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Review

Grid Nodes Selection Strategies for Power Quality Monitoring

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Abstract: In the past few years, technical progress has determined traditional electric power system conversion to Smart Grids, and consequently empowered a worldwide renaissance in the forgotten PQ field. Since the installation of PQ monitors is currently associated with high investments and operational costs, it is inappropriate to install a monitor on each grid busbar. Hence, grid operators must establish the best cost–benefit scenario for monitors installation and achieve maximal observability with a limited number of analyzers. Firstly, this paper presents a review of the state-of-the-art of displacement strategies, and discusses them regarding the tendencies of node selection criteria, the test schemes used, and the grid size. Secondly, the relevant fundamental issues which must be solved in the future in order to eliminate restrictions in PQ monitors' allocation planning are presented and discussed. These issues concern the treatment, interpretation, and assessment of PQ events, measurement chain technical features, PQ's role in the grid planning stage, communication technologies, and other remote monitoring aspects, and integration with other Smart Grid applications. The provided insights are based on experience which has been obtained during the PQ measurement campaign in the Lithuanian DSO grid. Finally, a PQ system development strategy—both short-term and long-term perspectives—in the Lithuanian distribution grid is presented, including monitors allocation criteria.

Keywords: Smart Grid; power quality; monitoring; nodes prioritization; allocation strategy

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Citation: Liubčuk, V.; Radziukynas, V.; Naujokaitis, D.; Kairaitis, G. Grid Nodes Selection Strategies for Power Quality Monitoring. *Appl. Sci.* **2023**, *13*, 6048. https://doi.org/10.3390/app13106048

Academic Editor: Hannu Laaksonen

Received: 30 March 2023
Revised: 28 April 2023
Accepted: 6 May 2023
Published: 15 May 2023

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1. Introduction

The development and smooth operation of the Smart Grid is impossible without various monitoring systems. One of them is power quality monitoring—the newly emerging field which has been attracting more and more attention in recent years.

Power quality (PQ) is both a qualitative and quantitative set of characteristics, defining voltage, current (in case current phenomena are not classified as electromagnetic compatibility (EMC) phenomena (as in Europe) but as PQ events, i.e., according to IEEE standards practice), their waveforms, and frequency compliance with the established requirements. PQ assessment and compliance verification is impossible without a monitoring process. The general structure of a PQ monitoring process is presented in Figure 1. The existence of a communications block defines whether the monitoring is remote or non-remote. Figure 1 shows an extended EN 61000-4-30 structure of a non-remote PQ monitoring process: a communication block is added, and consequently, the data processing part is separated into local and central processing.

Low PQ may seriously damage both sensitive loads and grid equipment, cause malfunctions of devices, decrease the power supply reliability, and increase the outage time of factories, which inevitably leads to huge economic losses and the deterioration of manufactured goods quality. Measurements are essential for situation assessment; however, PQ monitors installation is associated with high investments and operational costs. Ideally, PQ monitors must be installed on each busbar. However, full coverage is hardly implemented since a fundamental economics problem arises: the mismatch between the scarcity of resources and unlimited needs. Thus, a selection strategy for grid nodes should be determined in order to achieve the maximal (desired, optimal) observability with limited resources.

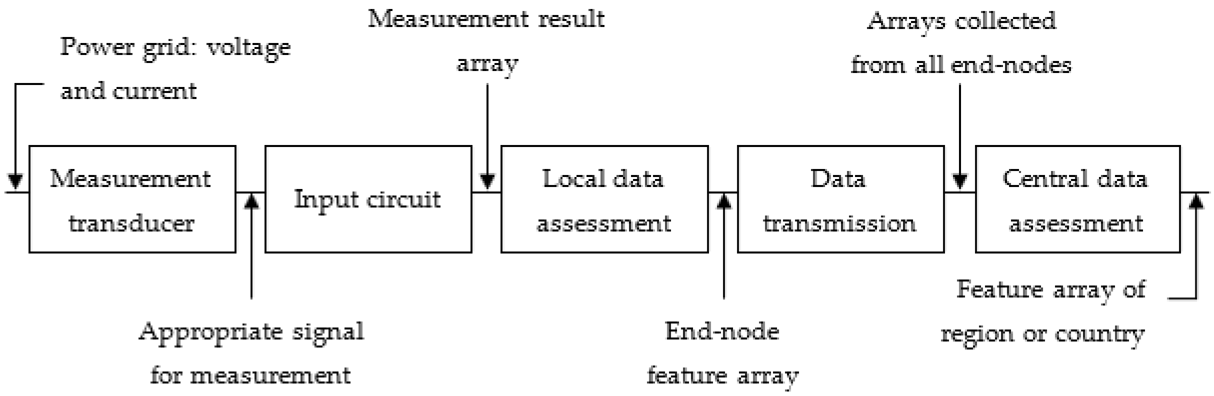


Figure 1. Structure of a remote PQ monitoring process: extended IEC 61000-4-30 block diagram of a non-remote PQ monitoring process.

In general, the prioritization strategies for nodes depend on the desired aim. Based on the authors' knowledge, the aim can be classified into two main groups regarding the main focus, focusing on either the customer or the electrical grid. Some examples are provided below:

1. Focus on customers—mainly low-voltage (LV) grid monitoring:
   - Industrial customers' complaints: point of common coupling (PCC) monitoring or any in-plant grid point monitoring.
   - Industrial, commercial, and residential customers' installed power ratio.
   - Load types: for example, priority to large electric motors or critical loads (i.e., sensitive to voltage sags, harmonics).
   - Random selection of PCC or other nodes for short-duration measurements with portable PQ monitors.
   - Yearly energy consumption.
   - Critical and problematic nodes which are known a priori by DSO.
2. Focus on the electric power grid—mainly high-voltage (HV) and medium-voltage (MV) grid monitoring:
   - Most critical substations and their technical conditions (for example, the availability of communications for remote monitoring).
   - Connection points of power plants or other PQ-mitigating devices, such as capacitor banks, synchronous compensators, surge arresters, etc.
   - Penetration of distributed generation and renewable energy sources.
   - Line length and presence of HVDC lines.

In addition, the type of monitoring must be considered. Firstly, measurements can be performed with either a fixed or a portable PQ monitor, a smart meter, or another device. Each option has its own features, such as measured PQ events, sampling frequency, accuracy, and cost. Secondly, monitoring can be either remote or non-remote. In the case of remote monitoring, additional communication issues must be addressed, but many advantages are offered, such as: diminished resources (time, human, transport) for data gathering, easier to process data, fast data loss, and error detection, etc.

The main aim of this paper is to examine the current state-of-the-art methods of PQ nodes selection and discuss and expand them with our own insights, experience, and proposals (including future prospects).

