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Low-Cost Energy Meter with Power Quality Functionalities

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***Abstract* – Nowadays, due to the changes in the energy scenario, the awareness of the power quality of the consumers and producers at the distribution level is increasing. In this scenario, different energy meters with enhanced functionalities have been introduced in the market. Recently, the availability of development platforms based on a single-board computer (SBC) has opened the door to the implementation of new types of low-cost meters. The SBCs can be used in different applications, thanks to the expansion boards connected to the general-purpose input-output (GPIO) interfaces. In this way, the SBC platform can be adapted to various applications, as energy meter or data logger. Specifically targeted measurement algorithms have to be implemented to exploit properly the available hardware resources and achieve suitable performance. In this paper, an improvement of functionalities of the commercial open-source energy meter SmartPi, based on the well-known platform Raspberry Pi, is proposed. The original software of the smart meter is replaced to extend its functionalities of power quality monitoring provided by the integrated circuit Analog Device ADE7878.**

I. INTRODUCTION

In recent years, the energy system has been changing due to the information and communication technology, particularly regarding support for the management of the electric grid. In this new context, which is now commonly identified as the Smart Grid, the traditional role of the consumers is evolving with the emergence of the new role of prosumer [1], who can also produce energy due to the high penetration of renewable energy sources at the distribution level.

The awareness of the prosumers regarding not only energy consumption but also the quality of the energy is rising. In particular, different projects with the aim of transferring knowledge from research into commercial activities are helping to increase the awareness about the power quality (PQ) topic and its impact on the working process [2].

PQ includes both scientific arguments and practical consequences on the final users [3]. Statistically, phenomena that reduce the quality of the energy supplied by the network represent a large portion of the electric anomalies that could be the cause of breakdowns and poor operation of any kind of appliance connected to distribution lines. The increasing need to perform detailed energy and PQ analysis in a large number of nodes of a distribution grid, or even inside the plants of single users, requires the installation of a large number of meters, which may become very expensive.

In recent years, single-board computers (SBCs) characterized by low cost, moderate power consumption and high performance have been developed. The Internet of Things paradigm allowed the connection of different devices to the Internet and the collection of data in the Cloud. The projects based on SBCs coupled with expansion boards span several measurement-related sectors, including synchronized measurements [4], data concentrators [5]-[6], air quality monitoring [7], and PQ applications [8]. An interesting overview of the low-cost energy meters with a comparison table of their characteristics is reported in [9]. The commonality between the different cited projects is the possibility of increasing the spatial resolution of measurement points or data concentrators thanks to the lower cost of devices.

One of the most well-known SBCs is the Raspberry Pi [10]. The board is a pocket size computer with the possibility of interfacing with different expansion boards to extend functionality. The SmartPi is an expansion module with energy meter functionalities specific to the Raspberry Pi platform [11]. The module can acquire low-level voltages and currents to control energy consumption or production and makes all the acquired data available thanks to a local or Internet connection. The entire system, SBC and its expansion module, which for the sake of brevity will be here called SmartPi, can be installed in a three-phase or single-phase system and can measure currents, voltages, powers, energy consumption, frequency, and power factor.

In this context, the aim of this paper is to present how the functionalities of the commercial energy meter SmartPi have been extended to activate the PQ features provided by the integrated circuit (IC). In particular, new embedded software has been designed and implemented, built on LabVIEW and framework LYNX [12]. The base software has been replaced, allowing the possibility to read the data provided by the expansion board through a serial

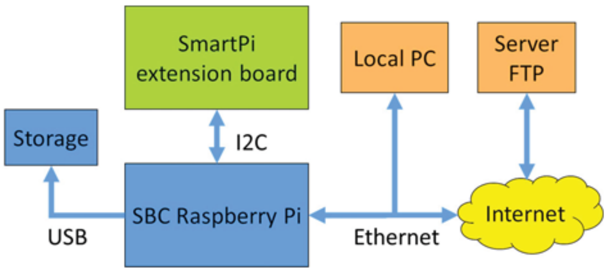

Fig. 1. Overall architecture of the energy meter.

communication channel. The new features of the updated software include phase voltage sag detection, peak detection, overvoltage and overcurrent detection. A series of tests will be presented to evaluate the performance of the proposed solution under different conditions.

