

## REAL-TIME SMART METERS NETWORK FOR ENERGY MANAGEMENT

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**Abstract:** In this paper, an architecture of a low-cost ARM-based Smart Metering network is presented. The system is designed to be suitable for Smart Grids applications aimed to a more efficient energy use according to the article 13 of Directive 2006/32/EC. The network is composed by several slave smart meters that continuously monitor loads and energy generator to make available information in real-time such as power and energy consumption/generation and several power quality parameters to specific master device called data aggregator via CAN bus. This device integrating the information coming from slave smart meters and information regarding co-generator status, the forecast renewable source availability and, through a web service access, current energy prices can take decisions to suitable energy management cost strategy. So the user can remotely control their consumption using the web browser (Client), and locally thanks to the display of the data aggregator. To prevent external attacks a low computational burden software protection based on Message Authentication Code (MAC) has been implemented. Finally, characterization test of realized apparatus have shown good performances both in terms of communication errors and measurement uncertainty.

**Keywords:** Smart Metering, Smart Grid, Power Meter, CAN Protocol, Real-time

### 1. INTRODUCTION

The traditional electricity distribution network has been designed essentially as a passive network that carries the energy one way: from a few power stations to the end users consumption points. The increased cost of energy production and the growing up of its demand require different management system, based on real-time measurements, which make more efficient its use. We are moving to an upgraded electricity network to which two-way digital communication between supplier and consumer, intelligent metering and monitoring systems have been added. These are known as Smart Grids paradigm. The Smart Metering is an integral part of a Smart Grids. Basically, it consists of electricity meters that records consumption of electric energy and communicates this information to the grid operator and energy supplier for monitoring and billing purposes [1].

The implementation of smart metering is the first step towards the creation of a "smart grid" electricity network that can intelligently integrate the actions of all logged users: generators, consumers and prosumers (those who perform the dual role simultaneously), in order to offer efficiency with a sustainable supply of electricity, cheapness and safety. Smart metering has the prerequisites to make available real-time consumption related to the various utilities, both the users and the operators of energy networks. Then new generation meters that should be able to transmit this information remotely are required. The ability of a system to exchange information or services, or any part of them, with other suppliers, also not homogeneous, can be implemented on the basis of a set of open standards. The most important initiative in this field is the Open Meter project. The main aim of the Open Meter project is to specify a set of open standards for AMI to support smart meters for electricity, gas, water and heat. The project's aim is to bridge the knowledge gap for the adoption of open standards for smart multi-metering equipment and all prescriptive aspects, smart metering functions; the communication protocols and data formats are also considered part of the project.

In a metering network smart meters are implemented with embedded microcontrollers designed for a specific application and capable of running stand alone. The microcontrollers contain communication front-end that are capable of interfacing one to each other and then they are able to exchange information within a network [2].

In paper is proposed a multi-meter device for smart grids applications capable to manage the energy consumption and to communicate in real-time with decentralized control unit by means of a modified CAN protocol. The smart energy meter network is projected with the aim to obtain a low-cost equipment for a sustainable use of electrical energy.

In the paper after a brief description of the architecture, and of the main blocks of implemented device, the choice of the protocol for the communication between the various meters will be discussed in detail and some experimental tests for data transmission characterization are reported. Several experiments will be conducted to demonstrate the accuracy of the meter and reliability of the protocol.

## 2. SMART METERING NETWORK ARCHITECTURE

In Figure 1, the simplified scheme of the proposed smart meter network is shown [3]. From a functional point of view, it consists of the following blocks: i) a metering unit that tracks the customer's utility usage and processes the billing, ii) a communication unit that enables two way digital communication with the utility company iii) a switching unit

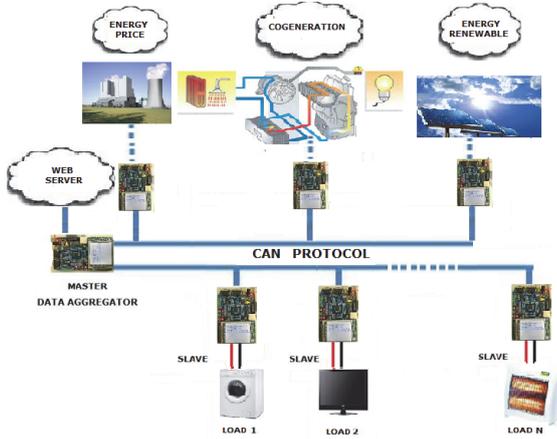


Fig. 1 Architecture of the proposed Smart Metering network

that starts and shut down the utility supply.