2. Literature Review

2.1. Legislation and Policy

Legislation is perhaps the most important factor promoting PQ monitoring and compliance verification. In the PQ field, legislation mainly consists of standards. In general, standards are not mandatory unless they are mentioned in national or international (e.g., European Union) legal documents. There are some additional nuances regarding European harmonized standards and national legislation (e.g., in Lithuania, along with the main PQ standard LST EN 50160:2010, time limit values for supply interruptions are added) but any detailed analysis of these cases is not relevant to the scope of this paper. Two main PQ standard groups defining different PQ concepts can be highlighted—European and North American (IEEE standards). In Europe, voltage phenomena are regarded as PQ events (in most cases, requirements are determined for grid, system), and electric current phenomena are regarded as EMC events (in most cases, requirements are determined for end-user equipment; but there are some exceptions, for example, IEC 61800-3). On the contrary, different PQ concepts and definitions are given in the IEEE standards, a more extended classification of PQ events is presented, and both current and voltage phenomena are regarded as PQ events (or at least closely related). Moreover, IEEE standards often highlight a good practice from the EMC standards (which are European harmonized standards, which are (can be) used to verify compliance with relevant European or EU legislation). Therefore, the analysis of world standards completeness, adequacy and comprehensiveness is perhaps the most important factor for world experience evaluation. The main PQ standards are listed below:

- EN 50160:2010 "Voltage characteristics of electricity supplied by public electricity networks" [1]. This European standard focuses on the PQ phenomena definition, normalization, and is imperative in most European countries.
- IEC 61000-4-30 "Electromagnetic compatibility (EMC)—Part 4–30: Testing and measurement techniques—Power Quality measurement methods" [2]. This harmonized standard defines the methods for measurement and interpretation of results for PQ parameters in an AC power system with a declared fundamental frequency of 50 Hz or 60 Hz. Measurement parameters (covered by this standard) are limited to conducted phenomena in power systems. Requirements for some parameters such as accuracy and dynamic range are given for part PQ events. However, the standard does not provide any information about appropriate measurement instruments' displacement and its importance.
- IEC 61000-4-7 is a harmonized standard which defines methods for voltage harmonics and inter-harmonics measurement, thus is outside the scope of this paper.
- IEC 61000-4-15 is a harmonized standard which defines methods for flicker measurement, thus, is outside the scope of this paper.
- IEEE Std 1159-2019 "Recommended Practice for Monitoring Electric Power Quality" [3]. This North American standard focuses on PQ phenomena definitions and provides more detailed and unique approaches than those of EN 50160. In contrast to EN 50160, current (including EMC) phenomena along with voltage are treated as either closely related or PQ events. Moreover, IEC EMC standards are often mentioned as a good practice. Despite being more informative, IEEE Std 1159 does not include any normalization (limits), but gives some important practical ideas about monitors' displacement:
    - PQ situation of monitored node depends on the monitor's proximity to the source, system impedances, and dynamics of the load;
    - Initial locations of PQ meters depend on the objective;
    - If the objective is to investigate the overall PQ of a facility supply, a monitor should be placed on the secondary winding of the main entrance transformer. The monitor can be moved down-stream for situation assessment in individual feeders;
    - If the objective is the harmonics, a monitor should be placed at the terminals of filters or other equipment (selected for investigation);
    - The monitor should be installed as close to the investigated symptomatic load as possible. It should be verified that filters, transformers, or other PQ mitigating devices are not connected in between;

- When measurements are taken in a higher voltage grid, monitoring allocation flexibility is reduced, because measurement transducers are essential (i.e., current and voltage transformers). According to IEEE Std 1159, many instruments are capable up to 600 V RMS direct measurement. The magnitude and phase frequency response of most measurement transformers can significantly distort measurement results since they were originally designed for fundamental grid frequency (only for energy accounting).

To conclude, provided ideas highlight the importance of appropriate monitors allocation for correct PQ situation assessment (not only for economic reasons, but also for technical and data processing).

- IEEE Std 1159-3-2019 "IEEE Recommended Practice for PQ Data Interchange Format (PQDIF)" [4]. The standard defines a unique file format (data packet structure) suitable for exchanging PQ related measurement, thus this is out of this paper scope.
- IEEE Std 519 provides limit values for voltage and current harmonics at the PCC; thus, this is out of this paper scope.
- IEEE Std 1564 defines different characteristics and indexes associated with voltage sags; thus, this is out of this paper scope.

In addition, the review can be supplemented with Smart Grid standards, and especially IEEE Std 2030-2011, the "IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power Systems (EPS), End-Use Applications, and Loads" [5]. The document focuses on the Smart Grid as a whole, and its components' interoperability. IEEE Std 2030 can be treated as the best in the world in the field of Smart Grid communications providing a guideline, knowledge base addressing terminology, fundamental principles, characteristics, functional performance, and evaluation criteria for an electric power system with end-use applications and loads. However, in the document, there are almost no mentions of PQ or any description.

2.2. Scientific Papers and Practical Reports

Despite there being no legislation dedicated to PQ monitors' allocation, the absence does not reduce the importance of the issue which can improve a project's cost-effectiveness. Many studies have been carried out to investigate how to optimize PQ monitors' allocation. In addition, different PQ monitoring campaigns have been executed over the past few decades in various countries. For this paper, only those researches were selected which are directly related or can be indirectly examined through a prism of PQ monitors' allocation strategy. Most of the practical and theoretical research is described in scientific papers, but other sources can also be found (e.g., grid operator report). In this subchapter, the review of 17 scientific papers, 1 state-of-the-art review, and 1 grid operator report is given: the oldest reference dates back to 2005, the latest—2021.

In [6] (2005), PQ monitoring campaigns are described, which have been carried out since the 1990s by Belgian DSOs. Fixed monitors were connected to MV busbars in HV/MV substations, starting with the most critical: 427 monitors were installed in 218 substations. In the MV grid, phase-to-phase voltages were registered, excluding some areas with many overhead lines where phase-to-ground measurements were taken (to investigate operation of protection systems). In addition, temporary measurements with 64 mobile monitors were taken in order to respond to customer's complaints, issue an advice, investigate disturbing effects of chosen LV load types. Approximately 1500 campaigns were executed until 2004.

In contrast to [6,7] (2008) focuses on TSO grid. A branch-and-bound algorithm is developed for optimal PQ monitoring nodes allocation, i.e., to find the minimum number of required monitors and localize them. A casual problem is raised—optimization between the monitor installation cost, bus voltage monitoring, and line current monitoring. The algorithm was developed using MATLAB. The objective function is defined as following:

$$f = \sum_{i=1}^{n} c_i x_i = \boldsymbol{c}\,\boldsymbol{x} = [c_1\ c_2\ \cdots\ c_n] \cdot [x_1\ x_2\ \cdots\ x_n]^{\mathrm{T}} \rightarrow \min, \tag{1}$$

where $\boldsymbol{c}$—cost vector; $\boldsymbol{x}$—existence vector (binary value which defines whether monitor is installed on the bus or not).

The branching (decision) tree diagram of the proposed algorithm (based on Equation (1)) is shown in Figure 2. Branching is a division of the original problem into smaller (specific) cases. The total number of possible solutions is equal to 2^{n-1}. The algorithm has been tested on IEEE 14, IEEE 30, IEEE 57, IEEE 118, and CEMIG (the Brazilian test system with 48 buses) test schemes. The results and test schemes' features are summarized in Table 1. Optimal amounts of PQ monitors were found considering different installation cost. Thus, the final solution depends on the case.

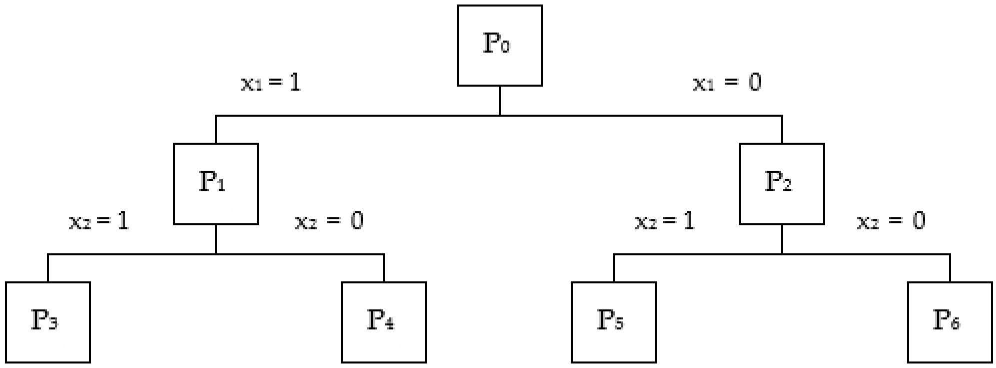


Figure 2. Decision tree with P^0–P^6 problems: 7-node grid example.

