Three Phase Watt-Hour Meter

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***Abstract*—This paper presents an electronic three phase watt-hour meter based on the MSP430F449 microcontroller. The developed system features a capacitive power supply obtained from the three phase network and circuits for signal conditioning to deal with the voltage and current signals. To protect the system from the grid's eventual power failures, a battery with a charging management system is included. The measured data is stored in a Flash memory and can be displayed through an LCD. Remote communication modules are implemented which allow infrared communication, serial port and optocouplers. The system's software implements the measurement of the voltage and current signals with a sample rate of 1 kS/s.**

Keywords: Watt-hour meter, Analog to Digital Converter (ADC), Operational Amplifier, Microcontroller.

I. INTRODUCTION

Traditional electromechanical meters measure energy based on the principle of magnetic induction. They consist of a motor whose torque is proportional to the power flowing through it. This motor's rotor is connected to a register that counts the number of revolutions, converts, stores and displays them as watthours [1]. In this way, electromechanical meters can only measure the consumed active energy.

One the other hand, electronic meters can measure active and reactive energy. By taking advantage of the technology available today, it is possible to create an accurate electronic meter with integrated flash memory, remote communication and advanced anti-tampering techniques, all of this at a relatively low production cost.

The purpose of the project presented in this paper is the development of a prototype for an electronic energy meter with a user interface, remote communication and the following requirements:

- Low Cost of production
- Maximum power consumption per phase of 2 W
- Compatibility with 50/60 Hz networks
- Protection angainst over-voltages of 2 kV
- Measurement of voltages up to 460 V_{ef}
- Measurement of currents up to 60 A
- Meet IEC standards for electricity meters [2] [3]

II. SYSTEM ARCHITECTURE

The system developed has for central processing unit a microcontroller with integrated ADC's. Surrounding this device, several modules were added to implement the desired system requirements. The complete system architecture is represented in Figure 1.

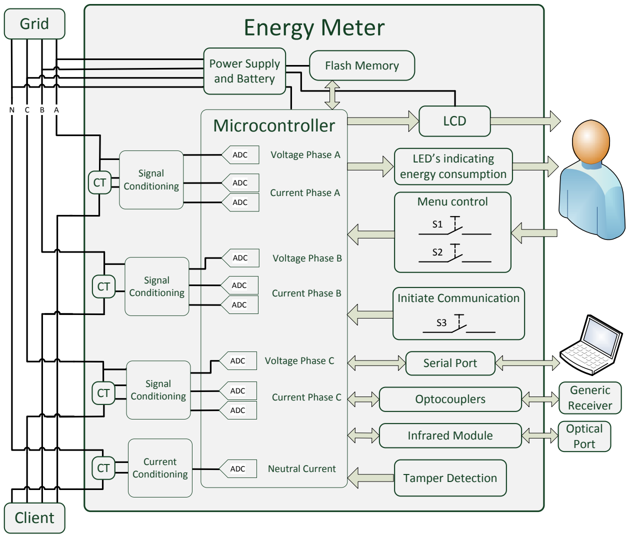

Fig. 1. System Architecture.

A. Power Supply

A watt-hour meter requires a power supply provided from the three phase network itself. The amount of power the meter can request is limited to the values imposed by regular standards [2] [3], in the case of the meter developed the maximum power consumption from the grid is 2 W per phase.

Taking into account the requirements of the meter, two existing topologies for power supplies were considered. The first was based on transformers. While this kind of supply guarantees a galvanic isolation between the meter and the grid, it is more expensive when compared to other alternatives. Also, the meter should request the same power from each phase, this implies that three transformers would be needed which increases the cost of the power supply.

The other supply topology considered was the capacitor based power supply [4]. Its sole considerable disadvantage is the lack of isolation from the grid. This topology is much cheaper than the previous one and can be used to request power from each of the phases equally. The circuit used for the power supply [5] is shown in Figure 2.

The determination of the component values of the power supply depends on the requirements of the hardware to be powered. The inductors are ferrite beads used to remove some of the electromagnetic interference caused by the three phase grid. Varistors are added between each phase and the neutral. And their purpose is to protect the power supply and the whole meter from over-voltages in the network. The capacitors C_{in} and C_{out} will determine the startup delay of the supply and

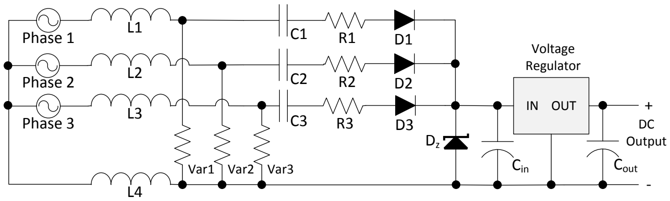

Fig. 2. Capacitor power supply.

the time it remains operational upon a power failure. At the startup, the largest C$_{in}$ is, the longest it will take for the supply to be fully operational. On the other hand, the value of C$_{out}$ will determine the time the supply will remain active once the power goes down, but since the system is conceived to integrate a battery, this capacitor is not so important.