From a physical point of view, each equipment consists of: i) a transduction section composed by voltage and current sensors and adapters level ii) a microcontroller that acquires the output of the sensors and processes the acquired samples iii) a display for several information iv) a memory section which stores for the billing value in EEPROM[4].

The transduction and conditioning section consists of electronic current and voltage transducer with insulated output which exhibits good accuracy and bandwidth. It is composed of simple electric and electronic components its low production cost and its features make it attractive for large scale utilization [5].

The hardware implementation is built around a STM32F107VCT6 microcontroller which its specific features are: the synchronous acquisition of two ADC channels, high data processing performance, the low power consumption, the availability of dedicated communication interfaces and the low cost [6].

### 2.2. Architecture Distributed System

As shown in Figure 1, the architecture of the smart meter network includes a master data aggregator microcontroller and several slave microcontrollers.

The data aggregator, thanks the web server implemented contains, in a table, information regarding:

- Renewable source availability
- Co-generator status,
- Actual Energy prices.

The first information is important because the level of energy generated by renewable sources often suffer of high time variability due to climatic changes. Therefore due to

this time variability is not possible guarantee the power efficiency required in specific time.

For this reason often the renewable source are used jointly with a cogeneration system. For an integrated management some information regarding the co-generator are needed such as the status, the availability etc.

Finally the data aggregator needs to know the energy price that can be update daily or even hourly.

The slave smart meters are connected to the single node of power network. Each microcontroller acquires continuously voltages and currents and it calculates Power and Energy consumption/generation and several Power Quality parameters.

The master microcontroller in addition acquire information about energy pricing, is therefore able to make decisions for an use efficient of the energy such as to disconnect a single load or to decide the time of use of a load.

### 2.3. Software Implementation

In this smart meter, the microcontroller is able to calculate the following parameters: i) Voltage and Current RMS values, ii) Active Power (P) and Power Factor (PF), iii) Energy consumption, iv) Frequency. v) Voltage and Current Total Harmonic Distortion (THDV and THDI) and vi) Power consumption profile.

As the implemented software is concerned, it adopts on line data processing to obtain mains quantity. An accurate synchronization is essential to estimate the fundamental frequency deviation. The synchronization of the input sequence is implemented through: i) the hysteresis block that selects a number of samples between the first and second zero crossing and ii) least square linear regression block that rebuilds the real index position of the input samples zero crossing. Defining  $f_0$  and  $f_c$  the fundamental and the sampling rate,  $x(1)$  and  $x(0)$  the indexes values respectively for the first and second zero crossing and  $\Delta x_1$   $\Delta x_0$  their residuals, adopting the following mathematical relation,  $f_0$  and  $f_c$  are the fundamental and the sampling rate, is possible to obtain the frequency value :

$$f_0 = f_c \frac{1}{(x(1) + \Delta x_1 - x(0) - \Delta x_0)} \quad (1)$$

A section looks for dips through rms continuous processing. Considering N the ratio between the sampling rate and the input signal frequency, the following algorithm, based on the Eulero's equation, calculates the rms values

$$V_{RMS}^2 = \frac{1}{N} \sum_{i=0}^{N-1} v_i^2 \quad (2)$$

$$I_{RMS}^2 = \frac{1}{N} \sum_{i=0}^{N-1} i_i^2$$

The algorithm adopts a sliding windows technique and leads to:

$$V_{RMS}^2(k) = V_{RMS}^2(k-1)^2 + \frac{(V^2(k) - V^2(k-N+1))}{N} \quad (3)$$

$$I_{RMS}^2(k) = I_{RMS}^2(k-1)^2 + \frac{(I^2(k) - I^2(k-N+1))}{N}$$

The Active Power is defined as:

$$P(k) = V(k-1)I(k-1) + \frac{(V(k)I(k) - V(k-N+1)I(k-N+1))}{N} \quad (4)$$

The Power Factor is calculated with the following:

$$\cos \varphi = \frac{P}{S} \quad (5)$$

where P is the Active Power and S the Apparent Power.