Table 1. Results (required number of monitors) when different installation costs are considered.

Test System	Buses	Lines	Solution
IEEE 14	14	18	4–6
IEEE 30	30	41	12
IEEE 57	57	80	18–19
IEEE 118	118	186	39–45
CEMIG	48	64	18–22

Moreover, it is considered that "the redundancy in the measurements is desirable" for system reliability enhancement in anticipation of data loss due to errors or noise. However, new challenges arise: despite data redundancy potentially being advantageous, optimal oversize must be determined in the case of large power system monitoring in anticipation of communication channel jamming, for data processing simplification purposes, etc. In the paper, the redundancy is estimated with Data Redundancy Factor (DRF) which is defined as follows:

$$\mathrm{DRF} = \frac{\text{Sumof observed state variable}}{\text{Total number of state variable}}. \tag{2}$$

In [8] (2009), a PQ monitoring campaign was initiated in 2005 by the Italian Regulatory Authority for Electricity and Gas. The aim was to investigate the present performance of MV network in terms of PQ. During 3 years, 600 instruments were installed on 400 MV busbars (11% of the MV network) of HV/MV substations. The analyzers were connected to the LV side of pre-existing voltage transformers. The mentioned selection criteria were: line length and type, number of MV customers, LV customers' density (customers/km^2), neutral mode. In addition, 200 MV nodes were freely selected by customers (73 installations) and DSOs (127 installations). Measurements were taken according to IEC 61000-4-30. Primary windings of voltage transformers are bonded between phase and ground, thus single phase-to-ground fault or line energization may cause the core saturation of voltage transformers. Moreover, a "false voltage dip" term was introduced to describe the core saturation effect on measuring performance, especially on the MV grid operating with isolated neutral. In order to mitigate the effect, measured voltage waveform asymmetry was tracked with a digital filter, and a more advanced detection method for the second voltage harmonic was developed.

In [9], PQ monitors allocation criteria selection (strategies) before 2013 are briefly summarized. At the EHV and HV level, monitoring of all EHV/HV, EHV/MV, HV/MV substations, connection points of customers, and power stations is considered as a good practice. At the MV level, it is recommended to monitor all EHV/MV and HV/MV, selected MV/LV substations, and connection points of MV customers. At the LV level, random monitoring of LV PCC with fixed and portable monitors (and possibly with smart meters in the future) is considered as good practice.

A novel algorithm for optimal PQ monitors allocation in both transmission and distribution systems is presented in [10] (2012). Two parameters are used to obtain an optimal solution—the topological monitor reach area and the coverage control parameter. The monitor reach area evaluation is based on the residual voltage matrix (obtained from the most severe short-circuit simulation) comparison with the coverage control parameter (defined threshold). Both the IEEE 34-node distribution system and IEEE 30-node transmission system are used for validation; however, any examples of application in practice are not presented. The approach is limited: the most severe short-circuit—three-phase short-circuit—occurs rarely (less than 20% of all short-circuit events). Grid operators are also trying to detect single-phase short-circuits (the most frequent event). In addition, the strategy requires a large number of short-circuit simulations (to determine monitor coverage) which would be hardly implemented in the case of any large power system.

Many papers validate their approaches (only) on IEEE bus systems. In [11] (2015), the aim is to reach the maximum quantity of both current and voltage measurements with minimum investments. The solution highly depends on system topology. Nodes prioritization strategies are not used. Matrixes, which are filled with Boolean values, are used for the mathematical model which represents grid topology, and both voltage and current observability status in busbars and lines. In addition, economical calculations are added. The created method is tested on IEEE 14, IEEE 30, and IEEE 57 systems; however, the application challenges remain unclear in the case of large power networks.

In [12] (2016), monitors allocation criteria are based on the P-median model for nontechnical losses assessment. According to the definition provided in the paper, nontechnical losses are losses before billing measurement, and are caused by additional (unexpected, perhaps in the design stage) loads. These losses are the main reason of a voltage drop in lines below nominal value threshold. In addition, an Integer Linear Programming model is used to estimate monitors observability in regions with the most important loads. An algorithm validation is performed on IEEE 14, IEEE 30, and IEEE 118 systems, and with a case study in the Brazilian DSO grid (40-busbar radial circuit belongs to metropolitan region of Recife, main city—Pernambuco). This network fragment is chosen as a representative example of other similar parts with high nontechnical losses. In the chosen grid, the total losses (consisting of nontechnical and technical) are equal to approximately 32% of the total load, nontechnical losses—24%. The algorithm solved a problem with 11 PQ monitors (i.e., the smallest possible amount). In addition, the authors highlighted some implementation challenges and drawbacks: no flexibility in monitor type selection and the model may provide a different solution when both DSO and TSO systems are considered (i.e., when the TSO grid is not simplified to an infinite power source).

In [13] (2016), similar to [11], the aim is to reach maximal grid coverage. The main motivation of [13] is Brazilian grid codes (for both transmission and distribution systems). According to the authors, one of the tasks of Brazil PQ regulation is an introduction of penalties in order to increase the correctness of grid players' activity.

To begin with, identical to [11], two lemmas derived from Ohm's law were used:

Lemma 1. *If voltage V_1 of bus No. 1 is observable and current I_{12} of line between buses No. 1 and No. 2 is observable, then voltage V_2 of bus No. 2 is observable.*

Lemma 2. *If voltage V_{12} through line between buses No. 1 and No. 2 is observable, then current I_{12} of the line is observable.*

In anticipation of further discussion, it can be remarked that the application of these lemmas requires input data of impedances of all branches or at least values of loads. This requirement for the initial data is very complex in the case of a real power grid.

In [13], similar to many theoretical PQ monitors allocation researches, the optimization problem is mathematically described as a minimization of the multiplication product of cost matrix and binary existence matrix (see Equation (1)). If a monitor is installed on a busbar, the existence value is 1, else—0. The algorithm is tested on the CEMIG (Brazilian) transmission system with 65 buses and 98 lines (500, 345, 230, and 138 kV). Four different scenarios are examined, taking into consideration both the allocation availability and costs (which can be either unitary or proportional to a number of installations since it correlates with a required quantity of measurement transformers). Calculation time (for 65 nodes) is relatively long—34–124 s. Similar to [7], the DRF of each scenario is calculated, and the solution with greatest DRF value is chosen: global DRF value interval (of all four scenarios) is 1.7607–2.7975, local—1.7607–3.4722.

In [14] (2018), the aim is to increase voltage sag observability and minimize cost with a Multi-objective Evolutionary Algorithm. The algorithm is tested only on small test systems: IEEE 13, IEEE 34, and IEEE 37. Two scenarios for IEEE 13 test are created: (1) when faults impedance is always equal to 0 Ω, and (2) when values from 0 to 5 Ω are possible. The authors concluded that the cost–benefit ratio is acceptable in both cases. IEEE 34 and IEEE 37 are examined only under conditions of the first scenario. If the algorithm had been successfully tested in large-scale systems, it would be a useful tool for voltage sag monitoring campaigns planned in practice.

In [15] (2019), the main allocation criterion is harmonic (up to 6.4 kHz) resonance conditions in MV network. The methodology is tested on 15-node and 24-node distribution systems which are based on the CIGRÉ MV test system, and the IEEE 34 system. In the case of both the 15-node and 24-node systems, the optimal solution is 4 PQ monitors (same quantity but different locations). It was concluded that the proposed approach is a promising tool for the grid operator to assess harmonic levels in MV grid.