B. Microcontroller

The key component in the development of the meter is the microcontroller. This device will be the central processing unit of the system and it integrates the Analog to Digital Converters required for energy measurement. In Table I three microcontrollers are presented, any of these is a viable option for the development of the meter.

The integrated circuit from Analog Devices [6] does not include a CPU and since its price is almost the same as the alternatives, this is a huge disadvantage. If this device is chosen, extra hardware must be inserted to meet the system requirements, thus increasing the complexity of the circuitry and the price of the meter.

TABLE I
COMPARISON BETWEEN MICROCONTROLLERS.

	Maxim	**Analog Devices**	**Texas Instruments**
Module	71M6513H	ADE7854	MSP430F4XX
Price[1] [€]	4.25	4.4	from 2.80 to 4.20
ADC	22 bit ΣΔ	24 bit ΣΔ	12 bit SAR
LSB [μV]	806	0.8	0.2
SRAM [Kb]	7	N/A	1 a 2
Flash [Kb]	64	N/A	16 a 60
Sample Rate [kHz]	2.5	8	2[2]
CPU	80515 MPU	N/A	16-bit RISC
RTC	Yes	No	No
SPI	No	No	Yes
I^{2}C	Yes	No	No

The microncontrollers from Maxim [7] and Texas Instruments [8] are equivalent to each other. They both have similar Flash Memory and RAM capacity, which is important given the complex implementation of the software to process all the voltage and current signals. When comparing the CPU architecture of these two microcontrollers, the 16-bit RISC stands above in performance and reliability. Another important aspect is the resolution of the ADC's included in each device, for this analysis it is important to consider the ENOB of the ADC's. This parameter determines the number of effective bits for the samples the conversions originate, and typically for the amplitude of the signals being measured most of the least significant bits will be nothing but noise, making the resolution of the microcontroller of Maxim drop significantly. For the reasons described, it is concluded that the device more adequate for the development of the meter is the MSP430 [9].

The supply of the device is 3.3 V, leading to a V$_{cc}$ of 3.3 V and a V$_{ss}$ of 0 V. These limits are also the dynamic range of the ADC's, and since the voltage and current signals assume negative values, a bias voltage must be added in the signal conditioning stages. The power supply is dimensioned for 3.3 V, and all the remaining components are chosen to be compatible with this value thus simplifying the hardware.

C. Voltage Signals Conditioning

In order to measure the voltage and current signals, these must be reduced until they are compatible with the range supported by the system. For this, voltage and current sensors are used, so a few different types are considered.

From the voltage sensors viable to the present project, two are considered, a voltage transformer and a voltage divider. The transformer guarantees a good accuracy in the voltage measurements, but is an expensive component when compared to a voltage divider. Since the voltage levels are mostly invariant in the three phase grid, a voltage divider can be used maintaining a good precision.

Based on this analisys, the type of sensor chosen for the conditioning of the voltage signals is the voltage divider. A circuit is dimensioned to meet the requirements of the meter, shown in Figure 3.

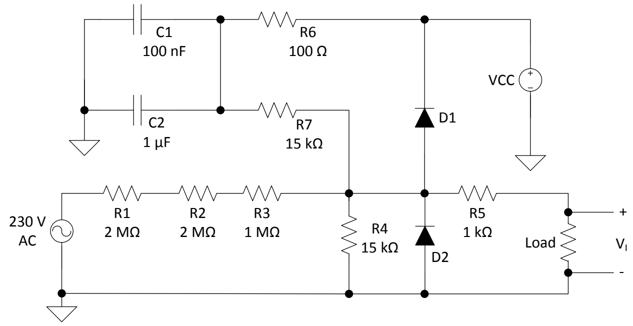

Fig. 3. Voltage conditioning circuit.

The voltage signals to be conditioned assume a maximum value of 460 V$_{RMS}$, so the circuit is dimensioned to reduce this signal into an equivalent with a minimum value of 0 V and a maximum of 3.3 V. A bias voltage is also needed because the ADC's are single ended, and it should be approximately half the range mentioned. For the bias voltage the supply voltage V$_{cc}$ is used and reduced into the desired value. Resistors R1, R2, R3 and R4 perform the voltage divider of the AC signal,

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[1] Prices relative to thousands of units (August 2012).