In the next section, a digital flick meter is implemented. Subsequently a digital re-sampling is made to obtain in exactly ten cycles of the fundamental a number of samples that is a power of two. The results of all the measurement sections are validated using flag control: flagged results are not accounted for subsequent analysis, not flagged data are grouped with reference to absolute time in order to obtain measurement with 10 min clock boundary. THDV and THDI are evaluated by Fast Fourier Transform (FFT) of voltage and current signals, after that they are resampled to analyze a number of samples equal to 256, i.e. a power of four [12]. The new samples are taken at non integer index corresponding to:

$$k\alpha = k \frac{T_{10\text{cycles}} f_s}{2^n} = m_k d_k \quad \forall k=1, \dots, 2^n \quad (6)$$

The integer and decimal part of the index corresponding to the k-th new sample  $y_R(k)$  are respectively  $m_k$  and  $d_k$ .

The value of new samples can be calculated as :

$$y_R(k) = y(m_k) + \Delta y = y(m_k) + \frac{d_k (y(m_k + 1) - y(m_k))}{10} \quad (7)$$

where  $y(m_k)$  and  $y(m_k+1)$  are two consecutive samples adopted to calculate  $y_R(k)$ , and finally the distance between  $y_R(k)$  and  $y(m_k)$  is  $d_k$ .

### 3. COMMUNICATION PROTOCOL

#### 3.1 CAN Protocol

The implemented smart meter requires a reliable communication low level interface. Its main required features are: i) low cost implementation ii) noise immunity iii) easy configuration iv) multicast network. For these reasons we chose the CAN protocol. It was specifically designed to operate seamlessly even if highly disturbed by the presence of electromagnetic disturbances thanks to the adoption as a means of transmission a line with potential difference balanced signals. The immunity to electromagnetic interference can be further increased by using twisted pair cable type.

The bit rate can be up to 1 Mbit/s to less than 40-meter nets. Slower speeds let you reach greater distances (125 kbit/s to 500 m) as in the considered case. The CAN communication protocol is standardized in ISO11898-1[8-9].

If the bus is idle, any node may begin to transmit. If two or more nodes begin sending messages at the same time, the message with the higher id (which has more dominant bits, i.e., zeroes) will overwrite other nodes lower id's, so that eventually (after this arbitration on the id) only the dominant message remains and is received by all nodes.

This mechanism is referred to as priority based bus arbitration. Messages with numerically smaller values of id have higher priority and are transmitted first.

The CAN communication was implemented by the STM32F107VCT6. It was managed to efficiently manage a large number of incoming message [9].

The simplified architecture of the STM32 CAN interface is shown in the Figure 3.

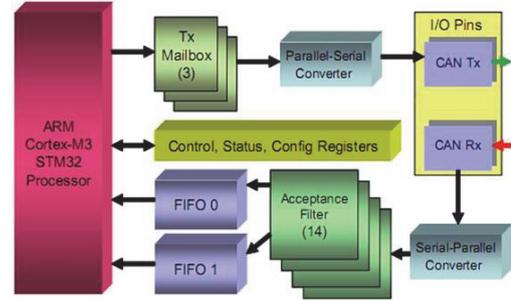


Fig.3 CAN architecture

#### 3.2 M-BUS

The M-Bus ("Meter-Bus") is a new European standard for remote reading of meters and it is also usable for all other types of consumption meters as well as for various sensors and actuators [10]. The remote reading of heat meters can take place in different ways, beginning with the classical method - manual reading by the personnel of the providers - up to the remotely controlled collection of all the meter values for a complete housing unit. The latter is a logical continuation/extension of the technical development of consumption meters and is realizable with the help of M Bus.

It main features are:

- Large number of connectable devices
- Possibility for network expansion
- Fail-safe characteristics / robustness
- Minimum cost
- Minimum power consumption in the meters
- Acceptable transmission speed

The standardisation of the m-bus results in further technical possibilities. In particular devices of different manufacturers can be operated on the same bus; the users are free therefore in the choice of the manufacturer. On the other hand, a stimulation of the market can be expected, also regarding other m-bus based counters, so that with the very variable configuration options even difficult problems can be solved.