In [16] (2019) and [17] (2021), the aim is to avoid the multiple estimation problem when impedance-based fault locators estimate fault location distance. If monitors' positions have been determined inappropriately, "fault can be observed but not necessarily identified". For example, if impedances are equal between PQ monitor M1 and faults F1 and F2 (see Figure 3), the monitor would not be able to differentiate these faults, because the output would be the same RMS voltage value (i.e., to be exact, would output close RMS values within the tolerance interval of measurement uncertainty). This problem is called the symmetry issue. Therefore, alternative positions should be determined for monitor placement, for example, the possible solution could be M2. The main aim is to achieve maximal fault differentiation with a limited number of monitors. In order to create a database, many faults simulations are necessary.

In [16], the proposed algorithm is tested on 13 schemes: IEEE test systems—IEEE14b10pc, IEEE30b10pc, IEEE30b5pc, IEEE30b2pc, IEEE57b10pc, IEEE63b10pc, IEEE118b, IEEE118b25pc; Brazilian test systems (Brazilian transmission grid configurations in 2016)—SBr9b10pc, SBr16b10pc, SBr33b10pc, SBr65b10pc, SBr107b10pc. Different fault types (three-phase, two-phase, two-phase-to-ground, single-phase-to-ground) and fault impedances (1, 5.75, 10.5, 15.25, and 20 Ω) are examined. However, in the case of any real power system, it is hard to determine all impedances (including transmission lines) a priori. The authors of the paper notice that the allocation result depends on both variation in fault parameters and fault locations (i.e., either faults occur only in busbars or in both busbars and lines). Moreover, the paper discusses that measurement uncertainty can distort the solution. Computational time in the smallest systems—SBr9b10pc (9 busbars) and IEEE14b10pc (14 busbars)—is 2 s and 0.97 s, respectively; in the largest—SBr107b10pc (107 busbars) and IEEE118b25pc (118 busbars)—159,957 s (more than 44 h) and 17,492 s (more than 4 h). Despite the very high computational time required for larger grids, it is concluded that the main contribution (novelty) of their paper is the presentation of a new approach, which considers the symmetry issue and proved to be applicable in networks of any size and topology. The authors notice that the result depends on means used for initial data obtaining (faults parameters and locations). If faults are simulated only in buses, the problem is simplified but results' reliability is reduced.

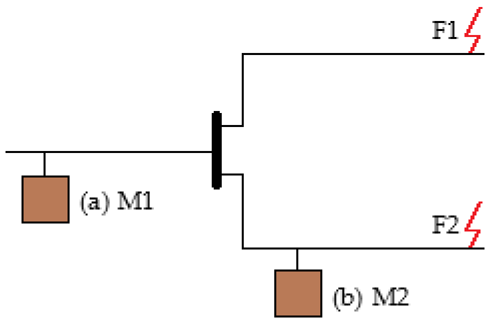


Figure 3. Multiple fault estimation problem—the symmetry issue: if impedances between monitor (**a**) M1 and faults F1 and F2 are equal, fault differentiation is impossible. Alternative monitor position should be determined, for example, (**b**) M2.

In [17], a similar methodology is investigated as in [16], but in a more specific case—an unbalanced distribution system. Firstly, the methodology is tested on a modified CIGRÉ 15-node test system and IEEE 123-node test system. The paper proposes an extension to the CIGRÉ model for unbalanced faults simulation, because the model does not consider two following points: (1) a bus may not have three phases; (2) a fault may cover less than three phases. Two different scenarios (topologies) are investigated—when a distributed generation (5 MVA steam turbine synchronous generator) is (1) connected, and (2) disconnected. The IEEE 123 scheme is selected to compare results with [18] (2017), where other authors present their approach for minimizing PQ monitors number required for voltage sags observation in the case of both balanced and unbalanced systems. The main difference between [17] and [18], and the advantage of [17], is the weight of the objective function. Secondly, in addition, the EPRI Ckt5 2998-node test is carried out, and it is concluded that the algorithm in [17] is suitable for practical application in large power systems. Despite being the first found example of a large-scale test system (2998 busbars), it remains unclear whether different scenarios were investigated and mentioned extensions were applied during IEEE 123 and EPRI Ckt5 2998 tests (as it was performed in the case of CIGRÉ when, for example, generator connection states were comprehensively investigated). Hence, the impact of large-scale (real) system topological changes (due to commutations, new lines installation, power plants construction, etc.) on final solution (monitors quantity and locations) has not been examined and remains unclear.

The authors of [18] also focus on short-circuit voltage sag monitoring, since voltage sags cause big damage to sensitive equipment and interrupt industrial processes. To begin with, the paper proposes a new method for illustration of voltage sag propagation, which significantly simplifies the analysis and highly contributes to the efficient solving of PQ allocation problems. A table-matrix (called voltage sag matrix) is created for that purpose—the example for a 6-node grid is given in Figure 4. Positions of busbars and faults are numbered in rows and columns of the matrix and cells are filled with residual voltage value. Obviously, in the general case, diagonal values are equal to 0. The algorithm is tested on IEEE 13 and IEEE 123 test systems, and the authors conclude that their paper gives "an innovative method" for different types of faults analysis. However, residual voltage calculation requires a bus impedance matrix (all three sequences) which will be very complicated in the case of massive application in large power systems. Node priority (for

PQ monitoring) is determined estimating the highest voltage sag observability in solution array (similar to [16,17]—kindred papers to [18]).

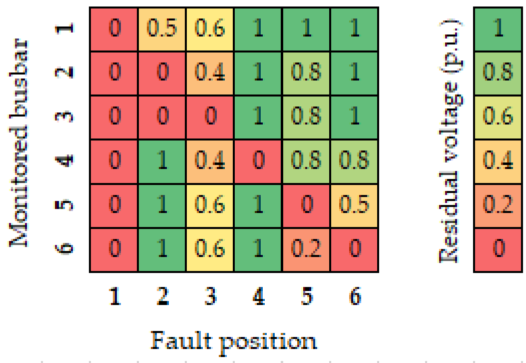


Figure 4. Voltage sag matrix: 6-node grid example.

In [19] (2020), a new allocation method flowchart consists of four stages, and the authors specify that all PQ phenomena are considered: RMS voltage, THD, unbalance, flickers, etc. The following tasks must be accomplished in order to find optimal placement strategy:

1. The estimation of a minimum number of monitors is based on sample size estimation theory. Existing monitoring system data are required for input. Statistical precision of non-repeating random sample is measured as a percentage of deviation of the sample mean from the true population mean, and is calculated as follows:

$$r = \frac{\sigma}{\mu} \cdot \frac{Z}{\sqrt{n}} \cdot \sqrt{\frac{N-n}{N-1}}, \tag{3}$$

   where r—simple random sampling precision; σ—standard deviation; μ—mean; Z—z-test critical value for required (chosen) confidence level; n—sample size; N—population size.

2. Establishment of an optimization targets quantization system is based on the issues, for example, of grid planning and grid operation, but the paper mainly focuses on disturbance source management, PQ maintenance management, and user marketing services. Considering the task, four targets with their own aim functions are established:
   i. High-importance (model parameters: coverage of interference source (i.e., pollution propagation mechanism), coverage of important sensitive users, total short-circuit capacity);
   ii. Weak-area coverage (model parameters: average line loss rate, power outages rate, complaints rate, number of damaged pieces of equipment);
   iii. Coverage of monitoring scope (requires states of as many power grid nodes as possible, nodes states without monitoring can be estimated with PQ propagation mechanism);
   iv. Excellent economic benefit (which should be achieved with minimum monitors).