[2] The sample rate depends on the signal conditioning circuits among other factors.

while resistors R6, R7 and R4 reduce V$_{cc}$ into half of its value. With the configuration described, the signal V$_i$ is compatible with the ADC and fulfills the requirement for the measurement of voltages in the grid up to 460 V$_{RMS}$.

D. Current Signals Conditioning

The current signals require a much more accurate sensor than the voltage, because the current goes from values close to zero to 60 A. In order to maintain a good accuracy of the current measurement in its complete range, four sensors are considered. Their main characteristics are described in Table II.

TABLE II
TYPES OF CURRENT SENSORS [10].

Sensor	**Shunt Resistor**	**Current Transformer**	**Rogowski Coil**	**Hall Effect Sensor**
Price	Very Low	Medium	Low	High
Linearity	Good	Medium	Good	Bad
High Current Measurements	Bad	Good	Good	Good
Consumption	High	Low	Low	Medium
Current Saturation	No	Yes	No	Yes
Temperature Sensitivity	Medium	Low	Very Low	High
Problem with DC offset	Yes	No	No	Yes
Saturation and Hysteresis	No	Yes	No	Yes
Isolation	No	Yes	Yes	Yes

The shunt resistor method is employed adding a resistor of small value in series with the load. By measuring the voltage across this resistor it is possible to estimate the current. This type of sensor, while being the cheapest of all, has a very low accuracy, high consumption and no isolation from the grid. The Rogowski Coil is an inductor that senses magnetic fields, originating at its terminals a voltage output proportional to the magnetic field. The biggest disadvantage of this type of sensor is that the coil is influenced by external fields. The Hall Effect Sensor is a transducer that varies its output voltage according to a magnetic field, making it vulnerable to noise. It has low linearity and is a high cost solution.

Lastly, the current transformer, while being an expensive device, guarantees a good accuracy across a large range of currents and guarantees a galvanic isolation between the meter and the grid. Given the characteristics of the sensors it is concluded that the most appropriate sensor is the current transformer [11]. Taking into account the transformer specifications, a circuit for the conditioning of the current signals is dimentioned, represented in Figure 4.

The current measurements are of extreme importance in any meter. To achieve the best accuracy possible for these measurements two amplification stages are implemented.

The ADC's can only measure voltage, so the current signal at the output of the current transformer must be converted into an equivalent voltage signal using a shunt resistor. This depends on the specifications of the transformer [11]. For the one used, R4 and C6 are defined in the specification sheet.

To generate a bias voltage and add it to the signals, a circuit is designed and dimensioned, represented in the upper part of Figure 4. Once again the bias voltage is obtained from the supply voltage V$_{cc}$ but now the desired DC signal is not half of the range, because the OPAMP's are also supplied by V$_{cc}$ and they saturate at a voltage of approximately $V_{cc} - 1.1\ V = 2.2\ V^1$. So in this case the voltage divider should have an output of $V_{Bias} = V_{cc}/3 = 1.1\ V$, which will fit the DC of the conditioned signal into half of the dynamic range available.

From Figure 4, the bias voltage is obtained by dimensioning resistors R1, R2 and R3 using

$$V_{Bias} = \frac{R3}{R1 + R2 + R3} V_{cc}. \qquad (1)$$

The capacitors C1, C2 and C3 are dimensioned to create a low pass filter together with the resistors. The purpose of the filter is to supress the interferences that come from the three phase network and are present in the supply voltage. The low pass filter is dimensioned to have a cutoff frequency below 50 Hz (so supress the fundamental frequency and its harmonics). The gain of the filter is given by

$$\frac{V_o(s)}{V_i(s)} = \frac{R3}{(1 + sR1C1)[R2 + R3 + s(C2 + C3)R2R3]} \qquad (2)$$

when V_o is the output of the filter and V_i is the input.

A unity gain buffer is inserted to isolate the current conditioning circuit from the remaining circuitry. This way, it is possible to use the Bias Voltage circuit to provide the offset of all the current signals from the three phases.