#### 3.3 Utilization description

The master microcontroller sends a message, with a "remote frame". It is a message without information content, aimed to request a Data Frame from the slaves.

Three transmit mailboxes are provided to the software for setting up messages. The transmission Scheduler decides which mailbox has to be transmitted first, for example the Energy consumption of a single load. The message is converted by a parallel-serial converter and is sent to the CAN TX Pin.

The master microcontroller receives the Remote Frame through the Pin CAN Rx. After, the message is converted in parallel through a serial-parallel converter. The frame is sent to an Acceptance Filter that is composed of 14 configurable identifier filter banks for selecting the incoming messages the software needs and discarding the others. Two receive FIFOs are used by hardware to store the incoming messages. Three complete messages can be stored in each FIFO. The FIFOs are managed completely by hardware.

When a Remote Frame is received, the microcontroller sets up a response message, a Data Frame corresponding to the Remote Frame, and sends it to the microcontroller that previously sent the Remote Frame.

The structure of the Data and Remote frame is the following:

The Start of Frame denotes the start of the Frame transmission. The ID is the identifier for the data and also represents the message priority. The Remote Transmission Request is set to dominant (zero). The Identifier extension bit and Reserved bit must be dominant (zero). The Data Length Code consists of four bits and indicates the number of bytes of data (0-8 bytes). The Data Field denotes the data to be transmitted (0-8 bytes) and it only is in the Data Frame. The Cyclic Redundancy Check, composed by 15 bits, is an error-detecting code using to detect accidental changes to raw data. The ACK slot is sent recessive (1) from the transmitter and any receiver can assert a dominant (0) and the End of Frame must be recessive (1).

#### 4. SMART METER NETWORK MANAGEMENT

In the data aggregator a web server collects the statistics of each household and extracts other information [11]. Through the web server, the user can monitor the Power profile of a single load.

Distributed energy meters transfer measurement results to the data aggregator through CAN protocol.

In the Fig. 4 is reported an example with two slave microcontrollers that communicates with a data aggregator. They continuously acquire voltage and current and calculate several parameters shows on the display.

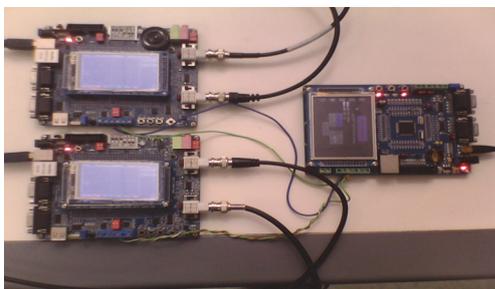


Fig.4 Example of transmission data

Several tests have been performed to evaluate the transmission time.

A first test was made to calculate the delay between the instant when the master microcontroller sends the request and the instant when a slave detects an interrupt for the reception of the request. The estimated time is approximately 3.6 ms (Fig. 5).

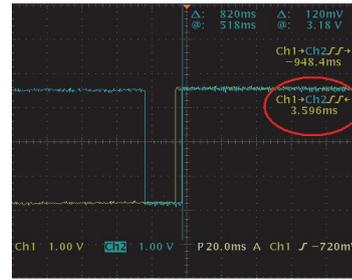


Fig.5 Time latency for the first test

In the second test, the data aggregator requires data relating to the active power to both with two different priority levels. It receives data from the slave with the highest priority approximately after 25 ms (Fig. 6) those relating to the second after approximately 60ms (Fig. 7).

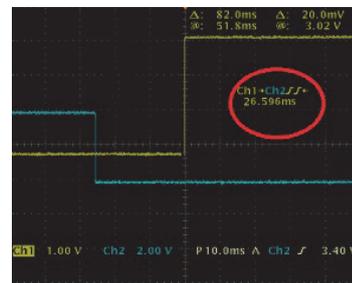


Fig.6 Time latency for the first test

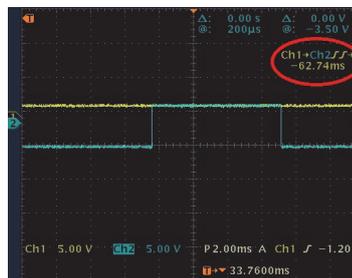


Fig.7 Time latency for the third test

In fact, the waiting time for the second slave is approximately 35ms (Fig. 8).

