Abstract— This paper presents an innovative smart measurement system, as well as investigates the challenges and trends in the development of distributed Power Quality (PQ) smart measurement systems. PQ monitoring is gaining importance for the customers even for the more sensitive modern equipment. Up today, the control and supervision of an industrial process has mainly been focused on the electrical protection, and little attention has been paid to the quality of the electrical supplies. Nowadays, measurement and communication systems have advanced to enable the installation of web-based sensors within a PQ assessment scenario. In this perspective, we propose a measurement instrument easy to use, chip, flexible, and with advanced world wide web capability. This paper also shows the first releases of prototypes already realised.

Index Terms—Distributed measurement system, Power Quality, (PQ), Smart sensors.

I. INTRODUCTION

Permanent and continuous Power Quality (PQ) monitoring is an emerging topic for an even wider range of users. Traditionally, the PQ problems were confined in the field of industrial sectors, very strictly linked to damages occurred to equipments for the PQ disturbances. Nowadays, instead, practically all the sectors of users are interested to know the quality of the power supply for different reasons.

Industrial users recognize the availability of continuous monitoring of the PQ as an important aid for managing issues. Preventive maintenance can only be initiated if such monitoring is available to detect the minor disturbances that may precede major disruptions. Obviously, the need, regarding the direct damages due to the PQ disturbances, remains of high interest.

Further sectors, like commercial and domestic users, are also interested to the availability of instruments for PQ monitoring for new challenges opened by the liberalized electrical market. In fact, quality objectives are becoming more and more explicit either in the form of contracts negotiated with the distribution company, or as definite objectives stated by the National regulatory bodies. They are going to impose penalties in the case of non-observance of the PQ objectives, like in the case of interruptions in Italy [1].

In this scenario, a measurement instrument for PQ monitoring able to satisfy the requirements of standards with low costs and easy usability also for low tech users is greatly attractive. The technological advances of algorithms and tools for the measurement of PQ disturbances have not yet reflected in the wide availability on the market of instrumentations easy to use, cheap, and adaptable to the needs of users even if not particularly expert of PQ.

The relevant literature presents several contributions that propose different PQ measurement instruments [2-7] complying with the Standards of reference [8, 9].

With reference to the harmonic and inter-harmonic distortion, in compliance with the analysis method of the Standards [8, 9], the measurement instrument is based on a Fast Fourier Transform (FFT) approach. The crucial point of the synchronization process in presence of harmonics and inter-harmonics is solved proposing additional hardware/software solutions to be enforced [2, 3]. Other analysis principles for automatic detection and classification of PQ disturbances were also proposed [4-7]. Some of them are based on time-frequency representations such as wavelet transform or short time Fourier transform, which are assisted e.g. by neural networks or fuzzy expert systems. Other useful solutions are based on the use of digital filters, also based on Field Programmable Gate Arrays (FPGA).

Several proposals in the literature are much focused on the development of low cost sensors. Fewer contributions are aimed to develop user-friendly PQ measurement instruments as in [10, 11]. The characteristic of easy usability is, instead, crucial to provide also to the users of commercial and residential sectors a valid aid to control and assess the PQ level of the power supply.

Paper [10] proposes virtual instruments based on LabView to reach the industrial sector where the virtualization is widely used for managing the automated processes; paper [11]...
describes the project called zEnergy; it is as an integral platform based on an open source approach for software and advanced algorithms for PQ. It is conceived as a community whose members are allowed to contribute their knowledge adding new functionalities by means of customized plugins.

This latter contribution is very attractive also for the recent trends in IoT (Internet of Things) communications [12] where the use of low-cost low-power devices are proposed as a further step toward lower power consumption, improved energy efficiency, and limited electro-magnetic pollution.

For electric systems, the evolution of distribution networks into Smart Grids (SG) combined with IoT has recently been conceived as the Internet of Energy (IoE) [13]. IoE can make use of IoT communication paradigm for the management of SG so it can be envisaged, both for customers and utilities, all the advantages of the most advanced frontiers of communication. In such scenario, this paper presents an innovative embedded prototype for the monitoring and the assessment of PQ. The architecture and the main characteristics of the proposed device, named PiKu, are described in Section II; Section III reports the results of the experimental activities aimed to verify its performances.

II. ARCHITECTURE AND MAIN CHARACTERISTICS OF PiKU

Fig.1 shows the realised system, named PiKu, an open system device with advanced World Wide Web capabilities.

The PiKu releases provide embedded solutions as well as the software and the hardware to interface the electric power system with a notebook or a PC. The utilization of an open-source software, “hacker-spaces” and “makers” hardware components, implies that this prototype will be cheaper and so suitable for sensing and processing many electrical busses and substations.

![Fig. 1. PiKu prototype system](image)

The technological approach proposed is completely different from what is available today on the market that proposes mainly closed systems, much more expensive and less powerful.