To implement the current amplification stages, two operational amplifiers are used in inverting amplifier configurations. The output signals of each stage are called V$_{low}$ and V$_{high}$. Given the configuration of the circuit in Figure 4, V$_{low}$ is given by

$$V_{low} = \left(1 + \frac{R7}{R6}\right) V_T, \qquad (3)$$

while V$_{high}$ is given by

$$V_{high} = -\frac{R9}{R8} V_{low}. \qquad (4)$$

V$_{high}$ is intended to be much greater than V$_{low}$ and so it is configured to be 16 times bigger. This in theory will guarantee an added accuracy of 3 bits for the measurement of small current signals. The microcontroller will use samples from V$_{high}$ whenever this signal is not satturated, otherwise the samples used are from V$_{low}$.

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[1] The saturation of the Operational Amplifiers was determined using the simulation tool PSpice and later confirmed with measurements.

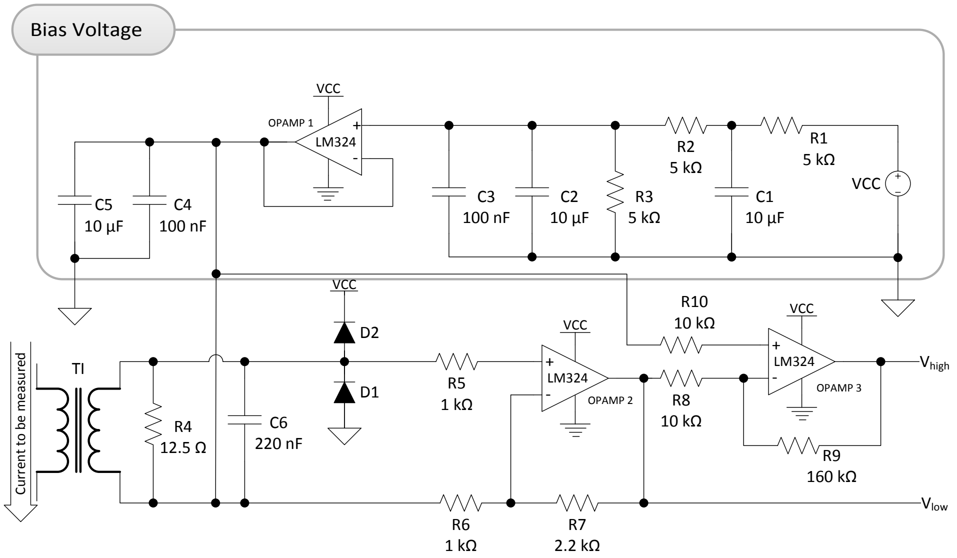

Fig. 4. Current conditioning circuit.

E. Memory Organization

The measured values of the meter are stored until they can be retrieved by an agent of the energy providing company. In this project standard parameters are stored:

- Active Energy (consumed and provided)
- Reactive Energy (consumed and provided)
- Apparent Energy
- Peak Value (of the consumed active energy)
- Energy by Quadrant (for each of the 4 Quadrants)

These values are stored in three different types of registers. One that is periodic and contains the data of 15 minutes. The second register is relative to the measured data of a month, and the last one that contains the history of the meter with the total accumulated values. The periodic registers should be maintained in memory for at least a year, which leads to the use of a flash memory of 32 MBit [12].

All registers, except for the history, require a time stamp to determine the period of time they represent. The type of stamp used is an absolute time UTC, which is the elapsed time in seconds since the Epoch (January 1^{st}, 1970) and is represented in a 32-bit unsigned integer. To obtain the UTC value there are libraries with the routines of conversion present in any compiler for the microcontroller used.

An advantage of the periodicity of the registers is a status entry that is added to the periodic register. The purpose of this entry is to record any detected failure or exceptional situation in the meter, thus allowing the easy detection of a possible meter malfunction. The status entry used is described in Table III.

To guarantee the correct operation of the flash memory, a CRC (Cyclic Redundancy Check) is included in the registers. The goal is to test each flash read and write for inconsistencies, recording any failures in the event of a malfunction. The type of CRC used is an 8-bit DOW [13].

TABLE III
STATUS ENTRY OF THE REGISTERS.

Bit	Functionality
1	Power Failure
2	Time Synchronization
3	Tampering: The meter was opened
4	Tampering: Electromagnetic interference
5	Watchdog Timer has been executed
6	Error in a Flash Read
7	Error in a Flash Write
8 to 16	Available for future versions

If a power failure occurs, the energy measurement is stopped. Once the power is restored the measurement resumes. The values are written to memory when the next 15 minute interval is reached, maintaining the correct alignment of the registers. In this register the status entry is flagged with the power failure bit.

F. Battery Charging System

The meter relies upon the energy provided from the grid to maintain its functionalities. Since the power might fail, in the developed meter a battery is included with a controlled charging system to keep the microcontroller running when the power is down. The block diagram of the power supply with the battery and its control system is shown in Figure 5.