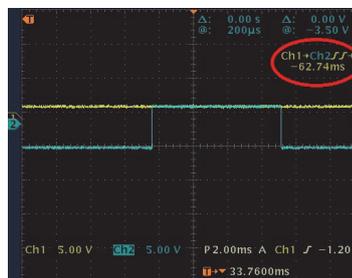


Fig.8 Time latency for the fourth test

The time latency was calculated through the microcontroller DAC. In particular, a single bit of the DAC has been used to generate a square wave. The results has been calculated through the oscilloscope Tektronix TDS3012B.

## 5. METROLOGICAL CHARACTERIZATION

In order to prove reliability of the implementation instrument, a preliminary characterization, in particular static and dynamic tests of the channels, has been performed [12][13]. The following instruments, as shown in Fig. 9, were used:

- Function Generator Yokogawa F300
- PXI 1042 chassis with a PCI-DAQ 6123
- STM32F107VC microcontroller
- Pacific Power Source 3120 AMX

Through the function generator the input signals were generated, and, as power amplifier, the Pacific Source 3120 AMX has been used. It has two different output channels which can provide signals appropriately phase shifted. In particular, dc signals and ac signal with offset were generated. These signals were acquired from both the two channels of the microcontroller and the PXI 1042. Through the Labview software it was possible to monitor and store the values supplied by the generator and to obtain the RMS and the Power values. These parameters were then compared with those shown on the display of the power meter.

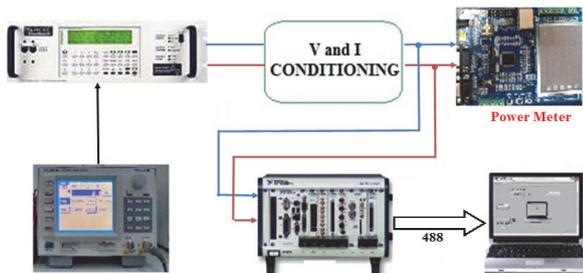


Fig. 9 Instruments for experimental tests

In order to prove reliability of the implemented instrument, a metrological characterization has been performed according to the [14]. In the first set of tests the dc voltage has been varied with a step of 10% F.S.. Each test was repeated ten times. The Set Value indicates the values set on the function generator

- The Mean Value indicates the mean of values read from the microcontroller
- The Real Value indicates the values acquired from PXI.

The mean error percentage is not zero, but it is in a range between 0.1-0.8 [%]. These value are too high and show a tendency of the two channels of the microcontroller to keep always below the real value. Evaluating the gain and the offset errors, a correction of the errors with the method of least squares was made. After the compensation the Mean Error is less than the 0.05% and the Standard Deviation is less than the 0.03 %.

Furthermore other tests in sinusoidal conditions, in order to evaluate the effect of frequency and phase angle variation on Active and Reactive Power, and in non-sinusoidal conditions , in order to evaluate the effect of the fundamental phase angle and the harmonic order variation on Active and Non-Active Power, averaging on the other parameters are reported. In particular, the sinusoidal tests

have been performed varying input parameters around rated values: frequency( $50 \pm 15\%$ ), input voltage (50% to 100 %), the same for the current and finally the phase displacement between  $-\pi/4$  to  $\pi/2$ . In the Fig. 10 and 11 Relative Uncertainty Percentage for Active Power and Reactive Power in sinusoidal conditions are reported.

