Web-based Application for Mapping of the Power Quality Level in the Power Distribution Grids

Denisa Rusinaru, Leonardo Geo Manescu, Marian Ciontu, Adrian Cojoaca, and Miron Alba

***Abstract*—** Poor power quality has negative consequences on the performances of the power networks' operation. Therefore the efforts of the power grids operators are perfectly justified for finding the best tools for managing and analysis of the power quality (named here PQ). This paper has focused on PQ investigation based on a new type of information report. According to this, the disturbances are reported by using the ranking of PQ levels based on normalized parameters. The paper presents the capabilities of a web-based application designed for mapping of the normalized PQ parameters, as an additional function of the integrate complex system for the management and analysis of PQ data presently operating in the local power distribution grids. This application is developed within a collaboration between the local power grid operator and the power engineering research unit of University of Craiova.

***Keywords*—** power distribution, power quality, web-based application.

I. Introduction

STARTING from the current situation and considering the evolution of the distributed generation (DG) sources connected to the power distribution grids (PDG), as well as the prerequisites for them moving toward the Smart Grids concept, there is a need for the comprehensive assessment of the impact of DG in terms of technological and performance indices, including PQ. In accordance with the Performance Standard for Power Distribution Service [1], the local power distribution grids' operator (DGO) must assume the obligations regarding: (1) Keeping within standards of the power reliability and quality; (2) Monitoring the power quality (PQ) and supply reliability.

Usually, the dedicated control and measurement systems of the power grid operators allow the PQ monitoring for a large number of supplying buses in their networks. Since this activity involves the management of a huge volume of data (GBytes order), derived from various vendors and technologies, the management of the PQ database is critical [2]. Most of the measurement equipment has own software that can be used as platforms for database management. It is preferable that the monitoring software to provide COMTRADE or PQDIF format data (specific to PQ parameters) [3] so that specialized analysis can be performed with an integrated platform (e.g. PQView® [4]) by using unitarily formatted input data.

The existing database provides a reference for the current PQ level, as well as for the evolution prospects of PDGs. This database is presently used by the local DGO to develop a standard monitoring procedure for setting the global or local PQ level. Moreover, maintaining a PQ data collection infrastructure in a very large number of locations over a very long time is time-consuming and prohibitive (the cost of purchasing equipment with the required performance amounts to approximately 10000 Euros).

The DGO's are constantly concerned about improving the services for their networks' users by investing in solutions for a higher transparency of the information, a more efficient complaints answering & settlement service, as well as the integration and developing of the Smart Grid concept [5, 6].

These considerations ask for an intelligent PQ management system for which clear criteria for data acquisition and methods for their reconstitution and management should be defined. Such kind of system is currently used and is being further developed by our local DGO.

Extending the functionality of the actual system is a project performed by the local DGO in collaboration with the University of Craiova within a knowledge/technology transfer project. This complex software system is designed to assists the utility's planners in analyzing the impacts of the network's users (including DG) on the PQ in the distribution grids. It also supports achieving regulatory compliance, and reliability enhancement by designing and implementing mitigation solutions for PQ disturbances. The application includes also a module for labeling and mapping of the PQ level, entitled MAPPQ, which is further introduced in this

This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS/CCCDI – UEFISCDI, project number PN-III-P2-2.1-BG-2016-0269, within PNCDI III.

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paper. Conceived as a web-based application, MAPPQ is an in-house developed product that facilitates the information accessibility of the utility's personnel regarding the PQ matters in the whole power distribution grid, in a unitary, compact and easily interpretable format.

II. PQ Regulation in Romanian Power Distribution System

According to the national regulation, the power distribution grid operators and their networks' users have certain obligations for keeping of PQ parameters within the limits specified in the Technical Code of the Distribution Grid [7] and the Performance Standard of Power Distribution Service (named here PSPDS), which are in accordance with the limits defined by EN 50160 (for LV and MV networks). These documents are issued by the Romanian Energy Regulatory Authority (named here ANRE) and define the national PQ regulation framework.

While DGO should guarantee the PQ minimum levels set as objective in the bilateral agreements/contracts, its networks' users should not exceed the maximum levels for emissions to the system. Otherwise, they may be required to find a mitigation solution, especially if they are established to impact the PQ delivered to other customers. Nevertheless, currently in Romania the technical approvals for the connection in the network, as well as the frame contracts for the large consumers provide no requirements for them to observe certain PQ indicators in the points of common coupling (PCCs) and boundary buses. The exception is made in the cases of issuing the connection approval for the wind power and photovoltaic plants.

