A smart measurement network for optimization of electrical grid operation

Dario Di Cara[1], Mario Luiso[2], Gianfranco Miele[3], Paolo Sommella[4]

[1] *National Research Council (CNR), Institute of Intelligent System for Automation (ISSIA)*
Via Dante Alighieri, 12, 90141 Palermo, Italy, dicara@pa.issia.cnr.it
[2] *Department of Industrial and Information Engineering, Second University of Naples, Via Roma 29, 81031*
Aversa (CE), Italy, mario.luiso@unina2.it
[3] *DIEI, University of Cassino and Southern Lazio, Via G. Di Biasio 43, 03043 Cassino (FR), Italy,*
g.miele@unicas.it
[4] *DIIn, University of Salerno, Via Giovanni Paolo II 32, 84084 Fisciano (SA), Italy, psommella@unisa.it*

Abstract-The electrical grid was historically created to collect large amounts of energy from generating stations and distribute them to a large number of consumers .With the advent of diffused generation, mainly produced from renewable energy sources, this classical view of the electrical grid must be completely revised. A new control system, which integrates electronics and telecommunications, is now required. Therefore, the aim of the paper is the development of a new smart measurement network, which allows the optimization of the management of a Smart Grid with a wide presence of power generation from renewable sources and decentralized storage systems.

I. Introduction

The electrical grid has been designed as a passive network. It had to collect large amounts of energy from power stations and distribute them to a large number of consumers. This has led to the employment of a centralized control, with unidirectional power flows from the power stations to the high voltage (HV) transmission grids, and then, through the transformer stations, up to the medium and low voltage passive distribution grids, that allow the consumers to get the amount of energy they need. With the advent of diffused generation, mainly produced from renewable energy sources (RES), this classical view of the electrical grid must be completely revised. The distribution grid, in fact becomes active: the small producers (mainly based on photovoltaic and wind power plants) generate energy and inject it into the distribution system, reversing the direction of power flow, which now goes to the transformer stations. Therefore, the electrical utilities must be ready to handle both the power flows coming from the large power stations (thermoelectric, hydroelectric, etc), and those coming from small producers (mainly solar, wind, thermal) connected to the distribution grid. To do this, grid management cannot anymore be centralized, it must become distributed in the territory: the power flows has to be locally monitored and controlled in order to guarantee both the stability of the grid and the maximum penetration of the distributed generation. Thus the power grid is not anymore only a channel to transmit and distribute energy from large power stations to end users, but an intelligent network, a "Smart Grid", that is able to interact with producers and consumers, in order to adapt with flexibility and instantaneously the energy production to the consumption request. It had to evolve toward a network composed of many small networks connected together, that are able to communicate each other, exchanging information on the power flows, managing with efficiency the energy demand and avoiding services interruption by reducing the load consumption when it is needed [1]-[3]. Lines, switches and transformers are not enough anymore for the management of the medium and low voltage distribution grid. A new control system, which integrates electronics and telecommunications, is now required. Authors have already worked on topics related to Smart Grid operation optimization, such as Power Line Communication (PLC) in Medium Voltage (MV) smart grids ([4]-[7]), metrological characterization of networks ([8]-[12]), design and realization of innovative transducers ([13]-[15]) and smart meters ([16]-[19]) for power networks and fault detection [20]. In this paper they present the first obtained research results relating the development of a measurement and diagnostic smart network for electric grids with distributed generation from renewable energy sources. They regard the implementation of a new smart network for optimization of electrical grid operation: it is composed of innovative smart meters, able to measure energy, power, power quality, to execute algorithms for fault detection identification. The network nodes are able to communicate among them and with the control centers of the electrical system, covering wide geographical areas. In section II, the design and implementation of the smart meter are reported. Section III discusses the communication network and section IV some details about fault identification technique are given.

II. Smart meters

A prototype of a smart meter has been specifically designed for the presented application ([17], [19]). From a functional point of view, it consists of the following blocks: i) a metering unit that tracks the energy usage of the customer and processes the billing, ii) a communication unit that enables two way digital communication with the energy company iii) a switching unit that starts and shuts down the energy supply. From a physical point of view, each equipment consists of: i) a transduction section composed by voltage and current sensors and level adapters, ii) an elaboration section that acquires the output of the sensors and processes the acquired samples, iii) a display monitoring several information, iv) a memory section which stores the billing value in a EEPROM.