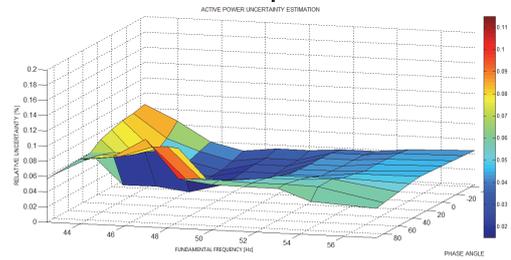


Fig.10 Active Power Uncertainty Estimation vs phase angle and fundamental frequency

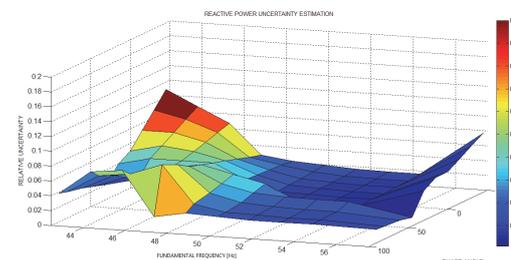


Fig.11 Reactive Power Uncertainty Estimation vs phase angle and fundamental frequency

For the non-sinusoidal tests, according to EN 50160 [15] a fixed THD to 8%, for voltage and current waveforms, has been adopted. For each tests five harmonic components spanning between 3 and 39 are superimposed to fundamental with fixed THD; the testing procedures in well described in [16].

In the Fig.12 and Fig. 13 Relative Uncertainty Percentage for Active Power and Non-Active Power in non-sinusoidal conditions are reported.

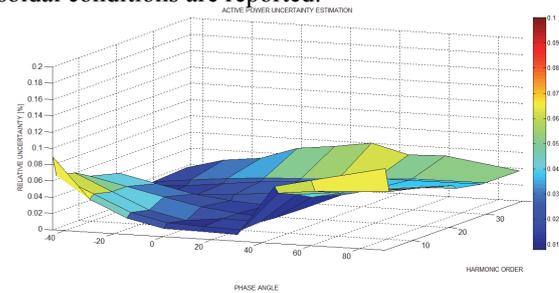


Fig.12 Active Power Uncertainty Estimation vs harmonic order and phase angle

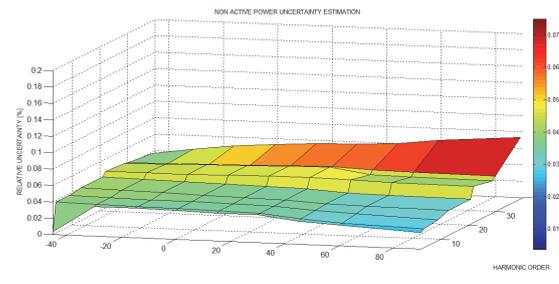


Fig.13 Non Active Power Uncertainty Estimation vs harmonic order and fundamental frequency

The obtained results are shown in the Table I reporting the uncertainty obtained for each measured quantity.

Table I: Value of the mean squared errors in the sinusoidal and non-sinusoidal tests.

| Quantity          | Uncertainty (sin. test) | Uncertainty (non- sin. test) | Units  |
|-------------------|-------------------------|------------------------------|--------|
| Voltage (r.m.s.)  | 0.03                    | 0.04                         | [%]    |
| Current (r.m.s.)  | 0.03                    | 0.04                         | [%]    |
| Frequency         | 0.67                    | 0.67                         | [mHz]  |
| Active Power      | 0.043                   | 0.061                        | [%]    |
| Apparent Power    | 0.13                    | 0.15                         | [%]    |
| PF (conventional) | 0.002                   | 0.002                        | [p.u.] |
| Non Active Power  | 0.60                    | 0.62                         | [%]    |
| Voltage THD       | ---                     | 0.072                        | [%]    |
| Current THD       | ----                    | 0.070                        | [%]    |

## 6. CONCLUSIONS

In this paper a real-time meter network is proposed for smart grids applications with the aim to obtain a low-cost device for a sustainable use of electrical energy. The implemented multi-meter is capable of measuring the energy consumption of individual users and to communicate with decentralized control unit through the CAN bus, which has the option to remotely monitor the activities of the devices connected to the system and manage the energy cost.

The architecture provides several slave smart meters connected to the single node of power network. Each microcontroller acquires continuously voltages and currents and calculates: Voltage, Current, Power, power factor, frequency and several power quality parameters. With these information, the user is able to make decisions for an efficient use of the energy.

Finally, characterization test of realized apparatus have shown good performances both in terms of communication errors and measurement uncertainty.

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