According to PSPDS, the parameters' limits for four PQ disturbances should be guaranteed by DGO at the interface with it's' grids users: slow voltage variations, voltage fluctuations, rapid voltage changes (normal operation), unbalances voltage, and waveform distortions. PSPDS considers the following objectives for PQ parameters:

1) *Slow voltage variations*

During one week, under normal operating conditions:

- 95% of the 10-min RMS voltage should be within U_n ± 10% and 100% of the 10-min RMS voltage should be within +10% / -15% for LV system;
- 99% of the 10-min RMS voltage should be within U_c ± 10% and 100% of the 10-min RMS voltage should be within U_c ± 15% for MV and HV system

where U_n is the nominal voltage of the system and U_c is the declared supply voltage.

2) *Voltage fluctuations*

PSPDS regulates the long-term flicker severity, P_{lt}. This one is calculated from a sequence of 12 P_{st} values (short-term 10 min flicker severity) over a 2-hours interval, according to (1):

$$P_{lt} = \sqrt[3]{\frac{\sum_{1}^{12} P_{st,i}^3}{12}} \quad (1)$$

The 95[th] percentile value of P_{lt} should not exceed the unity over one week.

3) *Supply voltage unbalance*

PSPDS regulates the voltage unbalance quantified by ratio between the negative-sequence voltage component V_- and the positive-sequence voltage component V_+:

$$k_{U-} = \frac{V_-}{V_+} 100 \quad (2)$$

For the LV and MV systems, the 95% probability weekly value of negative-sequence voltage unbalance factor should be within 2%; in some areas the voltage unbalance may be up to 3% (i.e. single-phase traction). In HV systems the objective is 1%.

4) *Harmonic distortion*

There are two waveform distortion parameters that are regulated in accordance with PSPDS: the individual voltage harmonic and the total voltage harmonic distortion factor, defined as in (3).

$$THD = \frac{\sqrt{\sum_{2} V_h^2}}{V_1} 100 \quad (3)$$

where V_h is the RMS value of the *h-th* harmonic component;
V_1 – the RMS value of the fundamental component.

Under normal operating conditions, in any period of a week the 95% value of THD shall not exceed 8% for the LV and MV system. In the case of HV grid, the objective is 3%.

Knowledge of PQ at the interconnection buses between the power distribution grids and their users and referring their parameters to the regulated limits allows a better assessment of the system operational conditions, the causes of PQ disturbances and the appropriate measures for PQ compliance. Therefore, the local DGO has registered important efforts for developing a high-performance system for permanent PQ monitoring in the MV and 110 kV grids. A complex software application PQView was implemented in order to manage and analyze the PQ data supplied by this system.

Some other extended functions are further added to the system in order to facilitate the PQ issues understanding and to provide useful information for locating the origin of disturbance, their direction or membership area.

III. The Concept of PQ Levels Ranking by Using Normalized PQ Parameters

Normally, a great volume of PQ data supplied by long terms measurements gives a better knowledge and control of the power grid operation. On the other hand, a large data volume is difficult to be processed, asking for great computer resources and a well-defined computing algorithm. An efficient solution proved to be based on a ranking procedure able to generate output general information more easily to be analyzed and understandable.

Moreover, while some grid users have the possibility under contractual agreement to claim for compensation in case of a poor quality of the delivered power, an important number of customers do not have either technical knowledge or proper information to claim for acceptable PQ level. Nevertheless, there are European grids operators initiatives answering to this situation (e.g. distribution power grid operator in the Netherlands) that have proposed an easy classification system based on PQ labeling and ranking of PQ global levels [8, 9].

This ranking format can be extremely useful for simplifying the dialogue between a grid operator and its customers regarding the PQ expected conditions and the non-compliance consequences. For the DGO it is important to facilitate the communication with the end-users, by proceeding to the aggregation of large amounts of the measured PQ data into a single index of quality.

Based on a familiar model applied for instance to classify the energy efficiency of household appliances or to assess the clients' eligibility in the bank system, the PQ ranking uses also an alphabetical representation and a color code for quantifying the PQ levels in the sites of the distribution grid [10].