A. Voltage and current sensing section

Voltage and current sensing section is composed by a prototype of a Combined Voltage and Current Transducer (CVCT) [16], [13]. A picture of the realized CVCT is shown in Figure 1. As it can be seen, it is made of simple electrical and electronic components and thus its cost is very low. The two sections of the CVCT take supply from voltage input: a simple half-wave rectifier and a linear regulator obtain single supply 5 V_{DC} from 230 V_{AC}. Voltage transducer is a high impedance resistive divider with a differential operational amplifier, current transducer is a low resistance resistive shunt with a differential operational amplifier. Input voltage is in the range $[-460\sqrt{2}, 460\sqrt{2}]$ V, which corresponds to a root mean square (rms) value equal to 460 V_{RMS}, in order to make the meter able to measure power quality parameters like voltage swells. Current input is in the range $[-30\sqrt{2}, 30\sqrt{2}]$ A, which corresponds to a rms value equal to 30 A_{RMS}. Both the outputs are in the range [0,3] V, in order to be suitable for microcontroller analog inputs; with zero inputs the outputs are 1.5 V_{DC}. The realized CVCT has been simulated in Multisim environment. Figure 2 and Figure 3 show, respectively, inputs (230 V_{RMS} and 15 A_{RMS}) and outputs of the CVCT. Analysing the plot reported in Figure 3 it is possible to highlight that: 1) outputs are inverted with respect to inputs, 2) the signal becomes stationary after a small transient due to stabilization of supply voltage by linear regulator, 3) mean values are 1.5 V for both outputs. In Figure 4 magnitude and phases of the outputs, from the AC analysis simulation, are shown: it can be seen that in the range of interest for power quality analysis, i.e. until 10 kHz, frequency bandwidth of the CVCT is suitable for the application for which it has been realized.

B. Elaboration section

The hardware implementation is built around a STM32F107VCT6 microcontroller, which incorporates the high-performance ARM®Cortex™-M3 32-bit RISC core operating at a 72 MHz frequency. Its main features are: 1) 256 Kbytes of Flash memory and 64 Kbytes of general-purpose SRAM, 2) Low power: Sleep, Stop and Standby modes, 3) 2 × 12-bit, 1 μs A/D converters (16 channels) with conversion range from 0 to 3.6 V and up to 2 MHz in interleaved mode, 4) 2 × 12-bit D/A converters, 5) 12-channel DMA controller, 6) up to 80 fast I/O ports, 7) CRC calculation unit, 96-bit unique ID, 8) Up to four 16-bit timers, 1 × 16-bit motor control PWM timer, 2 × watchdog timers, 9) Up to 2 × I2C, 5 USARTs, 2 × CAN interfaces (2.0B Active) with 512 bytes of dedicated SRAM, USB 2.0 full-speed device/host/OTG controller, 10/100 Ethernet MAC with dedicated DMA and SRAM (4 Kbytes) and with IEEE1588 hardware support.

C. Measurement Software Implementation

In this smart meter, the elaboration section 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) power consumption profile, v) frequency, vi) voltage and current Total Harmonic Distortion (THDV and THDI) and vii) voltage dip events.
As for the implemented software, it adopts on line data processing to obtain the desired quantities. For this aim, an accurate synchronization is essential because most parameters depend on the actual fundamental frequency, so frequency deviation from nominal value should be continuously monitored. 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 frequencies respectively, $x(1)$ and $x(0)$ the index values for the first and second zero crossing, Δx_1 and Δx_0 their residuals, adopting the mathematical relation (1) it is possible to obtain the fundamental frequency value.

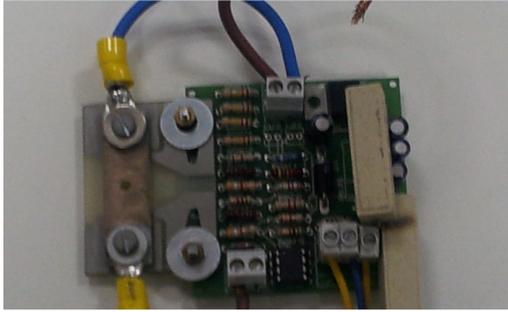$$f_0 = f_c \frac{1}{x(1) + \Delta x(1) - x(0) + \Delta x(0)} \tag{1}$$
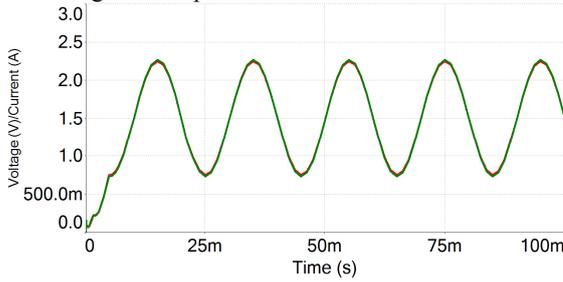
Figure 1. A picture of the realized CVCT.