The power supply voltage is constantly monitored using a voltage comparator available in the microcontroller. The purpose of this is to detect with short notice a power failure and shut down all peripherals so that the power request from the battery is the minimum possible. The time that the power supply maintains the full output voltage before failing is a few hundreds of milliseconds. This is plenty of time for the microcontroller to shut down all peripherals, disable the measurements and go into a low power mode. In this condition the consumption of the meter is very low, so the battery lasts for days. When the power comes back up, the microcontroller

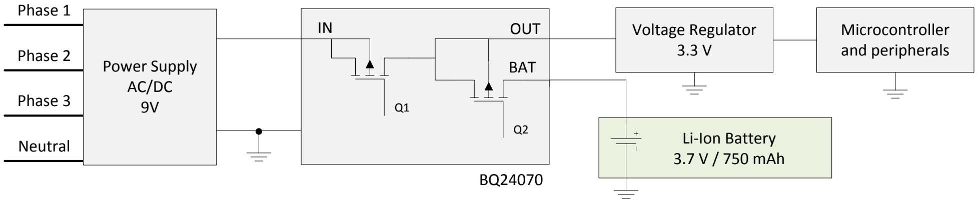

Fig. 5. Power Supply with Battery and a charging control system.

resumes normal operation and the battery control system proceeds with its recharging.

The battery charging system is implemented using a Li-Ion battery charging IC [14]. This device features various charging modes depending on its configuration. In the application of the energy meter, the battery will only be used once there is a power failure, which usually lasts for a few hours at most. Once the power comes back up, the charging of the battery takes place and is done with relatively low currents to request the minimum from the power supply and to not interfere with the meter.

G. Remote Communication

In order to allow the meter to be able to communicate with external elements, three types of remote communication are implemented: RS-232 using a serial port of 9 terminals, infrared through an emitter/receiver pair, and optocouplers. These three modules were implemented in hardware, whereas in software only the serial port was fully developed.

The working voltages of the RS-232 protocol are ±5 V, while the supply voltage of the meter is 3.3 V. In order to implement the serial port communication in the system, a driver is required. For this purpose the IC MAX3232 [15] from Texas Instruments is used.

By using one of the USART modules available in the microcontroller, the RS-232 protocol is implemented at 9600 baud. The communication is used for calibration and to obtain the registered values stored in memory.

H. Anti-Tamper methods

Nowadays, energy theft has become a worldwide problem. Consumers try to manipulate the meters, making them stop or register values lower than the real ones, successfully consuming energy without paying for it. In the developed meter, two types of anti-tamper methods were implemented. A switch is included in the system for tamper detection and once the meter is sealed, it is pressed down and remains that way until the meter is improperly opened. If this happens, the microcontroller will be notified and it registers this in the flash memory as an attempt to tamper with the meter.

The other anti-tamper method implemented is the detection of strong magnetic fields. It used to be common for consumers to use strong magnets to mess with the meters, affecting the correct operation of the current transformers. The system features a Hall Effect sensor close to the current transformers. If a strong magnetic field is detected, the microcontroller is notified and the attempt is registered.

III. ALGORITHMS

The algorithms for an energy meter involve the processing of the signal samples and several calculations to obtain the RMS values of the voltage and current signals, power factor and frequency. For the microcontroller used there is a library containing routines for most of the these calculations, optimized for better performance [16]. Some of them are used to implement the functionalities of the meter.

A. Background Process

The sampling of the several signals to be measured is a critical procedure that must be attended with high priority. Figure 6 presents the flowchart of the process that deals with the sampling of the signals, known as Background Process.

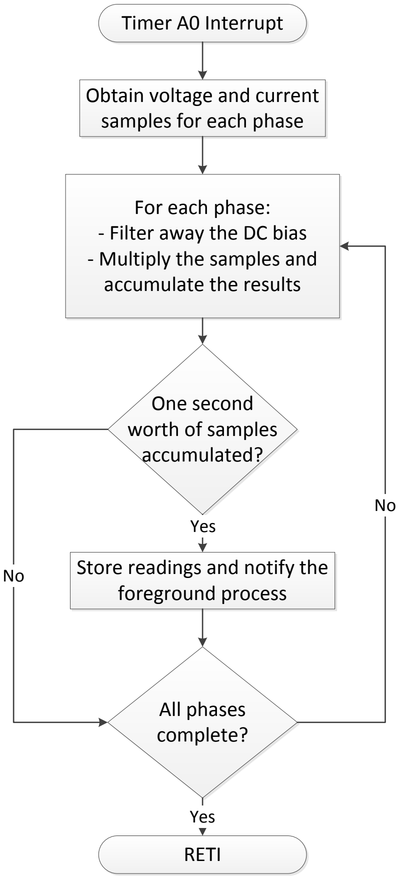

Fig. 6. Flowchart of the Background Process.