A. The concept of PQ level ranking

This procedure assumes performing two operations:
1) Defining a set of normalized PQ parameters, related to the standard limits (provided by PSPDS);
2) Introducing a hierarchy of PQ levels based on normalized parameters and using corresponding labels.

The first step forwards the defining such kind of classification system is to normalize those parameters considered important for the power grid operation and regulated by PSPDS. According to [7, 8], similar normalized parameters can be used for quantifying a PQ continuous disturbing phenomenon at points of common coupling PCC, as following:

$$p_{norm}(l,f) = 1 - \frac{|p_{m/e}(l,f)|}{L} \in [-1,1] \quad (4)$$

where p_{norm} is the normalized PQ parameter;
l- index of the PQ disturbance location;
f - phase index;
$p_{m/e}$ - current level of PQ parameter, measured/estimated by calculus;
L - standard objective (limit) of the PQ parameter.

By using this ranking system, the PQ standard compliance can be rapidly observed. Table 1 includes the PQ parameters regulated accordingly PSPDS for the distribution grid, as well as the corresponding normalized parameters.

An even more sensitive ranking (e.g. proposal in [10]) allows:
- Finer differentiation of PQ status in power distribution system;
- General estimation for the direction of PQ disturbances propagation or the area where these are located;
- Knowing the current disturbance level preceding a user's connection at the PCC's in order to inform the present end-users about the disturbance shares allowed to avoid exceeding the limits;
- Concluding a transparent voltage quality contract between the grid's users.

TABLE 1. DEFINING THE NORMALIZED PQ PARAMETERS REGULATED BY PSPDS IN MV GRIDS

PQ disturbance type	Current PQ parameter	Normalized PQ parameter
Supply voltage variation	Measured (95% of 10-min weekly values), [kV]	$p_U(l,f) = 1 - \frac{\lvert U_m(l,f) - U_n \rvert / U_n}{0.1}$ (5)
Flicker severity (long-term)	P_{lt} (95% value over a week)	$p_{flick}(l,f) = 1 - \frac{P_{lt,m}(l,f)}{1.0}$ (6)
Voltage unbalance	k_{U-} (95% value over a week), [%]	$p_{unb}(l,f) = 1 - \frac{k_{U-,m}(l,f)}{2.0}$ (7)
Voltage harmonic distortion	VTHD (95% value), [%]	$p_{THD}(l,f) = 1 - \frac{THD_m(l,f)}{8.0}$ (8)

The values of the normalized parameters allow establishing of a hierarchy of the PQ levels within the limits identified as VERY POOR (PQ) and VERY GOOD (PQ). This domain is divided into several sub-domains alphabetically and colorfully coded. An example is given in Table 2.

TABLE 2. NORMALIZED PARAMETERS BASED RANKING OF PQ LEVELS

Value of PQ normalized parameter	PQ conditions	Label	PQ level
0.5...1*	disturbance level within standard admissible limits	A	VERY GOOD
0...0.5		B	NORMAL
-0.5…0	disturbance level exceeds the admissible limits	C	POOR
-1…-0.5		D	VERY POOR

* No PQ disturbance for unitary value of p_{norm}.

A general assessment based on the PQ ranking procedure in the strategic sites of PDG involves the following steps:
1) Measurement of PQ parameters over a standard time period in a minimum number of sites in order to characterize the electrical environment.
2) Defining a set of PQ parameters in normalized format easy to interpret/analyze.
3) Setting the domain for ranking the PQ level based on the previous defined parameters.
4) Mapping the disturbances for the system buses.

On these maps each bus is identified by PQ normalized parameters having assigned the label shaped and colored in accordance with the PQ level.

B. Mapping of the PQ levels in power distribution grid

A set of PQ measurements collected in 110 kV and 20 kV buses of the local power distribution grids was processed in order to exemplify the PQ assessment concept based on the geographic distribution of PQ level labels.

The computed data were acquired from fixed PQ monitors integrated in 400 sites of the local DGO. The data are collected permanently, supplying sets of 7x24x6=1008 ten-minute average-values per site per week. The 95th percentile values of the PQ parameters are consequently computed.

The parameters extracted from the PQ database for labeling and mapping are the following: supply voltage variations, voltage harmonic distortion, voltage unbalance, and flicker.

In the analyzed grid's buses a snapshot view on the PQ level is given based on the ranking principle. The ranking of the PQ levels is depicted on Fig. 1-2, with the 95% values and corresponding normalized values given in Table 3.

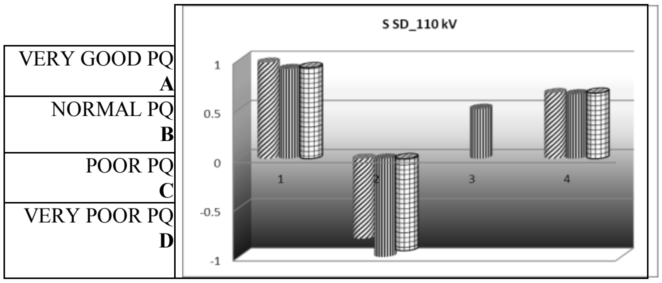

Fig.1. Labeling of PQ parameters at SS3_6 kV

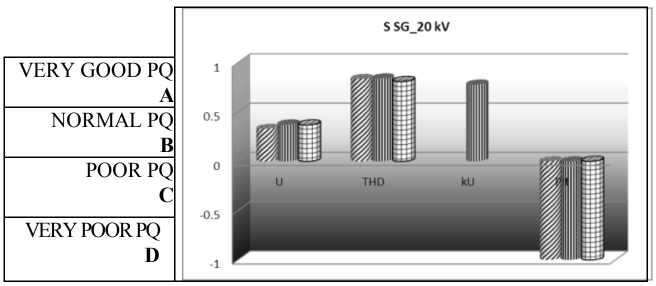

Fig. 2. Labeling of PQ parameters at SG_20 kV

TABLE 3. SUMMARY ON THE PQ PARAMETERS (3 PHASES)

Bus ID	PQ parameter	95% values	PSPDS values	Normalized values	PQ label
SD_ 110 kV	Voltage variations U	110.258 110.965 110.825	± 10%	0.9765 0.9122 0.9250	A A A
	Voltage distortion THD	***5.440*** ***6.005*** ***5.808***	3 %	***-0.8133*** ***-1.0000*** ***-0.9360***	***D*** ***D*** ***D***
	Voltage unbalance k_{U-}	0.493	1 %	0.5070	A
	Flicker P_{lt}	0.333 0.345 0.334	1.0	0.5837 0.5687 0.5825	A A A
SG_ 20 kV	Voltage variations U	21.340 21.250 21.260	± 10%	0.330 0.375 0.370	B B B
	Voltage distortion THD	1.310 1.260 1.510	8 %	0.836 0.842 0.811	A A A
	Voltage unbalance k_{U-}	0.441	2 %	0.780	B
	Flicker P_{lt}	***2.000*** ***2.100*** ***1.800***	1.0	***-1.000*** ***-1.000*** ***-1.000***	***D*** ***D*** ***D***

Using this condensed information the graphical report can be drawn up as PQ disturbances maps. Fig. 3 illustrates the concept of the PQ disturbances mapping in the analyzed grid.

The PQ state representation by using the disturbance maps has some certain advantages:

- It simplifies the format containing essential information for PQ assessment at the interest buses, so that the map`s user can understand more easily the PQ state in its network.
- It offers a compressed and unitary representation of the regulated PQ parameters.
- It allows DGO to locate preliminarily the main PQ disturbances sources in its grid. Further a preliminary evaluation of the planning limits of the PQ disturbances can be made.
- It makes more efficient the dialogue of the DGO with its grid users.

The symbols of PQ parameters used for buses identification on the disturbances map are:

Δ	Voltage value variation
▱	Voltage total harmonic distortion THD
◊	Voltage unbalance factor k_{U-}
□	Flicker indicator P_{lt}

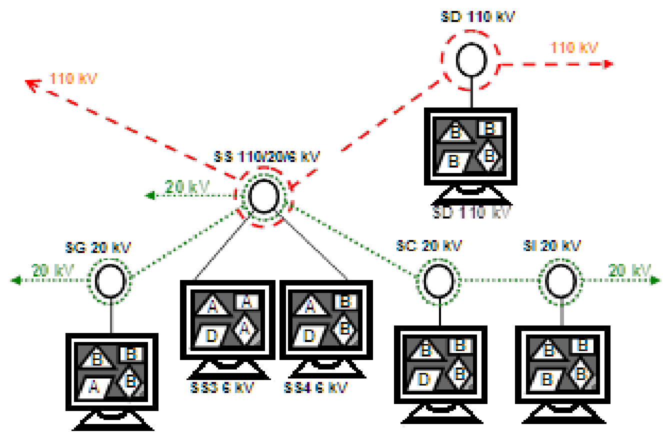

Fig. 3. Mapping of PQ disturbances in selected area of a distribution network

IV. MAPPQ – WEB –BASED APPLICATION FOR MAPPING OF POWER QUALITY IN POWER DISTRIBUTION GRIDS

The monitoring of PQ in the local PDGs is presently achieved by using three systems: (1) the PQ monitoring system (including almost 100 fixed PQ monitors MAVOSYS) connected to a central server and managed by PQView multi-component system; (2) the system for PQ monitoring at the interface between the distribution network and its users, without a central data management center. In the points of common coupling (PCC) with the distribution grid all the photovoltaic (PV) power plants are obligatorily equipped with PQ analyzers with remote data transmission; (3) the power monitors system (i.e. MEG) connected on the LV side of 20/0.4 kV substations. In order to answer to the customers' requests and/or complaints, the monitoring of PQ is periodically achieved by using portable PQ analyzers. For an additional assessment of the power supplying service partly of the central control and command system are used, too.

The local DGO uses PQView software system in order to manage, analyze and report the PQ data gathered from PQ monitors, as well as digital relays, fault recorders, smart meters, and SCADA.

The processing of the data acquired from the real metering system of the power utility, as well as their reporting into an intelligible format requires not necessarily a sophisticate graphical user interface, but rather a properly adjusted to user needs one. In the framework of a joined DGO-university project a software system was developed (SYMMPQI) [11] in order to facilitate this option. SYMMPQI is capable to assist DGO with analysis based not only on the typical operation regimes of a power grid, but also on the real historical evolution of its electric parameters.

An important component of SYMMPQI is MAPPQ, a web-based modular user-friendly component, which is suitable for continuous PQ general assessment in distribution grids. Its main purpose is to increase the accessibility of the local DGO's personnel to the PQ information managed by the centralized software PQView.

At the current stage of the development, MAPPQ has a browser-based user interface allowing a geospatial visualization of PQ level, by using the Google Maps™ mapping service. The database and analytical capabilities allow reading and writing data from .csv files to a MySQLdatabase, assigning them on sites. PQ labels for data evaluation are further dynamically generated with the help of some database query, and further placed on a map provided by the Google Maps API service. MAPPQ allows interactive, color-coded, geographic display of the locations of the PQ labels, and consequently of the disturbance sources.

The application is based on a three level system:

1) The *client level* presents data to and collects data from the user

2) The database level stores and retrieves the data

3) The middle level brings together the other levels: it drives the structure and content of the data displayed to the user, and it processes input from the user as it is formed into queries on the database to read or write data.

Basically, the components of the middle level are a web server, a web scripting language, and the scripting language engine. A web server processes HTTP requests and formulates responses. In the case of web database applications, these requests are often for programs that interact with an underlying database management system, in our case MySQL DBMS.

The PHP scripting language was used as the middle level scripting language. PHP is an open source project of the Apache Software Foundation.

The architecture of the application is given in Fig. 4.

A. MAPPQ tables (MySQL tables)

For the MAPPQ use, two tables were created:

1) The “***station***” table - contains attributes of the markers on the map. The columns of the table are the following attributes: „id_station”, „station name”, „lat”, „lng” and „type”.

id_station	serves as the primary key
lat / lng	allows the fields to store 6 digits after the decimal, plus up to 4 digits before the decimal
type	stores the label’s path in memory (on server)

The phpMyAdmin interface is given in the Fig.5 with the query necessary to generate the "station" table.

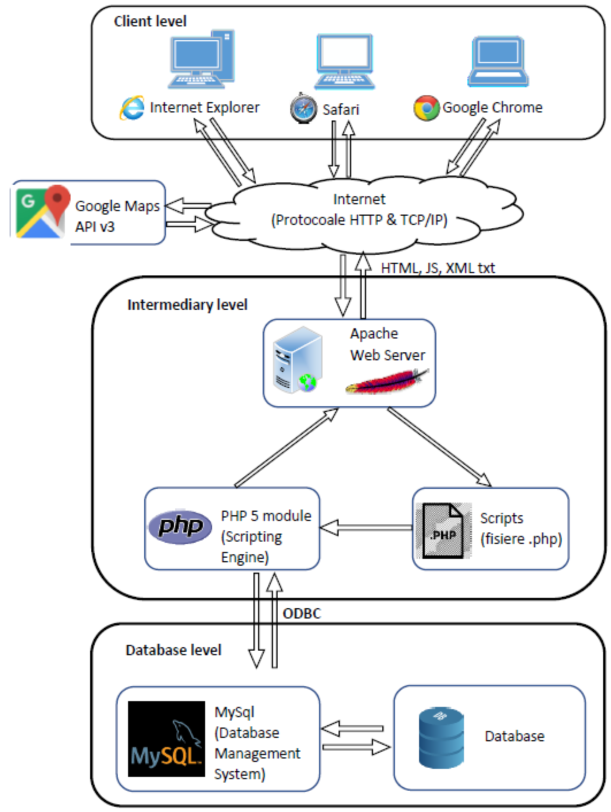

Fig.4. The architecture of MAPPQ web-based application

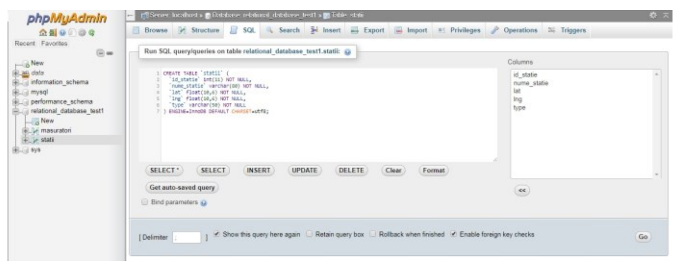

Fig.5. The architecture of MAPPQ web-based application

2) The "***measurements***" table stores the data extracted from *.csv files obtained from the PQ monitor system. The columns of the table are: id_mas, id_station, data, time, u1_rms, u2_rms, u3_rms, u1_thd, u2_thd, u3_thd, plt1, plt2, plt3, k_u.

id_mas	serves as the primary key
id_station	corresponds to the primary key in table "station" (the name of a site changes in time).
u_rms, u_thd, plt, k_u	corresponds to the measured data

B. Mapping PQ labels interface

The application allows to the user to navigate and select the .csv file corresponding to chosen site (given that are in the "station" table). Further, the data are uploaded and written into the MySQL database.

Next step, the user is completing the text boxes with calendar dates, in order to extract a report on the needed. This operation triggers a series of MySQL queries, which extracts from the database the mean and the standard deviation of the electrical measured values and perform others computations in order to return PC95% for each PQ parameters involved.

With the help of a PHP echo, the values are displayed in a browser – see Fig. 6.

Fig. 6. MAPPQ interface for configuring outputs

By appealing “Map”, the PHP functions, based on the previous computations, sorts and concatenates distinct pictures to form the label, which is saved in a specific memory location. The table "station" is also updated with the label path corresponding to its own site. After that, a XML file is generated, being loaded by the JavaScript code that displays the map with the labels, as in Fig. 7.

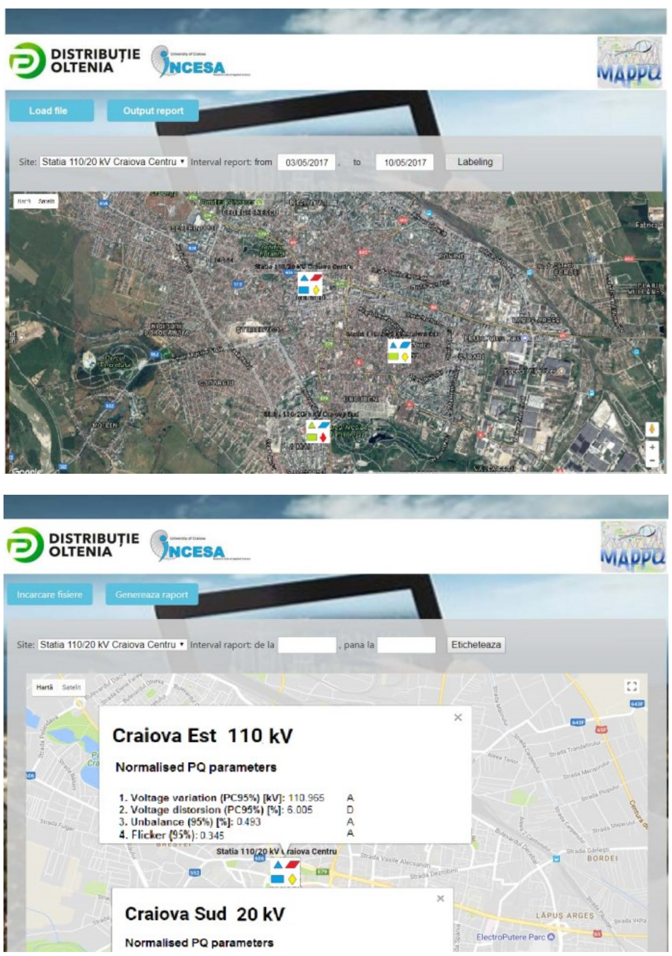

Fig. 7. MAPPQ graphical user interface for mapping PQ levels in PDG

The personnel should be authorized to access the mapped labels, and authorized measuring points are concluded with the logging into this solution. After logging in, the main page with basic information is presented. Nevertheless, no extensive knowledge about PQ issues is required for interpreting the level of disturbance in the network

V. Conclusions

This paper has focused on presenting a web-based application integrated in the actual complex software system specialized for the management and analysis of the PQ measurement data in the substations of the local power distribution grid. The application entitled MAPPQ increases the accessibility of the network operator's personnel to those information hold by the centralized software PQView, used by the DGO to analyze and manage the power quality (PQ) parameters in its grid.

MAPPQ is designated to support the activity of distribution company personnel in assessing the PQ level in a unitary and easy-to-understand format. The PQ levels in the monitored sites of PDG are labeled according to a color code similar to the energy efficiency ranking. The resulting labels are mapped according to the geographic position of the surveyed substations and contain the compact unitary information about PQ parameters represented.

The application will be available from mobile devices as well, and can be used by the company’s members, without asking for further knowledge in PQ field.

References

[1] The Electricity Distribution Service – Standard of Performance, Romanian Standard 2016 (OG 11/2016), www.anre.ro.

[2] M. Music, N. Hasanspahic, A. Bosovic, D. Aganovic, S. Avdakovic, “Upgrading smart meters as key components of integrated power quality monitoring system”, *EEEIC 2016 - International Conference on Environment and Electrical Engineering*, August 2016, Paper 7555554.

[3] IEEE, 2008, IEEE Std 1159.3 Recommended Practice for the Transfer of Power Quality Data.

[4] PQView User Manual and Quick Start Guide, Electrotek Concepts, Inc., 2013. Available: www.pqview.com.

[5] M. Music, A. Bosovic, N. Hasanspahic, S. Avdakovic, E. Becirovic, “Integrated Power Quality Monitoring Systems in smart distribution grids”, 2012 IEEE International Energy Conference and Exhibition (ENERGYCON).

[6] S. Gheorghe, G. Gheorghe, N. Golovanov and C. Stanescu, “Results of power quality monitoring in Romanian transmission and distribution system operators”, International Conference on Applied and Theoretical Electricity (ICATE), 2016, Craiova, Romania, Paper 4.10.

[7] The Electricity Distribution Grid - Technical Code, Romania, 2009, www.anre.ro.

[8] W.T.J. Hulshorst, E.L.M. Smeets, J.A. Wolse, “Premium Power Quality contracts and labeling”, 2007, Available: www.leonardo-energy.org.

[9] Cobben, J.F.G., van Casteren, J.F.L., Classification Methodologies for Power Quality, Electrical Power Quality and Utilization Magazine, vol.I, no.1, 2006, pp. 11-18.

[10] D. Rusinaru, L.G. Manescu, M. Merfu, P. Postolache, “Power quality general levels in distribution networks”, *16th International Conference on Harmonics and Quality of Power (ICHQP)*, 2014 IEEE, Bucharest, Romania, 25-28 May 2014, pp. 58 – 62.

[11] L.G. Manescu, D. Rusinaru, C. Popirlan, G. Stoian, M. Ciontu, G.C. Buzatu, M. Alba and A. Cojoaca, “Complex Software System for Data Management and Analysis of Power Distribution Grids,” presented at the International Conference Mathematics and Computers in Sciences and Industry MCSI 2017, 24-27 August 2017, Corfu, Greece, Paper mcsi-142.