PiKu is able to evaluate the classical PQ indices, but it is conceived for easy upgrades to evaluate also new PQ indices and further quantities in compliance with actual and future Standards. In particular, for the harmonic indices, PiKu starts from the computation of the single harmonic components by means of the Fourier analysis. PiKu adopts the grouping procedures reported in [8, 9].

In respect of [8], the RMS value of a harmonic group is the square root of the sum of the squares of the RMS value of a harmonic and the spectral components adjacent to it within 200 ms window.

The instrument allows also the time aggregation on longer time periods. In respect of [9], the duration of the time period can be selected at values of 3s or 10m, allowing in these cases the proper time integration of the harmonic components.

Currently, PiKu presents the following capability:
- Waveform and post-processing data logger
- Monitoring and assessment of harmonic distortion
- Monitoring and assessment of the flicker
- Monitoring and assessment of the unbalance
- Monitoring and assessment of events (voltage dips, swells and interruptions)
- Analysis, visualization and control in both local and web.

PiKu also offers the possibility of integration in the IoT, thus enabling monitoring, commands and post processing even remotely. The system is, in fact, able to be linked with the GSM, Wi-Fi and LAN networks.

The architecture of PiKu is shown in Fig.2; it is mainly constituted by voltage sensors with a conditioning system, in order to sense and adapt the phase voltages, a micro-controller unit, that digitizes and processes the analogue signals, and a Linux based quad-core system to process and store the information.

In particular the software used for the quad-core system, that is the top level software layer, is written in Python. Python is a powerful and open-source programming language. It has efficient high-level data structures and a simple but effective approach to object-oriented programming.

The Python interpreter and the extensive standard library are freely available in source or binary form for all major platforms and may be freely distributed.

![Fig. 2. Block diagram of PiKu](image)

The Python interpreter is easily extended with new functions and data types implemented in C or C++ (or other languages callable from C). Python is also suitable as an
extension language for customizable applications. Another advantage is that it is easy to implement a multi-platform script in order to extend the portability of the developed software.

III. EXPERIMENTAL RESULTS

A number of tests have been executed to compare the performance of PiKu with the results of the measurements effected by means of a reference instrument. To perform such experimental tests, a suitable measurement station has been realized; the corresponding block diagram is reported in Figure 3.

![Block diagram of the experimental set-up](image)

The measurement station of Fig.3 is composed by a power source, the reference instrument, the PiKu and a passive linear load.

The three phase power source is the Pacific 360AMX with the UPC-32 programmable control. Its main features are a maximum voltage of 270 V together with a maximum current of 16 A per phase. The UPC-32 controller allows generating phase voltage and current arbitrary waveforms with harmonic components up to 2500 Hz.

The reference instrument is based on the NI LabView software packages and the Yokogawa DL708E unit. These are full-compliant with standards and allow the measure of all the considered harmonic quantities in the respect of [8, 9]. Its optimal accuracy and synchronization capability make it suitable for our purposes.

Several cases selected from an adequate sensitivity analysis have been experimentally tested by the measurement system mentioned above. Next, for the sake of conciseness, only the following three cases are presented and discussed:

**Case 1: simplified voltages;**
**Case 2: square wave voltage;**
**Case 3: triangular wave voltage.**

**Case 1**

In this case more tests were performed. In the Case 1a) the phase voltages are sinusoidal; in the other cases, from Case 1b) to Case 1d), single harmonic components are present. If present, the value of the harmonic component in each case is equal to the 10 % of the fundamental.

Fig. 4 shows the time evolution of the phase voltage waveforms measured by PiKu. In particular, Fig. 4-a) reports the case of sinusoidal voltage ($V_{rms}=230$ V), Fig 4-b) reports 

the distorted voltage with the presence of the third harmonic, Fig 4-c) shows the distorted voltage with the presence of the fifth harmonic, Fig 4-d) reports the distorted voltage with the presence of the seventh harmonic.

![Time evolution of the phase voltage measured by PiKu](image)

Fig. 4. Time evolution of the phase voltage measured by PiKu: a) sinusoidal case, b) fundamental plus 10 % of third harmonic, c) fundamental plus 10 % of fifth harmonic, d) fundamental plus 10 % of seventh harmonic.

Fig. 5 shows the error on the individual harmonic components of the phase voltages of the waveforms measured by PiKu in the cases 1 from Case 1a) to Case 1d); Fig. 5 also shows the average error on the three phases.

![Histogram of the errors on the phase voltages](image)

Table I shows the results of the various waveform compositions of the Case 1). In particular the results are the value averaged on the three phases of the measured fundamental and of the measured harmonic components. The measurements are effected by the Yokogawa instrument, by PiKu; Table I also shows the corresponding average percentage errors. It is evident that the average error is less than 0.5 %.

<table>
<thead>
<tr>
<th>Case</th>
<th>Voltage Composition</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a)</td>
<td>Sinusoidal</td>
<td>0.1</td>
</tr>
<tr>
<td>1b)</td>
<td>Fundamental + 10%</td>
<td>0.3</td>
</tr>
<tr>
<td>1c)</td>
<td>Fundamental + 10%</td>
<td>0.2</td>
</tr>
<tr>
<td>1d)</td>
<td>Fundamental + 10%</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table I shows the results of the various waveform compositions of the Case 1). In particular the results are the value averaged on the three phases of the measured fundamental and of the measured harmonic components. The measurements are effected by the Yokogawa instrument, by PiKu; Table I also shows the corresponding average percentage errors. It is evident that the average error is less than 0.5 %.
Tab. I. Measured values of the Case 1 for the fundamental and for each harmonic order

<table>
<thead>
<tr>
<th>#Case</th>
<th>Harmonic order</th>
<th>Yokogawa [V]</th>
<th>Piku [V]</th>
<th>ε [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a)</td>
<td>1</td>
<td>230.73</td>
<td>230.71</td>
<td>0.01</td>
</tr>
<tr>
<td>1b)</td>
<td>3</td>
<td>22.96</td>
<td>23.03</td>
<td>0.30</td>
</tr>
<tr>
<td>1c)</td>
<td>5</td>
<td>22.95</td>
<td>22.91</td>
<td>0.16</td>
</tr>
<tr>
<td>1d)</td>
<td>7</td>
<td>22.95</td>
<td>22.91</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Case 2

Fig. 6. a) Time evolution of the phase voltage measured by PiKu in Case 2

Fig. 6. b) Histogram of the errors on the phase voltage at the fundamental and at the harmonics in Case 2

In this case the generating voltage is a square wave as an example of a more complex waveform with respect to the waveforms of Case 1.

Fig. 6 a) shows time evolution of the phase voltage measured by PiKu, and Fig. 6 b) shows the error on the individual harmonic components on each phase voltage and the average error on the three phases measured by PiKu.

Table II shows the results averaged on the three phases. In particular, it reports the average value of the fundamental and of the harmonic components measured by Yokogawa and PiKu instruments and the corresponding average percentage errors. It is evident that in this case the average error is less than 1%.

Tab. II. Measured values of Case 2 for each harmonic order

<table>
<thead>
<tr>
<th>Harmonic order</th>
<th>Yokogawa [V]</th>
<th>Piku [V]</th>
<th>ε [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>207.73</td>
<td>207.93</td>
<td>0.09</td>
</tr>
<tr>
<td>3</td>
<td>69.21</td>
<td>69.31</td>
<td>0.26</td>
</tr>
<tr>
<td>5</td>
<td>41.50</td>
<td>41.59</td>
<td>0.23</td>
</tr>
<tr>
<td>7</td>
<td>29.66</td>
<td>29.78</td>
<td>0.40</td>
</tr>
<tr>
<td>9</td>
<td>23.04</td>
<td>23.21</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Case 3

Fig. 7. a) Time evolution of the phase voltage measured by PiKu in Case 3

Fig. 7. b) Histogram of the errors on the phase voltage at the fundamental and at the harmonics in Case 3

In this case the generating voltage is a triangular wave as a further example of a more complex waveform with respect to the waveforms of Case 1.

Fig. 7 a) shows time evolution of the phase voltage measured by PiKu, and Fig. 7 b) shows the error on the individual harmonic components on each phase voltage and the average error on the three phases measured by PiKu.

Table III shows the results averaged on the three phases. In particular, it reports the average value of the fundamental and of the harmonic components measured by Yokogawa and PiKu instruments and the corresponding average percentage errors. In this case the average error is less than 1% for harmonics up to the 7th order, and lightly greater than 1% for the 9th harmonic.
### Tab. III. Measured values of Case 3 for each harmonic order

<table>
<thead>
<tr>
<th>Harmonic order</th>
<th>Yokogawa [V]</th>
<th>PiKu [V]</th>
<th>ε [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>229.09</td>
<td>229.15</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>25.49</td>
<td>25.56</td>
<td>0.29</td>
</tr>
<tr>
<td>5</td>
<td>9.14</td>
<td>9.10</td>
<td>0.38</td>
</tr>
<tr>
<td>7</td>
<td>4.68</td>
<td>4.69</td>
<td>0.50</td>
</tr>
<tr>
<td>9</td>
<td>2.82</td>
<td>2.85</td>
<td>1.06</td>
</tr>
</tbody>
</table>

### IV. CONCLUSIONS

This paper presents an innovative smart measurement system, conceived and realised in the new paradigm of the IoT. The device, named PiKu, presents advanced capabilities for monitoring, commands and post processing even remotely. The system, in fact, can be linked with the GSM, Wi-Fi and LAN networks.

This paper also shows the first releases of the prototype already realised, and some experimental results obtained during laboratory activities for testing its functioning on distorted voltage waveforms. The first results confirm its appreciable performance. More developments are in progress to evaluate PiKu for other PQ disturbances, like voltage dips and swells.

### REFERENCES