3. Multi-targets optimization is defined as follows:

$$\begin{cases} \max f_1, \max f_2, \max f_3, \min f_4 \\ \ni X \in \mathbf{R} \\ \mathbf{R} \subseteq \mathbf{U} \end{cases} \tag{4}$$

   where f_i—target functions of four scenarios; X—independent variable; $\mathbf{U}$—universal set; $\mathbf{R}$—subset of $\mathbf{U}$.

4. Solving the optimal allocation problem for different scenarios. Optimization targets weights and the final decision must be agreed by experts, considering different scenarios and objectives (such as planning, marketing, operation, and maintenance).

The proposed method was applied to 110–750 kV regional grid in eastern provinces of China. Total bus number is 205; other features of the grid: 135 critical substations, 2 HVDC converters, 2 electrified railways, 4 sensitive customers, 5 wind farms. Case results: 15 PQ monitors are required for the grid planning stage, 19 for the operation and maintenance stage, 37 for the grid market scenario.

In [20] (2018), an example of a practical measurement campaign in Italy is given. The authors affirm that they present the data which are "obtained by the most extensive program in the world for monitoring PQ." The program was established by the largest DSO in Italy—"Enel Distribuzione". About 3500 analyzers (IEC 61000-4-30 class A) were installed in 2014 on MV busbars in chosen HV/MV substations, i.e., at PCC between TSO and DSO property zones; thus, the research can be considered as an example of a massive monitoring campaign. The main focus was on voltage sags monitoring and their assessment methodology research, regarding voltage sag propagation and events counting (if voltage sag is registered with few neighboring PQ monitors). Therefore, detailed PQ monitors displacement strategies were not applied.

The Turkish monitoring experience is presented in [21] (2009). A PQ measurement campaign was carried out in Turkish TSO grid (63, 154, 220, and 400 kV) with mobile analyzers for July 2006–February 2007. Weekly measurements were taken in 205 nodes with approximately 20 portable monitors (IEC 61000-4-30 class B). The criteria for nodes selection are as follows: frequency of faults, consumption density, and amount of modern industrial loads. In addition, an Estonian PQ measurement campaign (2004–2017) with portable analyzers is described in [22] (2018). The total number of sites was 73 and measurement weeks were 160. In contrast to the previous papers, measurements were taken in the LV network and initiated after customers' complaints.

In [23] (2017), an Australian "large and long-running" PQ monitoring campaign is presented, which was initiated by the University of Wollongong and was executed since 2002. The main target of the campaign was an assessment of network compliance. Since the beginning, data were gathered from over 12,000 sites provided by 12 of the 16 Australian DSOs. In 2017, the project database contained approximately 500 GB of data (900 million records) which were measured in the LV grid along with the MV and HV grid (6.6–132 kV). The participants supply electricity to at least 90% of the Australian population. Measured parameters: steady state voltage magnitude, voltage unbalance, voltage harmonics (up to 25th and THD), flickers, and voltage sags. In the paper, it is concluded that "installation of PQ instrumentation remains costly". Moreover, many devices (e.g., smart meters, protection relays) monitor only a subset of parameters required for compliance verification. Many questions were raised for further research, including the required (optimal) number of sites for both PQ surveys (focus on compliance of LV and MV grid) and transmission systems (focus on HV grid). Two general case recommendations are given for the search of optimal number of required LV and MV sites, and it is affirmed that the literature available on this topic is very limited (until 2016, i.e., until date of publication):

1. According to CEER guidelines (published in 2012), the solution is: (1) 20 sites if averages of all locations will be (must be) reported; (2) 200 sites if 95th percentile values will be reported; (3) 1000 sites if 99th percentile values will be reported. However, concerns can be raised, because despite giving the exact numbers of sites, the recommendation has not been verified in practice, and it is still not verified to this day.
2. If population has a normal distribution, the number of samples can be determined by the following equation:

$$n = \left(\frac{Z \cdot \sigma}{E}\right)^2, \tag{5}$$

where n—number of sites; Z—z-test critical value for required (chosen) confidence level; σ—population standard deviation; E—accepted error value. However, it is unclear how to apply the approach in the specific PQ case. In addition, there is limited literature in the field of PQ parameters probability density functions, in other words, usually it is unknown whether a population has a normal distribution.

In [24] (2021), the monitoring campaign carried out in Great Britain is presented. "Western Power Distribution" company, one of the British DSOs, has been executing the "Primary Networks PQ Analysis" study since 2018. The reports are publicly accessible, and according to our opinion, currently, this project is one of the best PQ studies examples, both novel and non-resembling. The main aim of the project is to reduce uncertainties around the PQ within Primary Networks, and facilitate increased integration levels of low carbon technologies (LCT). A total of 24 monitors were installed during the first stage of the project (mainly at 33 kV nodes). The following criteria were used for trial sites prioritization: the main criterion is LCT penetration; criterion No. 2—additional features such as rapid electric car chargers, new LCTs about to connect, and the presence of existing PQ issues; criterion No. 3—similar networks selection (considering total circuit length, the proportion of overhead lines, infeed substation demand) in order to compare them; criterion No. 4—remote PQ monitoring feasibility (voltage and current transformers and their secondary terminals availability, mobile communication signal strength, substation layout, etc.). In the second study stage, sites containing onshore wind, battery energy storage, and large EV charging stations were included. A total of 46 monitors were installed in total. Despite the low scale of the campaign, many communication problems were faced and solved or discussed. In addition, the study is innovative not only due to communication aspects and frequency response laboratorial research of existing measurement transformers (in order to accurately determine harmonics levels), but also due to attempts and contributions to laboratory test methodology improvements.

3. Discussion

3.1. Criteria

Grid nodes' selection criteria highly depend on the research aim, resources, and size of the campaign. Research can be classified into three groups: theoretical, practical, and state-of-the-art reviews. Most papers, which have been reviewed in this work, are either directly focused on the topic or at least are slightly related. In total, 19 references were reviewed: 10 theoretical researches, 8 practical campaigns, and 1 literature review. PQ monitoring campaigns of Australia, Belgium, China, Estonia, Great Britain, Italy, and Turkey are presented. Almost all papers notice that PQ monitors are expensive, thus both appropriate allocation strategy and cost-effectiveness analysis are essential in order to maximize project's economic benefit.

After the literature review, it can be noticed that nodes selection criteria can be classified into two large groups—abstract and exact. Abstract criteria are (can be) found only in the case of practical research. The criteria are described without any concretization: terms such as critical substation, specific load, and randomly selected nodes are used. Two main aspects can be provided to explain abstract criteria origin:

1. Not informative definition and description of the strategy; however, indeed some arguments can be found in favor of the selection. If the strategy description was more detailed, a criterion would be classified as exact. Not detailed description complicates the analysis.
2. Even if the grid operator declares not using any strategy and criteria, indeed there are some hidden (invisible) aspects which influenced the choice. The reasons could be: communication access in substation, technical conditions (such as appropriate and safe ambient environment to install monitoring devices), existence of voltage transformers, etc. In general, more convenient places for measuring are selected.

Not having a detailed description complicates our discussion, the criteria, and paper classification and distorts results. The strategy remains uncertain in all abstract cases:

1. Which substation is considered as a critical? It could probably be a major hub of HV grid—an important substation or switching station. Moreover, an old substation or a substation in poor technical condition can be considered to be critical.
2. Which loads are specific? It could probably be industrial equipment or appliances which are sensitive to PQ issues. For example, voltage fluctuation, harmonics or flickers can distort the output signal of medical or other high-precision equipment; voltage sags can be the reason for false protective relay operation, or can cause electric motor stoppage and consequently interrupt the whole industrial process. Moreover, power electronics can be referred to PQ pollutant equipment.
3. Which algorithm is used for random selection (random number generation)? Are all nodes and all voltage levels equally weighted? Or does it (random selection) mean more convenient places for measuring? In the reviewed papers, two approaches were distinguished which have their own specifics and are (can be) treated as random nodes selection: (1) "200 freely selected MV nodes" in [8], and (2) selection of 12,000 sites (HV, MV, LV) in [23]. In the first case, the MV nodes sample is extracted (from whole system) for the further random selection of 200 nodes; however, the algorithm (of random selection) remains unclear; the selection perhaps is intuitive. The second case is a blind selection of majority elements in the system (i.e., statistical population). This strategy led to the further conclusion that such an approach is not cost-effective. There is no paper which uses random number generation for PQ nodes selection.