II. SMARTPI LOW-COST ENERGY METER

Focusing on the SmartPi, the device is an expansion module that extends the Raspberry Pi functions with an external interface to measure voltages and currents and adapts it into an energy meter (Fig. 1). The main characteristics of the overall system are shown in Table I. The four currents are measured via inductive current sensors (YHTC - SCT013). In the commercial version, currents up to 100 A can be measured. Moreover, as reported on the producer's website [11], it is possible to modify the internal circuits so that other sensors, which measure currents up to 300 A, can be used. The device is supplied with the required operating voltage via the first (L1) measurement voltage. Alternatively, a DC power supply can be used.

The information provided about the metrological performance is limited to a declared overall accuracy of 2 %. The core of the SmartPi is the IC specific for electric monitoring applications Analog Device ADE7878 [13].

Table 1. SmartPi technical characteristics

Voltage	0 – 400 V_{RMS}
Current	Depending on the current transformers (0 -100 A)
Overall Accuracy	2 %
Power Consumption	10 W
Power Supply	DC current or integrated power supply from the voltage channels (L1)
Digital output	Relay for switching

The IC is built with 7 ADCs to acquire up to three voltages and up to four currents with the appropriate transducers. The current channel consists of four pairs fully differential voltage inputs [13]. The IC offers different PQ functionalities that are not included in the base software of the SmartPi. It is important to highlight that the technical datasheet of the IC ADE7878 reports detailed accuracy information [13]. For example, the stated maximum accuracy for the fundamental active energy is equal to 0.2 %.

One of the main characteristics of the SmartPi is the easy access to memorized data. To acquire and read the measurements provided by the device, the users can obtain the information through a web server integrated into the platform. The instantaneous values of powers, currents, voltages, and power factor are displayed on the website. Statistical information about the energy consumption of the last eight days is shown with a bar graph. The web interface provides the possibility to extract the data for a selectable temporal range in the CSV format.

Moreover, one of the appreciable characteristics of the device is the open access to the source code installed in the devices. The binary code can be automatically updated by the public repository that can be integrated into the operating system of the device (Raspbian). Furthermore, the source code can be downloaded and compiled from a GitHub repository. This permits desired modifications to be made.

III. THE NEW IMPLEMENTED FUNCIONALITIES

Table II lists the base (software provided by the manufacturer) and the additional functionalities implemented in the SmartPi. Concerning the former ones, the device is programmed as an energy meter. Nevertheless, the IC ADE7878 has different features of interest in PQ monitoring, which allow implementing the enhanced functionalities summarized in the second row of the table. The functionality "phase voltage sag detection" is intended to detect when the absolute value of any phase voltage drops below a specific value. The IC can detect the sag event and assesses its duration in terms of number of

Table 2. Comparison of SmartPi software functionalities.

Base SmartPi Measurements	voltages and currents active, reactive, apparent power and energy consumption and production power frequency power factor
SmartPi Additional Functionalities	phase voltage sag detection peak detection overvoltage and overcurrent detection

half-cycles involved. The threshold value for the detection of the voltage sag is selectable by the user and is stored in an internal register. The function "peak detection" saves the maximum values reached by the voltage and current channels over a certain number of half-cycles and stores them into a specific register. The "overvoltage and overcurrent detection" functions detect when the instantaneous absolute values measured on the voltage and current channels become higher than the threshold values memorized in the registers of the IC.