The Background process is an interrupt service routine sourced by a Timer. It runs shortly after the sampling of all the channels is completed and for each phase this routine filters the DC bias, chooses which current amplification level to use, multiplies the samples and accumulates the results. Once a second worth of samples has been accumulated, the Background Process notifies the Foreground Process.

B. *Foreground Process*

The main algorithm of the meter is the Foreground Process. This is the routine that handles most of the signal processing and the lower priority activities such as menu browsing and writtings to the Flash memory. The Flowchart of the Foreground Process is represented in Figure 7.

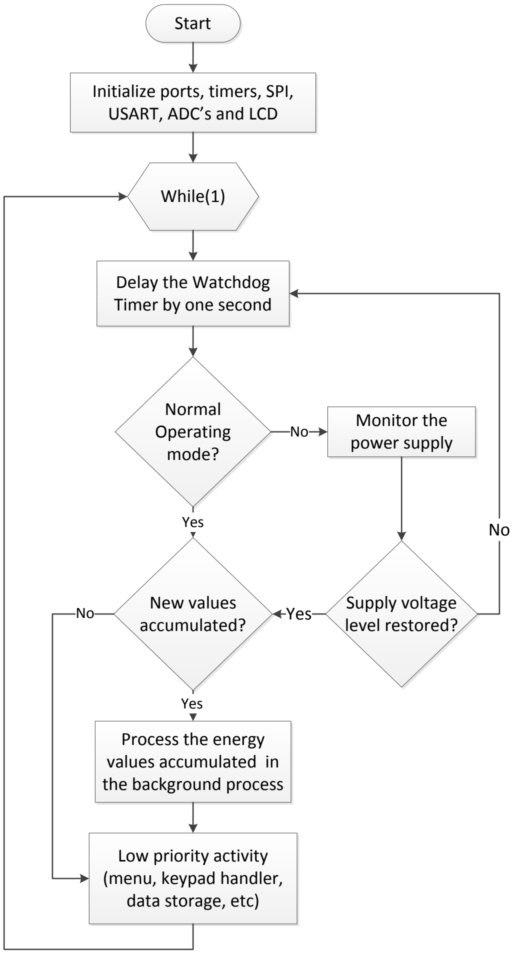

Fig. 7. Flowchart of the Foreground Process.

C. *Real Time Clock*

An energy meter needs to be aware of the date and time its readings refer to. The microcontroller used allows the implementation of an accurate RTC using a quartz crystal of 32.768 kHz. The only disadvantage of this type of clock is that the meter cannot be shut down, but since it features a battery, this is not a problem. The RTC is implemented using a Basic Timer of the microcontroller configured to run every second.

IV. RESULTS

A. *Power Supply*

The Power Supply should have a startup delay as small as possible. If the power goes down and the meter keeps operating from the battery, the energy measurement is halted. So, once the power comes back up the meter needs to resume normal operation as fast as possible. The startup of the supply was tested and the results are shown in Figure 8.

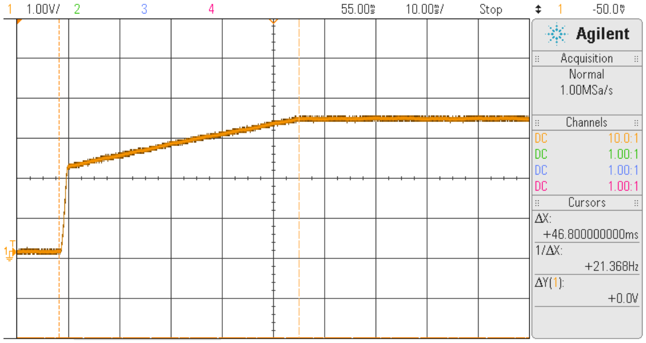

Fig. 8. Power Supply Startup.

The signal monitored in the graph of Figure 8 is V_{cc} (output of the voltage regulator). It is possible to observe that the startup delay is of 46.8 ms, which is perfectly reasonable with the set of requirements of the meter.

Another result to take into account is the time the supply maintains operation once a power failure occurs. In Figure 9 the result of this test is shown.