The summary of the papers reviewed is given in Table 2—allocation strategy and its application. A strict division among the papers can be noticed: authors test their methods either with theoretical validation or during practical PQ monitoring campaign.

Table 2. Reviewed papers summary regarding PQ monitors allocation strategy.

Reference	Monitors Allocation Criteria	Application in Practice	Theoretical Validation
[6] (2005)	Fixed monitors—in critical HV/MV substations, on MV side; portable monitors—regarding customer's complaints and consultation, and for specific load investigation	Monitoring campaign in Belgian grid since late 90s	No
[7] (2008)	All TSO grid (voltage and current) observability	No	IEEE 14, IEEE 30, IEEE 57, IEEE 118; Brazilian 48-busbar test system
[8] (2009)	Only MV: line length and type, customers' density (and quantity), neutral mode, random selection	Monitoring campaign in Italian MV grid in 2005	No
[9] (2013)	Power stations, all EHV/HV, EHV/MV, HV/MV, and selected MV/LV substations, all HV and MV PCC, random LV PCC	State-of-the-art review	
[10] (2012)	Most severe short-circuit observability (coverage) defined by residual voltage threshold	No	IEEE 30, IEEE 34
[11] (2015)	Total observability of grid, i.e., voltage and current measurements of all nodes without prioritization. Costs are taken into consideration	No	IEEE 14, IEEE 30, IEEE 57
[12] (2016)	Value of nontechnical losses caused by additional loading	No	IEEE 14, IEEE 30, IEEE 118; Brazilian DSO 40-busbar test system
[13] (2016)	All TSO grid (voltage and current) observability	No	Brazilian TSO 65-busbar test system
[14] (2018)	Only symmetrical short-circuit observability at minimal costs	No	IEEE 13, IEEE 34, IEEE 37

Table 2. *Cont.*

Reference	Monitors Allocation Criteria	Application in Practice	Theoretical Validation
[15] (2019)	Expected unallowable level of harmonics	No	IEEE 34; CIGRÉ MV grid
[16] (2019)	Multiple estimation problem: to reach maximal faults (voltage sags) differentiation	No	8 IEEE, 5 Brazilian TSO test systems
[17] (2021)	Multiple estimation problem: to reach maximal faults (voltage sags) differentiation	No	CIGRÉ 15; IEEE 123; EPRI Ckt5 2998
[18] (2017)	Faults (voltage sags) observability	No	IEEE 13, IEEE 123
[19] (2020)	Interaction between emission source coverage, sensitive user coverage, damaged equipment ratio, short-circuit capacity, customer's complaints, line losses, outages, component of "all grid coverage" idea, and component of optimal economic benefit	Application in Eastern China TSO grid	No
[20] (2018)	Only at MV side at all HV/MV substations of the regional network	Monitoring campaign in Italian grid in 2014	No
[21] (2009)	TSO grid: frequency of faults, power consumption density, modern industrial loads	Monitoring campaign in Turkish TSO grid in 2006–2007	No
[22] (2018)	Customers' complaints	Monitoring campaign in Estonian LV grid in 2004–2017	No
[23] (2017)	Random selection (or no criteria) to cover the majority of grid: measurements were taken in 12,000 sites	Monitoring campaign in Australian HV, MV, and LV grid since 2002	No
[24] (2021)	(1) LCT penetration; (2) EV chargers, LCT connection prospects, PQ issues; (3) similar network selection for comparison; (4) remote monitoring feasibility	Monitoring campaign in British DSO grid in 2018–2021	No

Table 3 summarizes the criteria selection frequency in the reviewed papers. There is no most common criterion in the practical papers. The most common criterion in the theoretical papers—focus on PQ issues and related parameters observability: the most common case is residual voltage and short-circuits calculation. Table 4 presents the cross-section product of Tables 2 and 3. It is important to distinguish exact criterion from abstract. In this paper, the proposed criteria groups are as follows:

1. Random selection (abstract criterion). Used only in the practical papers. Those papers do not specify selection principle; nodes are identified as "freely chosen". In case of theoretical papers (hypothetically), the random number generator should be specified; however, this approach is not used, and perhaps is senseless.
2. Critical substation (abstract criterion). Used only once in the practical papers. The authors do not specify exactly which substation is considered to be critical, for example, it could be in a poor technical condition or important transmission grid node.
3. Specific load investigation (abstract criterion). Used only once in the practical papers. Research can be focused either on an emission source, or on PQ immunity. In this case, the authors do not provide any exact information about load features.
4. Customers' complaints usually are an important factor for an operator to begin at least temporary measurements at PCC with a portable monitor. In addition, attention to the client is important from a successful business perspective.
5. All selected-type substations, busbars. Includes maximal coverage tasks, and encompasses such concepts as "all HV or MV busbars in most HV/MV substations" and "whole grid observability". In general, the criterion reflects a massive campaign.

6. PQ issues, short-circuits, residual voltage. It is the most common criterion which focuses mainly on voltage sag observability. Until nowadays, almost all papers agree that voltage sags have remained the main reason of industrial outages. Short-circuit and residual voltage are closely related terms since voltage sags can be analyzed through a prism of residual voltage and are mainly triggered by short-circuits. Sometimes, the criterion can encompass focus on another specific PQ event, for example, harmonics.
7. Faults frequency, power supply reliability. This criterion highly correlates with focus on short-circuits and voltage sags but includes only their severe consequences—supply interruptions which cause outages, and are the reason for poor reliability indexes (SAIDI, SAIFI, MAIFI, etc.).
8. Renewable energy penetration, EV chargers. Currently, this criterion is chosen for investigation only in modern papers with the beginning of green energy trends and growth of renewable capacity. Solar and wind power plants are large PQ emission sources due to usage of power electronics equipment and wind flickers.
9. Power losses. In general, this encompasses the classical definition of losses caused by conductor heating when current flows (i.e., conductor resistance). This leads to voltage drop in lines which also correlates with poor PQ situation. The effect of voltage drop is clear in long and highly loaded feeders. The effect of voltage rise is clear in long unloaded feeders (capacitive mode). RMS voltage variation beyond allowed limits (in most cases $\pm 10\%$ nominal voltage) is harmful for equipment.
10. Customers' density, quantity; line length. The criterion is oriented to grid regions with a higher number of clients. "Line length" is interpreted as a sum of lengths in the region or overall line length connected to the busbar, i.e., the priority is not given to a longer or shorter feeder as it was in the previous case (No. 9).
11. Industrial regions or loads. This criterion excludes households and commercial customers but it is similar to previous one. One reason of this separation is that voltage sags and power interruptions affect industrial customers more seriously than households.
12. Remote monitoring possibility. The most modern criterion which arises along with the Smart Grid concept. At the moment, only [24] has executed a pilot project which aimed to test 4G LTE communication network connecting 40 PQ analyzers, thus the criterion is in its beginning state.

Table 3. Criteria selection frequency.