It is essential to recall that the SmartPi is sold as an energy meter, and not all the functionalities of the IC ADE7878 are available on the board. In the physical layout, different pins of the IC are not physically connected to the board. This implies some limitations: first of all, not all the registers of the IC can be used; for example, it is not possible to acquire the samples directly or to use the interrupt when an event is detected. To overcome this limitation, the data from the available registers are obtained using the polling technique with a refreshing time of one second. The software-only solution allows obtaining the information from the IC but limits the speed of event detection to the polling rate. As mentioned above, the original software is written as open-source code, thus allowing to extend the base functionalities of the device.

In a project ongoing at the University of Cagliari, the SmartPi is an element of complex monitoring architecture designed in LabVIEW environment for PQ applications and composed of several devices installed at different voltage levels. In this scenario, a single programming language is an essential prerequisite to share information. For this reason, the source code of the SmartPi was rewritten in the LabVIEW environment. LabVIEW cannot be interfaced directly with the Raspberry Pi platform. To overcome this inability, the platform LINX was used to import the virtual instruments from LabVIEW [12]. LINX is a framework for Linux-based systems that can be installed in the operating system Raspbian of the Raspberry Pi. With this feature, it is possible to integrate, in the same LabVIEW project, different heterogeneous devices and program them to collect and share measurement data.

The software developed for the project can be divided into embedded and client software. The embedded code is the application that runs in the monitoring devices. The I2C protocol is used for the communication between the SBC platform and the extension board. The meter is programmed to work with other devices installed in the same area to correlate the measurements. For this aim, a good level of time synchronization is necessary. To reduce the cost per unit, Raspberry PI is not equipped with a real-time clock, and the time can be either set at start-up by the operator or provided by the network time protocol (NTP). The extension board is instead equipped with a real-time clock and a battery to keep the correct date and time also when the device is turned off. In the proposed configuration, if the internet connection is available, the device acquires the time with the NTP protocol and then keeps it. To avoid the unwanted time drift, the NTP synchronization is required every 15 min.

In order to increment the redundancy of the data storing, the measured values are saved both in an external USB memory able to store six months of continuous acquisitions and into a private FTP server.

The user interface is specifically designed to be easily handled by any operator (Fig. 2). The client program runs on a Windows-based PC and can communicate with all the SmartPi devices equipped with the new software and installed in the network. To discriminate the different devices with the same software, the MAC address is used as identification code. The application is directly connected to the devices to read the information with a reporting rate of one measurement per second. To provide simple and clear information to the user and to avoid compromising the bandwidth of the host, not all the information is sent to the user interface. Nevertheless, all the data are acquired and stored for statistical analysis.

IV. TESTS AND RESULTS

To verify the functionalities of the new software developed for the SmartPi platform, a series of tests were performed following the scheme shown in Fig. 3. The power signal generator and calibrator Omicron CMC 256 plus generates three-phase voltage and current signals

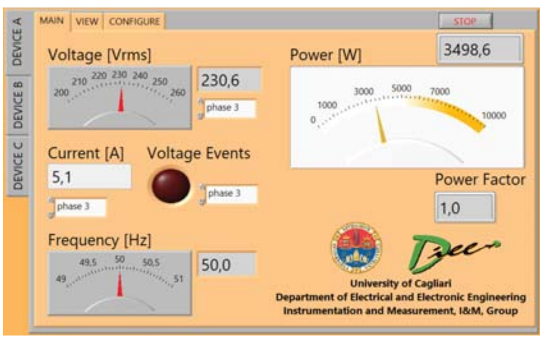

Fig. 2. Client software user interface.

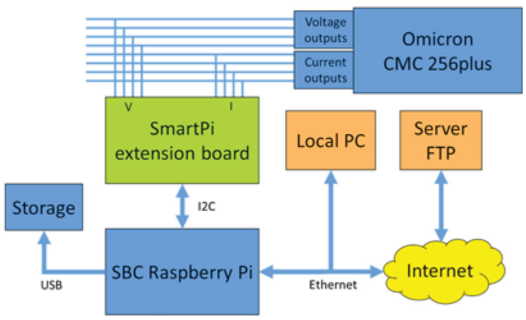

Fig. 3. Test setup.