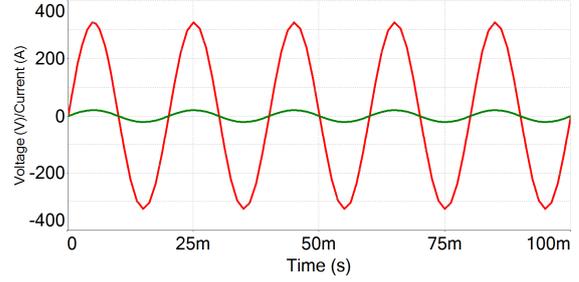Figure 2. Voltage and current at the input of CVCT.

Figure 3. Outputs of CVCT with voltage and current input of Figure 2.
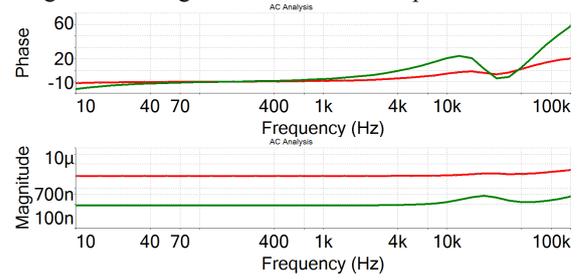

Figure 4. AC analysis of the realized CVCT: magnitudes and phases of the outputs.

A section monitors dip events through rms continuous processing. Considering N the ratio between the sampling rate and the input signal frequency, the relations (2), based on the Eulero's equation, calculate the rms values.

$$V_{RMS}^2 = \frac{1}{N}\sum_{k=0}^{N-1} v_k^2, \ I_{RMS}^2 = \frac{1}{N}\sum_{k=0}^{N-1} i_k^2 \tag{2}$$

The algorithm adopts a sliding window technique and this leads to (3).

$$V_{RMS}^2(k) = V_{RMS}^2(k-1) + \frac{v_k^2 - v_{k-N+1}^2}{N}, \ I_{RMS}^2(k) = I_{RMS}^2(k-1) + \frac{i_k^2 - i_{k-N+1}^2}{N} \tag{3}$$

The Active Power is calculated as in (4),

$$P(k) = P(k-1) + \frac{v_k i_k - v_{k-N+1} i_{k-N+1}}{N} \tag{4}$$

while the Power Factor is calculated with (5):

$$PF = \frac{P}{S} \tag{5}$$

where P is the active power and S the apparent power. 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 through Fast Fourier Transform (FFT) of voltage and current signals, after a resampling process to obtain a number of samples equal to 256 for each signal, i.e. a power of four [17]. The new samples are taken at non integer index corresponding to (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 in (7).

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

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

The quantities $y(m_k)$ 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.

III. The network characteristics

To realize a secure and reliable communication network able to operate on geographical extensive areas, several standards and emerging communication technologies, both wired and wireless, that best fit the amount and type of data to be transmitted, have been studied. Particular attention has been given to the implementation of techniques that can ensure the reliability of the network, the security of the transmitted information and, at the

same time, adapting to the needs of cost containment of nodes and operation of the network itself. Among the communication systems the attention was focused on the power line communication, solution that provides coupling of communication signals on power distribution network. PLC is the only wire line technology that enables low installation cost, comparable to wireless solutions, but with lower operating costs, given that the energy distributor also becomes owner of the communications service. In different countries (as in Italy), narrow band (NB) –PLC, operating in the CENELEC bands (3-148.5 kHz), are already used for supporting Automatic Meter Reading (AMR) and Advanced Metering Infrastructure (AMI) in LV networks [21]. On the other hand, different communication technologies are currently employed (as GSM or Wireless) in the MV networks, which entail extra services and equipments. Thus the possibility to employ NB-PLC also in the MV network can be the key for the realization of a complete and reliable low cost communication system for electrical distribution networks. The proposed solution for PLC in MV cable power lines is presented in Figure 5, where a two-ways communication was realized between two secondary substations. The core-shield signal injection was used, because of the easier coupling modality with respect to the core-core configuration [4]. In the core-shield configuration the signal is injected between the core of one cable and the shield, which is connected to earth at the ends of the line. An EVALST7580-1 board was used to transmit and receive a FSK or PSK modulated signal. The EVALST7580-1 coupling interface is designed to allow the ST7580 transceiver to transmit and receive signals on the low voltage mains [5]. A CU7.C2-2 capacitive coupler, by ADD Production S.r.l., was further used to connect the signal to the MV network. A complete PLC system model [6], which also comprises the power transformer model [7], was developed in Matlab-Simulink environment and experimentally validated both in laboratory and field tests. Different cases were studied transmitting or receiving both from the MV and the LV network, demonstrating the feasibility of the proposed solution. The transmission performance was evaluated considering the success rate, which is the percentage of information bit packets received respect to the transmitted ones. An experimental test campaign was carried on a MV cable line connecting two MV/LV substations of Ustica Island MV network. The 1.4 km long MV line is made up of three unipolar MV shielded cables of type RG7H1R, with aluminum core of 25 mm^2 cross-sections. The PLC transmission station and the capacitive coupling device, connected in one of the two MV/LV substations, are shown in Figure 6. The experimental results are reported in Table I in the case of MV-MV transmission. A 100% success rate is obtained with low bit rate modulation techniques (FSK, BPSK-coded and QPSK-coded), while a lower success rate is obtained when the bit-rate is increased (QPSK).

IV. Fault Detection Issues

One of the most important research issues concerning with Smart Grids is the development of suitable Fault Detection techniques able to improve the reliability and maintainability of electrical distribution according to a pro-active approach. Although some events (for example, those one introduced by lightning) are unpredictable, in many other cases distribution system faults result from the gradual degradation at component level. In Smart Grid scenario, *fault-tolerance* features are also required when the smart measurement network is designed. More in detail, *Instrument Fault Detection & Isolation* (IFDI) should be addressed through the definition and exploitation of analytical redundancy and/or knowledge-based techniques able to: *i)* determine the correct operation for each node of the proposed distributed measurement system, and *ii)* exclude unreliable/fault Meters from the corresponding Fault Detection architecture of the electrical system. Following the metrological characterization suggested in [22], the true performance provided by the consensus protocols have been investigated when the measurement uncertainty and transmission non idealities are taken into account for the smart meters within the network.
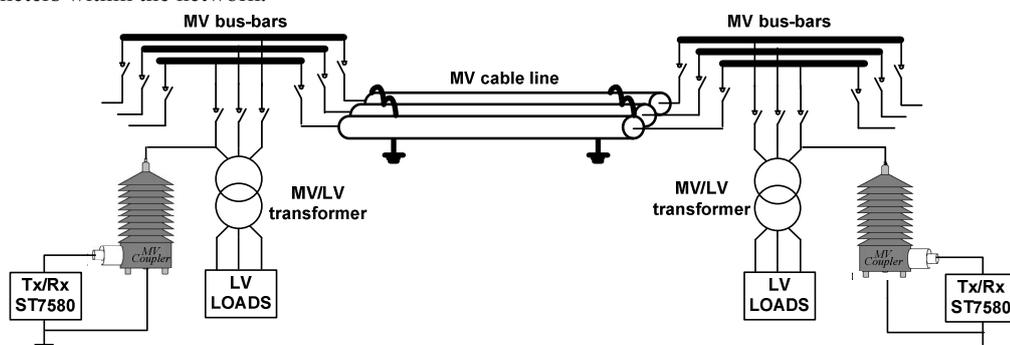

Figure 5. Schematic representation of the proposed PLC solution.

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Figure 6. Transmission station (left) and capacitive coupling device (right) in a MV/LV substation of Ustica Island.

TABLE I.
TRANSMISSION SUCCESS RATE AT DIFFERENT FREQUENCIES AND DIFFERENT MODULATION TECHNIQUES IN THE MV-MV EXPERIMENTAL TEST

Modulation	Symbol rate [baud]	Information bits per symbol	*bitrate [bit/s]*	*Center Frequency [kHz]*	Succees rate
FSK (4800 bps)	4800	1	4800	86	100%
BPSK-coded	9600	0.5	4800	86	100%
QPSK-coded	9600	1	9600	86	100%
QPSK	9600	2	19200	86	98%
FSK (4800 bps)	4800	1	4800	110	100%
BPSK-coded	9600	0.5	4800	110	100%
QPSK-coded	9600	1	9600	110	100%
QPSK	9600	2	19200	110	94%

V. Conclusions

This paper presents the first theoretical and experimental results relating the implementation of a smart measurement network for optimization of electrical grid operation. It is composed of innovative smart meters, able to measure energy, power and power quality, to execute algorithms for fault detection identification. The network nodes are able to communicate among them and with the control centers of the electrical system, through Power Line Communication. Future works will regard the metrological characterization of smart meters, communication network and fault identification algorithms.

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