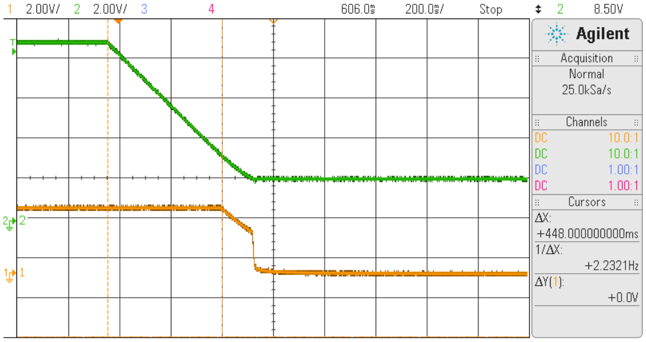

Fig. 9. Response of the Power Supply to a power failure.

The orange signal is V_{cc}, and the green signal is V_{supply} (input voltage of the regulator). The time that goes from the power failing to V_{cc} start dropping is of 448 ms, which is a very long time. The microcontroller monitors V_{supply} and once it drops under a defined voltage level it is considered that a power failure has occured. In this way it is possible for the system to be aware of the power supply going down with roughly 448 ms of notice.

The Supply was also tested for its maximum current output, the result was 82.5 mA.

B. *Voltage conditioning*

The voltage signals to be conditioned have a range from 0 to 460 V_{RMS}. The conditioning circuits were dimensioned accordingly. With the meter connected to the three-phase grid, the output of the voltage circuits was measured. The results are shown in Figure 10.

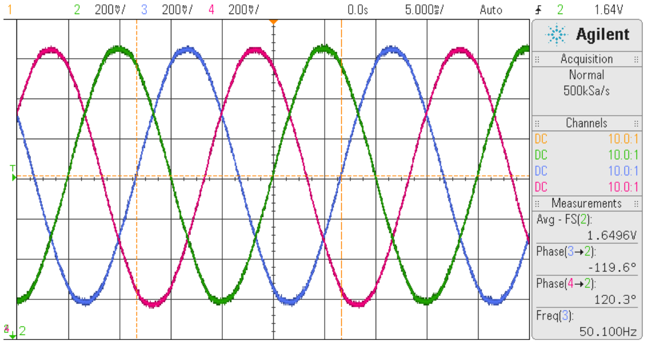

Fig. 10. Conditioned Voltage Signals from each phase.

The amplitude of the sinals is 600 mV and their offset is 1.65 V, this matches the expected operation of the voltage sensors.

C. Current conditioning

The current conditioning circuits have two amplification stages. Their purpose is to increase the resolution of the measurements for low currents. In order to test both amplification stage, two different tests are applied. The first one consists of connecting an incandescent light bulb of 40 W to one of the phases. The results can be observed in Figure 11.

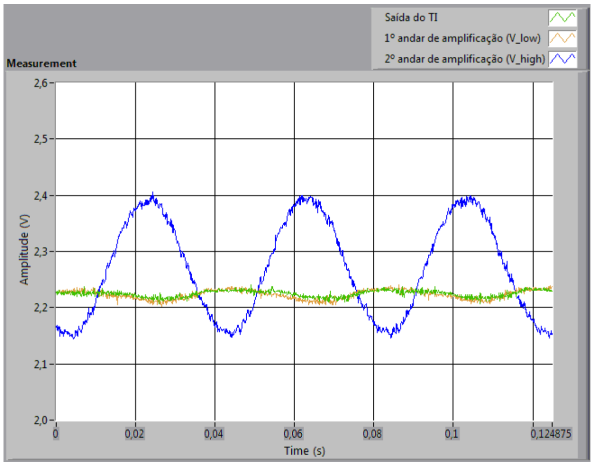

Fig. 11. Current amplification stages for a low current.

The current to be measured has an amplitude of about 200 mA, so the proportional voltage signals have a very low amplitude. In this test we can verify the successful employment of the second amplification stage, V$_{high}$. If the signal was measured using V$_{low}$ the measurement would contain more noise, thus leading to a less accurate reading.

The second test to be applied to the current conditioning circuits consists of connecting a 1800 W device to one of the phases. The results of this test are presented in Figure 12.

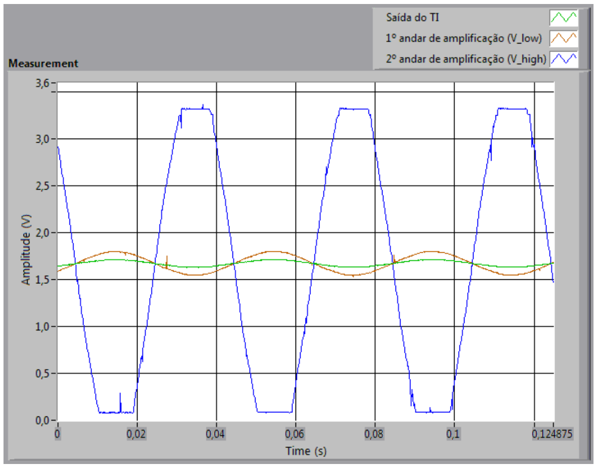

Fig. 12. Current amplification stages for a high current.

In this case the current is high enough to saturate V$_{high}$. The microcontroller is aware of the saturation levels and uses the samples from V$_{low}$ whenever V$_{high}$ is saturated.

D. Consumption of the meter

It is important for any meter to consume as low power as possible. An analisys was performed in the consumption of the different elements of the system. The results are presented in Table IV.

TABLE IV
CONSUMPTION OF THE METER.

Modules operating	Consumption (mA)
Everything OFF	5,2
LCD	9,3
LCD and LED 1	10,7
LCD, LED 1 and 2	12,2
LCD, LED 1, 2 and 3	15,5
LCD, LED’s and infrared emitter	22,8
LCD, LED’s, infrared emitter and receiver	29,6
LCD, LED’s, infrared and optocouplers	34
LCD, LED’s, infrared, optocouplers and RS-232	35,2

It is concluded that the maximum consumption of the meter is of 35 mA, however this limit is not reached because not all the modules can be operating at the same time. Another characteristic of the system to take into account is the charging of the battery. The charging current was dimentioned to 11 mA through the circuitry of the charging IC [14]. The battery should rarely be required and is used for short periods of time, so its charging can be slow.

Three types of LED’s are used and their power consumption is different. The purpose of the LED’s is to blink everytime a defined amount of energy has been consumed. They are the first element to take into account when evaluating the performance of the meter.

E. Calibration

Calibration is key to the performance of any meter. Before being calibrated, meters present a lower accuracy due to silicon-silicon differences and component tolerances, therefore all meters must go through the calibration process before being installed.

For the calibration to be performed correctly, an accurate source should be used. This source must be able to generate any desired voltage and current, as well as phase shifts between them. In addition to the source, a reference meter can be used to act as an arbitrator between the source and the meter being calibrated.

In order to perform the calibration of the meter an application from ”MSP430 Energy Library” [16] is used. The interface between the meter and the calibrator is achieved using the serial port. This calibrator allows the visualization of the live measurements and can be used to change the scaling factors of the meter. By using an accurate source together with the calibrator, the prescicion class wanted can be reached.

V. CONCLUSIONS

Electronic watt-hour meters ease the process of energy measurement. In these meters it is possible to implement in an efficient and economic way a set of functionalities that bring advantages both to consumers and energy providers.

The developed system features an RTC which allows it to control the different measurement periods and store the data for each of them in an external flash memory. The interface with the consumer is done using an LCD controlled by two switches. These are used to browse though a menu where the different measurement values can be visualized. To prevent the system from going down in the event of a power failure, a battery with a controlled charge system is included.

The system is capable of communicating with external elements through a serial port, an infrared emitter/receiver pair and optocouplers. These three modules were implemented in hardware whereas in software only the serial port was developed due to the unavailability of test modules for the other two.

The meter is autonomous and distinguishes between hourly rates. It can also detect two types of tampering, unauthorized opening of the meter and the presence of strong magnetic fields that could influence the current transformers.

For future improvements, a few suggestions of modifications to the system are presented. The operational amplifiers used saturate at a voltage level of 2.2 V which limits the resolution of the current measurements. The ideal amplifiers would saturate in their supply voltage.

The microcontroller chosen for the meter operates at a maximum frequency of 8 MHz. Given the large amount of instructions it has to perform for each sample of the 9 signals and the other activities, the sampling frequency is limited at 1 kHz. This is a disadvantage for the phase compensations the system must perform between the current and voltage signals. A possible solution is to replace the microcontroller with another one of the MSP430 family that operates at a higher frequency. For example, the MSP430F5438A has all the required modules at the cost of increasing the consumption of the system in about 6 mA. Another approach to the sample frequency problem is to implement in the software a FIR filter to compensate the phase shifts.

Finally, an application can be created to smoth the exchange of information between the meter and external elements. By taking advantage of the communication modules already available for the serial port, the application can be developed to obtain measurement values or other system parameters, thus making it possible to modify these without having to perform a firmware update.

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