[14]. Its high accuracy allows the testing of a wide range of devices, including energy meters of class 0.2, to be made. The calibrator is managed by Test Universe software, which includes a specific module to verify PQ monitoring devices.

The calibrator presents four voltage outputs with a common neutral. The voltage output works in two ranges of accuracy, 0–150 V and 0–300 V. The calibrator offers two independent three-phase current outputs with two different ranges: 0–1.25 A and 0–12.5 A. To increase the range of current, the individual outputs of the current generator A are connected to the generator B, increasing the range up to 25 A. Table 3 reports the accuracy of the voltage and current outputs.

Table 3. Calibrator accuracy.

Voltage Generators	error < 0.015% reading + 0.005% range (typical at 0–300 V) error < 0.04% reading + 0.01% range (guaranteed at 0–300 V)
Current Generators	error < 0.015% reading + 0.005% range (typical at 0 ... 12.5 A) error < 0.04% reading + 0.01% range (guaranteed at 0 ... 12.5 A)
Frequency and Phase (analog current and voltage outputs)	Freq. range: 10–3000 Hz Freq. resolution: < 5 μHz Freq. accuracy: ± 0.5 ppm Freq. drift: 0.1 ppm Phase error: 0.005° typical (< 0.02° guaranteed)

Various tests have been conducted not only to prove and verify the monitoring capability of the energy meter with the newly designed software, but also to test the various configurations of power supply and communication that can occur in different operative scenarios. Therefore, the tests can be divided into two groups: metering and auxiliary functions.

In the following, the main test results are summarized.

a) Metering and power quality capabilities

A preliminary test is performed to verify the metering capabilities of the device under different load conditions. A three-phase current, with amplitude ranging from 2.5 to 25 A, is generated by the calibrator. Four turns of wire are considered in the current sensors, so that the actual measured current is four times the generated one and the entire operative range (0–100 A) is analyzed, in steps of 10 A. In this scenario, the voltage is 230 V, the frequency is 50 Hz and the power factor is equal to 1.

This preliminary test has highlighted the presence of high errors, in the order of 5–8%, in the current channels. Thus, a proper compensation of the current sensors is a fundamental initial operation to keep a sufficient measurement accuracy for the current and, consequently, for the active power. The compensation procedure is performed for each current sensor with a simple linear approximation using the least square method. It is important to highlight that the IC circuit implements a specific register for the compensation of the current, and the SmartPi is pre-calibrated from the factory.

The efficacy of the performed compensation has been then assessed for the ten current steps, by repeating the test 60 times for each current step. Fig. 4 shows the maximum relative error (with sign) for each phase. The highest error is in the range 10–20 A and is lower than 2 %. For higher currents the error rapidly decreases.

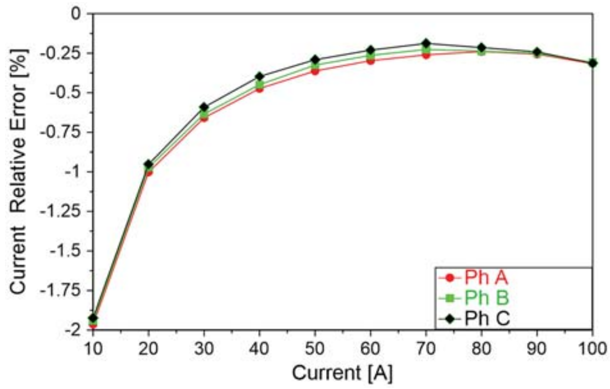

Fig. 4. Maximum relative errors for compensated current measurement under different load conditions.

The results for current and active power measurements, in terms of mean value and standard deviation, are summarized in Table 4, which refers to the worst cases obtained among the three phases and in the presence of 10 %, 50 %, and 100 % of the maximum current.

In particular, two results are shown for active power: the "calculated active power" is the value provided by the new software release from the measurements of voltages and currents, while the "IC active power" is the value directly provided by the SmartPi IC. The differences in terms of maximum relative error can be seen in Fig. 5.

Table 4. Mean values and standard deviation for current and active power under different load conditions.

Load [%]	**Quantity of Interest**					
	Current [I]		**Calc. Active Power [W]**		**IC Active Power [W]**	
	Mean	σ	Mean	σ	Mean	σ
10	9.801	3E-3	2251.5	0.8	2360	1.6
50	49.814	3E-3	11446.7	1.2	11832.4	1.4
100	99.675	2E-3	22894.2	1.7	23639	2.2

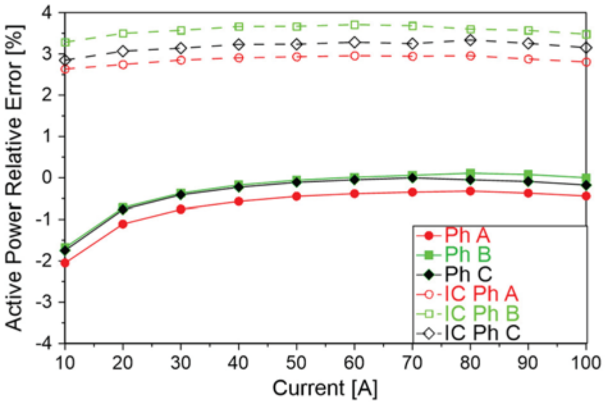

Fig. 5. Maximum relative errors for active power considering the calculated values and the data reported by SmartPI

Concerning measurements of voltage, power factor, and frequency, Table 5 reports the worst case maximum errors during the different load conditions.

Table 5. Maximum errors for voltage, power factor, and frequency under different loads conditions.

Quantity of Interest	Max Error
Voltage	0.44 %
Power factor	-0.0017
Frequency	0.04 %

Focusing on the frequency measurement, the same accuracy level has been achieved under off-nominal conditions, by varying frequency from 47.5 to 52.5 Hz with steps of 0.5 Hz.

Similarly, the same level of accuracy was achieved for the voltage measurements ranging from – 20 % to + 10 % with respect to the rated valued.

Finally, focusing on the capabilities to recognize voltage dips, a three-phase voltage signal is generated, introducing a series of rapid voltage variations with different amplitudes, which are applied sequentially, every ten seconds in each phase, with a duration from 20 to 300 ms. As a dip threshold value, a residual voltage of 90 % was imposed, while the residual voltage in the tests ranged from 80 % up to 10 %. During the tests, the instrument has detected correctly all the voltage events.

b) Auxiliary functions

The auxiliary functions concern the communication capabilities and the power supply of the device. The communication tests are intended to assess the capability to communicate and send data to the external USB memory and the private FTP server. The measurements are collected every second and saved into a file every minute. Finally, the data are sent to the server every hour. The device can communicate with both Ethernet and WiFi connections. During two weeks of laboratory test, the meter was able to save all the measurements both in the local memory and in the cloud, without loss of data.

The meter can be power supplied either from an external 5 V DC or directly from the measured voltage. Commonly, the Raspberry Pi is used with an external 5V power supply, but this standard solution needs a socket in the point of measure. The expansion board adds the possibility of using the second type of power supply, which could make the installation of the measurement device easier.

V. CONCLUSIONS

Low-cost platforms specific for the monitoring of the electric power systems are getting more interest, especially for the prosumers at the distribution level. In this scenario, a commercial low-cost and open-source energy meter has been updated to perform additional power calculations and enhanced power quality functionalities. To overcome the hardware limitations, an embedded software specific for the device has been designed and developed. Moreover, a specific user interface has been created to handle several instruments, making remote monitoring easier. In this way, the developed meter can be a useful instrument and may be used in combination with other, more performing devices, for monitoring a large site.

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