No.	Criteria	Type [1]	T [2]	P	Σ	Remarks
1.	Random selection	A		2	2	
2.	Critical substation	A		1	1	
3.	Specific load investigation [3]	A		2	2	
4.	Customers' complaints	E		3	3	
5.	All selected-type substations, busbars [4]	E	3	2	5	massive campaign case
6.	PQ issues, short-circuits, residual voltage	E	6	2	8	
7.	Faults frequency, power supply reliability	E		2	2	
8.	Renewable energy penetration, EV chargers	E		1	1	since 2018
9.	Power losses	E	1	1	2	
10.	Customers' density, quantity; line length	E		2	2	
11.	Industrial regions and loads	E		1	1	
12.	Remote monitoring possibility	E		1	1	since 2018

[1] Type of criterion: A—abstract, E—exact. [2] Type of research: T—theoretical, P—practical. [3] Includes abstract definitions such as "all sensitive equipment", "all interference sources". Additionally, it can include investigation about both emissions and immunity. [4] Includes the idea about maximal grid coverage, observability.

Table 4. Cross-analysis of nodes selection criteria in Tables 2 and 3.

Reference	Type [1]	1A [2]	2A	3A	4E	5E	6E	7E	8E	9E	10E	11E	12E
[6] (2005)	P		+	+	+								
[7] (2008)	T					+							
[8] (2009)	P	+									+		
[9] (2013)	R												
[10] (2012)	T						+						
[11] (2015)	T					+							
[12] (2016)	T									+			
[13] (2016)	T					+							
[14] (2018)	T						+						
[15] (2019)	T						+						
[16] (2019)	T						+						
[17] (2021)	T						+						
[18] (2017)	T						+						
[19] (2020)	P			+	+		+	+		+			
[20] (2018)	P					+							
[21] (2009)	P							+			+	+	
[22] (2018)	P				+								
[23] (2017)	P	+				+							
[24] (2021)	P						+		+				+
Total:		2	1	2	3	5	8	2	1	2	2	1	1

[1] Type of research: T—theoretical, P—practical, R—state-of-the-art review. [2] Type of criterion: A—abstract, E—exact.

3.2. Massiveness

In almost all the reviewed theoretical papers, the validation of proposed algorithms is begun from IEEE schemes. Then, sometimes in addition, the validation is supplemented with other schemes—CIGRÉ, EPRI, or Brazilian. The largest sizes of test schemes, which were used for validation in the theoretical papers, are summarized in Table 5.

Table 5. Maximum size of testing schemes used for theoretical validation.

Test	[7]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]
IEEE	118	34	57	118		37	34	118	123	123
CIGRÉ							24		15	
EPRI									2998	
Brazilian	48			40	65			107		

The IEEE, CIGRÉ, and Brazilian schemes used in the papers are small—up to 123 busbars. Only in [17] is the EPRI scheme used for a massive system test. Theoretical simulations are limited. Firstly, the usefulness and efficiency of the proposed algorithm remains unclear in the case of a real (large) electric power system. Larger test schemes require more computational resources; however, many authors highlight only fast computational time which was required for their test in small schemes. Secondly, the variety of potential monitoring locations increases with grid size. In the works reviewed it is clearly seen that different results are obtained under various conditions (scenarios) regarding both the quantity of monitors and their locations. In addition, low algorithm adequacy can be expected in the case of small radial grids development, for example, the advance of distributed generators since the most test schemes were created before the worldwide growth of renewable penetration. Many researches use only radial test schemes, i.e., with only one—an infinite—power source. Many test results can be expected to be valid only if system topology remains unchanged. Thirdly, since many algorithms require input data about grid nodes impedance, the final result can be influenced by every grid reconstruction (modification),—for instance, the replacement of conductors or other equipment will change grid impedance and characteristics of PQ. Fourthly, it is a complicated (impossible) task to obtain impedances of real (massive) system nodes, and other information which is required for initial data input. On the other hand, there are not many alternatives which could be without any limitations; thus, small-size theoretical tests are suitable at the beginning research stage in anticipation of future worldwide progress. Fifthly, after theoretical validation, there are still many unexpected issues which may be faced in practice during algorithms' application, for example, some locations may be technically unsuitable to install monitors (e.g., absence of appropriate measurement transducer).

In addition, many test schemes are not compatible geographically. IEEE schemes have their own unique features representing the North American grid, thus they do not necessary reflect the situation in Europe. For example, IEEE 13 operates at 4.16 kV nominal voltage, IEEE 34 is an actual distribution feeder located in Arizona, USA. Nominal voltage of this feeder is 24.9 kV; the system has very long and considerably loaded lines, loads are unbalanced, and modelled as concentrated and distributed. As a comparison, the Lithuanian power grid is incorporated into post-Soviet BRELL ring where nominal voltage levels are as follows: HV—330 kV and 110 kV, MV—35 kV, 10 kV and 6 kV, LV—0.4 kV. Authors very rarely highlight features of used test schemes and their test results flexibility which can be influenced by various factors: topology (radial, ring), presence of power plants, load percentage, load symmetry, line length, etc.

On the contrary, simpler strategies are used during practical research: they are not based on complex mathematics and require less initial data. In eight reviewed papers, including [23] where all voltage levels are investigated, the HV grid is investigated three times, MV—five times, LV—three times. In general, the HV grid has fewer nodes and a better PQ situation. PQ law of the HV grid has its own specifics since European PQ standards are not applicable to HV; thus, each TSO has its own grid code (national regulation) with PQ requirements. In general, dealing with PQ issues in the HV grid is not a priority because: (1) many phenomena do not propagate through the transformer (including from LV to MV and from MV to HV, i.e., upstream—against the power flow); (2) it is almost impossible to fully mitigate propagation of severe effects (short-circuits, transients) in the TSO grid and avoid their propagation to the DSO grid. Along with PQ mitigation devices installed in the HV grid (synchronous generators, lighting arresters, static synchronous compensators, etc.), preventive measures must be taken considering all possible risks and hazardous effects, for example, wind park flickers, probability of lighting and insulators' ageing.

Contrary to the HV grid, LV grids are more polluted, and have a larger number of nodes which implies that permanent monitoring with fully functional monitors is almost impossible. At the moment, PQ-measuring smart meters and protection devices seems to be promising to cope with this problem of massiveness. However, many authors do not include monitor types classification in proposed strategies, rarely analyze their functionality limitations and cost efficiency. To compare with a casual fixed PQ monitor, smart meters are (can be) less accurate, have a lower sampling frequency, and do not offer many processing options of measured data, but these limitations highly correlate with project cost reduction. A fully functional and accurate fixed monitor in the LV grid could be used only in special cases: for example, for sensitive and critical loads in hospitals, industry, or laboratories, where poor PQ can not only cause damage or cause disconnection, but harmonics and flickers can also distort the output signal which is critical for decision making (e.g., medical images). An alternative option to reduce limitations for non-critical applications is the use of portable monitors. However, it often remains undefined how long temporary measurements should be taken for both—better PQ situation analysis and better ratio of duration to measured nodes quantity. According to EN 50160, most PQ parameters can be assessed only from a weekly array. It is noteworthy that, in the case of a problem, user equipment must additionally be verified for EMC. The experiment must be based on IEC EMC compatibility standards, despite any initial tests at design and manufacturing stage (required for CE marking). The tests usually require complex procedures such as equipment disconnection from grid and artificial line impedance stabilization network.

Focus on the MV grid is slightly more common in the papers, and a possible reason could be that the MV grid is between HV and LV through a prism of PQ: (1) EN 50160 is applicable to MV; (2) the majority of industrial motors and renewable power plants (including their power transformers) are directly connected to the MV grid; (3) grid size is in-between HV and LV, thus it is possible to reach at least partial coverage; (4) most severe faults propagate to the LV side, but do not propagate to the HV side; (5) PQ situation is in-between HV and LV, since many emissive loads are on the LV side, harmonics do not propagate through transformer to MV winding, and voltage sags propagation is slight.

Practical campaign sizes are summarized in Table 6. In the case of using portable monitors, monitors quantity to measured nodes quantity ratio along with measurement duration are given (if known). As has been mentioned before, in [20,23] the authors concluded that massive monitors installation remains costly and more effective allocation strategies should be applied.

Table 6. Massiveness of practical researches.

Voltage [1]	**[6]**	**[8]**	**[19]**	**[20]**	**[21]**	**[22]**	**[23]**	**[24]**
HV grid			15–37 [2]		205/20 [3]		12,000 [4] (jointly)	46 [5]
MV grid	427 [5]	600 [5]		3500 [5]				
LV grid	1500+/64 [6]					73/? [7]		

[1] In case of various countries, boundary between HV and MV can be different. In this paper, voltage levels are classified according to thresholds of European standard EN 50160:2010. [2] Fixed monitors in case of different scenarios: grid market scenario requires the largest number. Total number of buses of the test grid is 205. [3] Weekly measurements with 20 portable monitors. [4] Example of massive campaign with various monitors including limited PQ functionality devices (smart meters, protection relays). Detailed information about device types is unknown. [5] Fixed monitors (quantity is equal to number of busbars). [6] With 64 portable monitors. [7] With portable monitors (exact amount is unknown), overall measuring time is 160 weeks.

4. Problems and Future Prospects

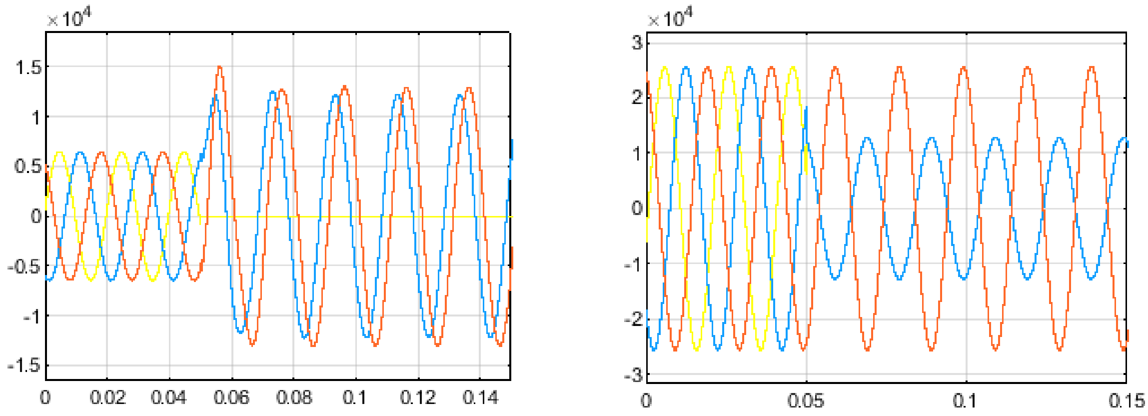
4.1. Sophisticated Attention to Every PQ Event

Dealing with each PQ issue must be start from fundamentals. The allocation problem is not an exception. An initial step should be PQ events targeting. Different target groups of PQ events will lead to a different monitors' allocation strategy. PQ events assessment problems which will be described below must be solved in the future, these solutions are vitally important in order to create an efficient allocation strategy. However, it is impossible to present all experiences and describe everything in one paper, thus only a part of the problems, which became obvious to the authors during PQ monitoring campaign (in Lithuanian DSO grid) and review of the literature, standards, and other legal documents, will be presented. In spite of the fact that European legislation requires the monitoring of the whole list of PQ events for situation assessment, currently it is a difficult task to deal with, firstly, due to many universally unsolved issues (i.e., lack of a universally unified approach) regarding both: uncertainties in PQ events assessment methodologies, and technical possibilities (progress) of monitors which highly correlate with cost. Hence, many papers limit their approach to a selected target group and investigate the most beneficial method for individual (most problematic) events monitoring. Nowadays, authors agree that voltage sag has remained the most problematic PQ event to industry for more than the past two decades. Other main issues are harmonics (which cause power losses, machine vibrations), and RMS voltage drop below a lower limit of 0.85–0.90 p.u.

Some authors affirm that their approach is suitable for all of the PQ events list, however, that is only a half-truth. Each phenomenon has a different origin and propagation mechanism, which will determine different measurement requirements and cost–benefit monitors displacement strategy. Reading between the lines, suitability for "all PQ events" at least means exclusion of a "special" group—flickers and transients. Let us explain why we can call it "special". Firstly, in IEC 61000-4-30, no measurement and aggregation requirements are given for both types of transients—impulsive (fast) and oscillatory. These phenomena (including overvoltage caused by lightning) require very sophisticated monitors with a high sampling frequency and broad dynamic range. Moreover, transducers with adequate magnitude and phase frequency response are required in order to avoid results distortion. It is a very complex task. In [24], the Great Britain DSO faced many problems even with harmonics which are assessed up to 40th (i.e., spectrum is limited to 2 kHz). According to IEEE Std 1159, typical spectrum content of oscillatory transient can be up to 5 MHz and a typical duration of impulsive transient ranges from less than 50 ns to more than 1 ms [3]. Hence, it is impossible to extensively monitor transients; currently, only pilot projects can be executed. Secondly, flickers also have a complex nature, and a separate EMC standard IEC 61000-4-15 [25] is dedicated to them. In the general case, flicker assessment is not integrated in a casual fixed PQ monitor, thus a separate special device is needed. Even EN 50160 admits that the flicker severity index is not objective: the index tries to analytically evaluate flicker impact on humans with the lamp–eye–brain response model, and the last version of the model dates back to 2010 (or earlier). It is noteworthy that the assessment of harmonics and inter-harmonics also have a separate standard IEC 61000-4-7 [26]; however, many questions remain open, since a complex calculation methodology is used for spectrum assessment (in all scientific fields, even if it is simply called FT—Fourier Transform): windowing function, Heisenberg uncertainty issues, window size, spectrum artefacts, data grouping to determine harmonic value, etc. In addition, most voltage transformers have been initially designed for their primary purpose—energy accounting (i.e., for 50 or 60 Hz component), thus they may not be not suitable for wideband frequency measurements due to distortive magnitude and phase frequency response. This problem is described in IEEE Std 1159 [3] (only for the case of magnitude frequency response) and the Great Britain DSO "Western Power Distribution" began to investigate it in [24]. The availability of appropriate measurement transducers highly influences allocation selection criteria. Perhaps, relay protection can be considered for some event monitoring and assessment (e.g., voltage harmonics, unbalance, etc.). Moreover, the nature of each harmonic and its phase are different, and currently not examined in detail (including damage to loads); thus, the need for experiments remains. Harmonics are classified into three groups: positive, negative, and zero sequence. In the general case, harmonics do not propagate through transformers; some harmonics interfere and compensate each other, and some can be resonant.

In this paragraph, let us continue the discussion about PQ events, and focus on the most critical problem to industry—voltage sag. To begin with, according to EN 50160 definitions, the standard encompasses only symmetrical phase-to-phase voltage sags, however, it is the rarest fault type. The most common short-circuits are asymmetrical: phase-to-ground short-circuit is the most common fault type, but from the legal point of view, it is not compulsory to research and mitigate them. Different types of voltage sags have dissimilar propagation mechanisms (especially through transformer), which highly relates to monitoring coverage parameter often used in allocation strategies. Authors often limit their strategy for particular type: for example, [10] focus only on three-phase faults. The importance of propagation research to monitors allocation strategy can be reasoned from literature review chapter: for example, [18] proposed a new graphical method for propagation investigation—voltage sag matrix (Figure 4). Besides, the problem when the same voltage sag is observed with several monitors has arisen in [20]. