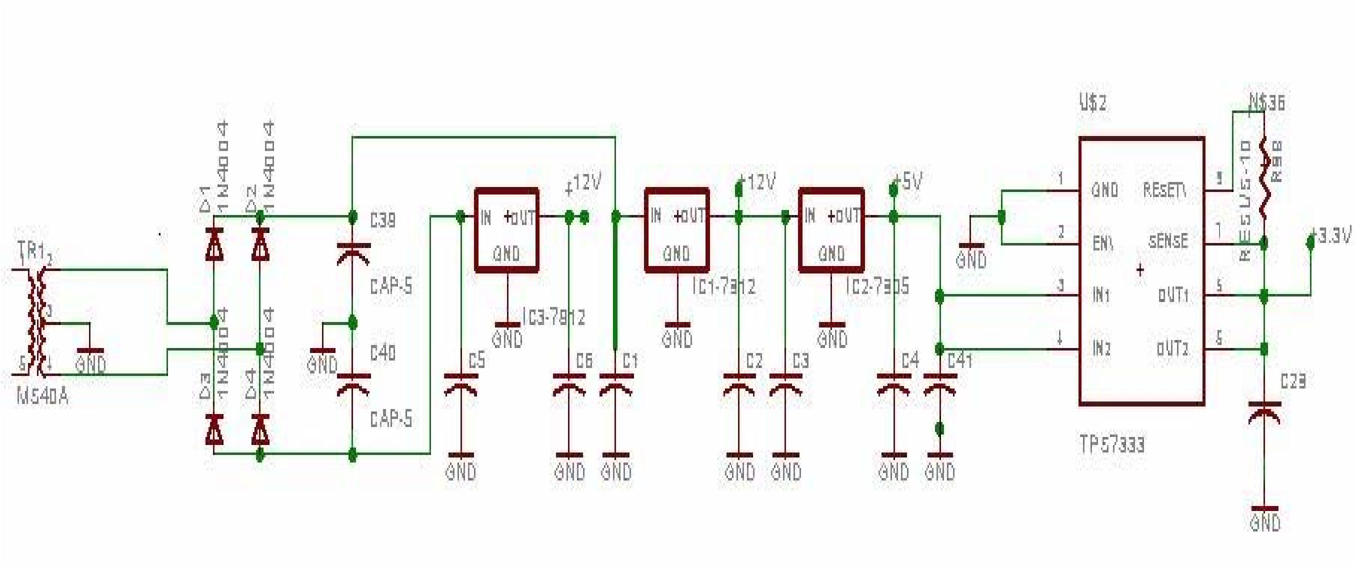


Fig. The power module

4. Voltage Sampling Circuit

Components and sub-modules

- TL072 – Operational Amplifier (low-noise)
- Differential amplifier
- DC Level shifter using an Adder Circuit

Circuit Description:

Since the ADC of the MSP430 can samples analog signals in the range of 0 V to 3.3 V, we have to reduce the input line voltage so that is lies in the desired range. Typically, the phase voltage is of the order of 230 V rms. Hence the peak voltage is approximately 325 V. Our design should be robust to fluctuations in the mains voltage. If we consider a deviation or fluctuation of 10%, the voltage will lie in the range of -360 V to +360 V (peak to peak). Hence the input voltage to the Operational Amplifier (TL072) which is operated in the differential mode is -360 V to +360 V. The voltage to the ADC should not exceed 3.3 V. Hence we scale down this mains voltage so that it gives an AC voltage varying between -1.6 V and +1.6 V. Thus the ratio of resistors R_2 and R_5 in the differential amplifier stage (see figure below) should be 360 / 1.6 = 225. To ensure that we get exactly this value of the attenuation constant, we use highly accurate metallic film resistors.

Since the voltage to the ADC cannot go negative, we have to shift the attenuated AC voltage by a DC value so that the resulting voltage sent to the ADC channel is unipolar. Therefore the differential amplifier stage is followed by an adder circuit. A DC shift of 1.6 V is given which leads to the output voltage in the range of 0 V to 3.2 V. In the adder stage, we take care not to alter the amplification ratio of the AC signal. The output voltage is $V_0 = A*V_{ac} + B*5$ V. Since we have unit gain for the AC signal, it follows that A = 1. As we need a level shift of 1.6 V, the value of B = 1.6 / 5 = 0.32. The resistors in the adder stage are selected appropriately to attain the above values of A and B.

Circuit Diagram

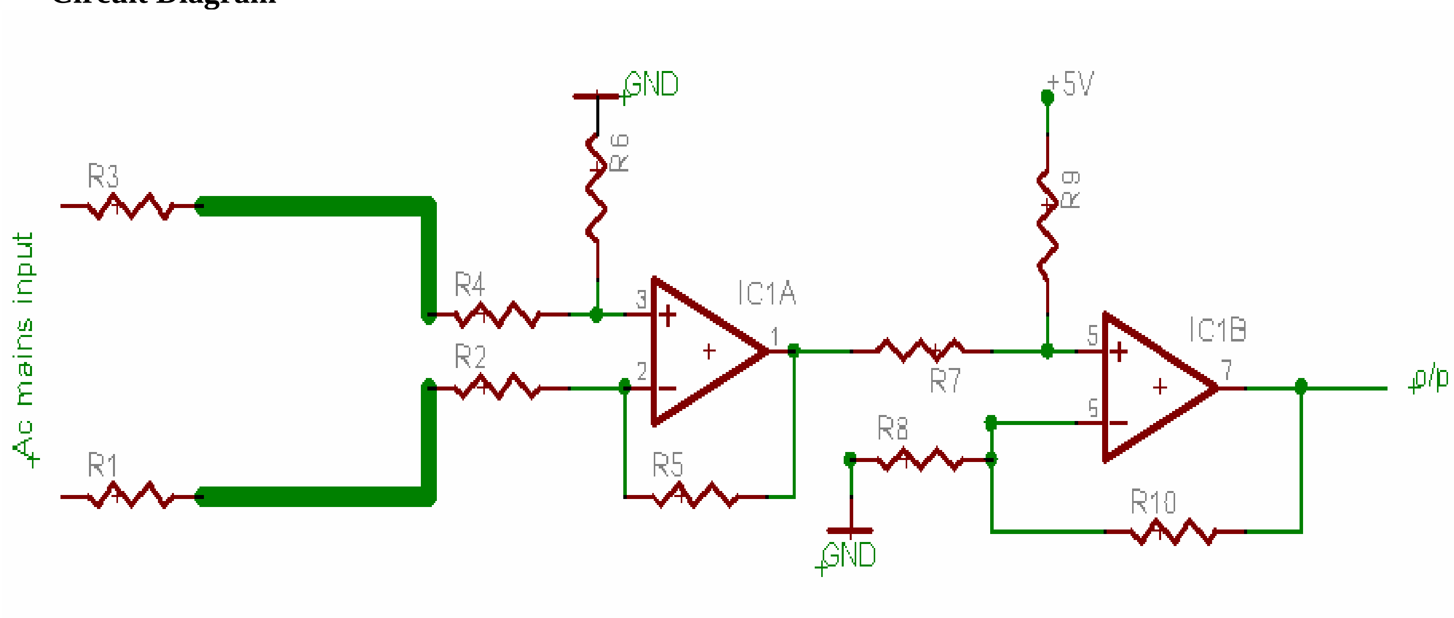


Fig. The voltage sensing module

5. Current Sampling Circuit

Components and sub-modules used

- Operation Amplifier- TL074
- Rogowski coil for converting current to voltage
- Inverting Amplifier stage followed by buffer for impedance matching
- Filter centered at 1 KHz (with minimal phase shift)
- Integrator with 90^0 phase shift

- DC Level shift using an adder circuit

Circuit Description

In order to sample the current, we first need to convert it into voltage. This is done using a Rogowski coil which essentially is a coil wound on the board, with the tracks alternating between the top and bottom layers. The voltage across the terminals of the coil is proportional to the derivative of the flux with respect to time. Using Amperes law, we get that the flux passing through the coil is proportional to R_1*log (R_2 / R_1), where R_1 and R_2 is the inner and outer radius of the coil respectively. In order to maximize the flux (and hence the voltage across the terminals of the coil), we differentiate the above expression with respect to R_1 and set it to 0. This gives us the condition for maximum voltage. We arrive at, $R_2 = e*R_1$. This gives the flux proportional to R_1. We select $R_1 = 0.5$ cm giving an inner diameter of 1 cm. The outer diameter is then calculated as 2.72 cm. A bigger coil gives us a better output voltage, but also increases the size of the board. Taking these two factors into consideration, we have chosen the inner diameter to be 1 cm. Also, since we need three such coils which are placed on the same board, care must be taken to ensure that the current in one coil does not induce a voltage in the other coil. This effect is minimized by placing the coils at vertices of an equilateral triangle. The output voltage of the coil is in μV. We therefore use very large amplification ratios of around 1000 so that the output lies in the range of -1.6 V to +1.6 V. This is achieved using cascaded stages of inverting amplifiers. Each amplifier is followed by a buffer for impedance matching.

During testing, it was observed that there exists a DC offset after the amplifier stage, possibly due to the input offset voltage of the Operation Amplifier. This is removed using a capacitor between the amplifier stage and the filter stage. The filter is centered around 1 KHz so that it removes high frequency noise content but allows for harmonics to pass through, so that they can be measured if required. The filter is designed as a second order filter. The filter output is given to the integrator which introduces a phase shift of 90^0. The integrator reproduces the current waveform without any phase shift. Thus essentially, we have converted the current waveform to an amplified voltage waveform without any phase shift.

A DC level shifter shifts the waveform by 1.6 V so that it can be given to the ADC channel. The circuit is designed to accurately measure current upto 12 A.

Circuit Diagram

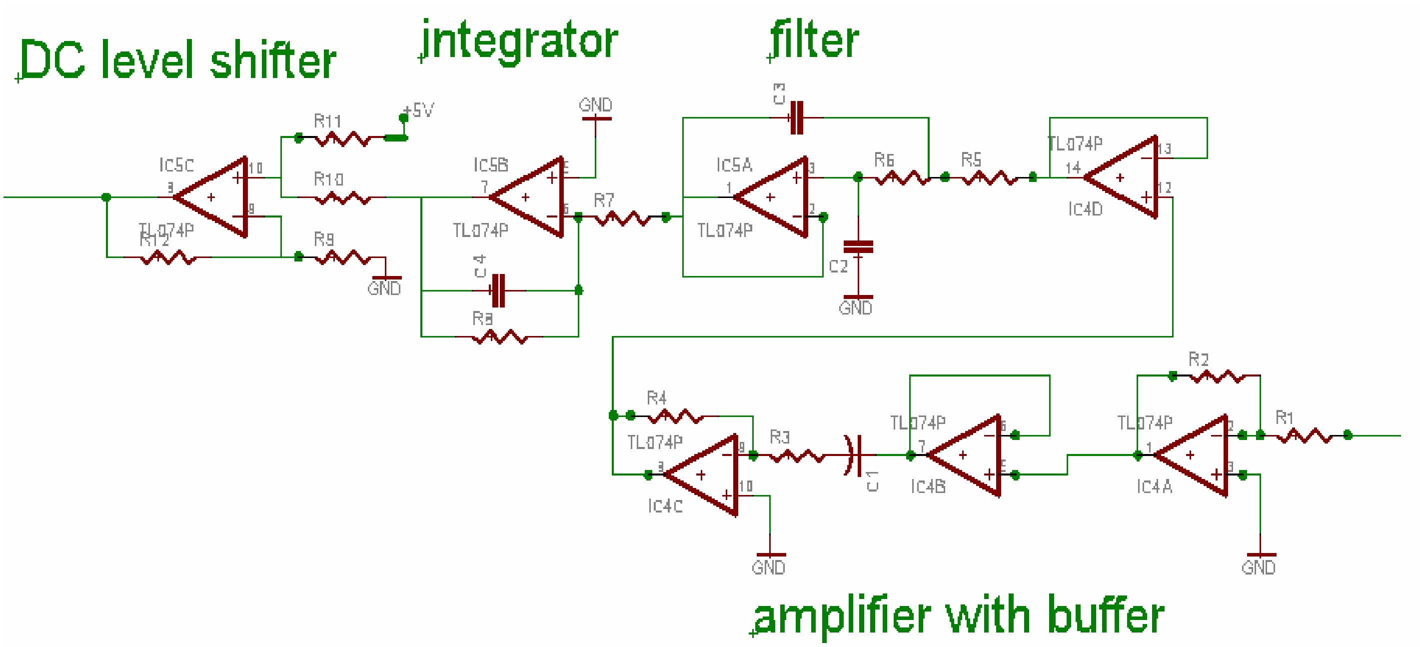


Fig. The current to voltage conversion circuit

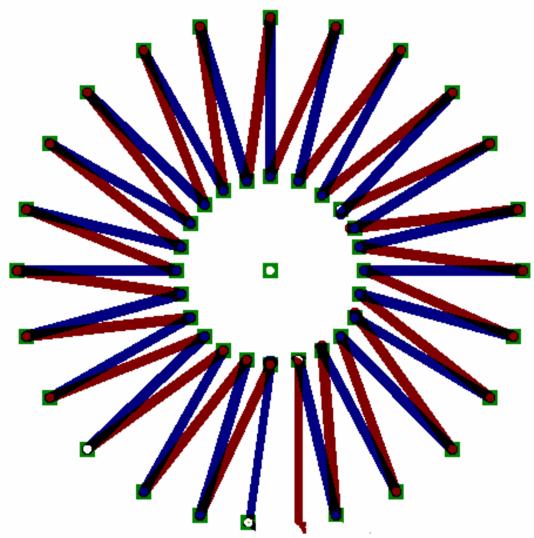


Fig. The Rogowski coil. Different colors indicate different layers on the board

Since we need to measure 3 phase current, the combined block of the current circuit and the Rogowski coil is present three times.

6. Waveform sampling and storage

The MSP430 is a low power micro-controller with an inbuilt ADC. There are 8 ADC channels which are multiplexed with port 6. The ADC will sample signals in the range of 0 to 3.3 V since the inbuilt reference voltage of the ADC has been selected to a maximum of 3.3 V. To sample the 50 Hz signals of current and voltage, we use 100 samples per period. This is done using timer A which is configured to run as a saw tooth generator with frequency of 5 KHz, and interrupting whenever the peak value is reached. This gives us a 200 µs interval between two samples, and allows us considerable time between two interrupts to perform the necessary calculations. The sampled current and voltages are multiplied giving instantaneous powers. These instantaneous powers are summed up over a period and then divided by 100 to give the power over one period. The average power over one second is then displayed on the LCD. The energy is updated every second by adding to it the average power over one second.

The RS232 interface provides a two way communication between the micro-controller and the host computer. The host machine can program the MSP430 and can also save the voltage and current plots after they are sampled. Testing was carried out on a single phase mains voltage of 230 V. The voltage has been converted to 1.6 V and then DC level shifted by 1.6 V. The values are represented in Q15 notations. The maximum hexadecimal value that the ADC will generate is 0x0fff, since it is a 12 bit ADC. The Q15 notation is the value normalized with respect to the maximum 16 bit value of 0xffff with 15 digits to the right of the decimal point. Thus 0xffff will have a Q15 notation of 1 while 0xfff will have a Q15 notation of 0.0625. When the samples were plotted, it showed a clear sinusoidal waveform.

7. PCB Layout

We have used two PCB's for our project. The first PCB contains the Power module along with the voltage sensing module. Also present is the MSP430 micro-controller and the RS232 interface. The LCD display is mounted on the side of the board. The tracks for the supply lines are made thicker to allow larger currents to flow with less resistance. The size of the PCB is approximately 5.3`` x 4``, the main reason being that we need three voltage blocks for the three phases.

The second board consists of the three Rogowski coils placed at the vertices of an equilateral triangle. This is done in order to reduce the effect of one current on another coil. The current circuit is placed in the remaining area. The supply voltages to the Operation Amplifiers and the output voltages of the current stage are connected to the first board through a connector. Due to the three Rogowski coils, the size of the board is quite large and measures 7.5`` x 4``.

8. Conclusion

Voltage and current waveforms are good indicators of the quality of electricity supplied by the utility services. Waveforms stored over a period of time can help us predict the health of an electrical system. Using this board, one can monitor the voltages, current, power and energy consumed by an electrical system and can take necessary actions to control it. We are able to samples currents upto around 12-15 A, using the Rogowski coil.

One can also convert the measurement system to the two wattmeter method by changing the gain of the differential amplifiers, and by making appropriate changes to the program loaded on the MSP430. We have left out additional slots for resistors incase parallel or series combinations are needed.

One way of improving the performance of the system is to reduce the effect of the current in one Rogowski coil on another coil.
Finally this board can also be used as a test board for MSP430 based applications, since we have two ports brought through connectors. Peripherals can be connected to these ports and can be tested. The system can be further enhanced by including LAN based support using TCP/IP. One can pass on the data of voltages, currents, power, energy to a web server, hence allowing monitoring of power from remote locations.

9. References

[1] D. A. Ward, J. L. T Exon, ``Using Rogowski coils for transient current``, *Engineering Science and Education Journal*, 1993.

[2] Texas Instruments, Design Resources: Code Examples [online] http://focus.ti.com/mcu/docs/generalcontent.tsp?familyId=342&templateId=5246&navigationId=11477&path=templatedata/cm/mcugen/data/msp430_desres_code

[3] Robert Bradley, (2001) Gnuplot interface in ANCI C: [online] http://ndevilla.free.fr/gnuplot/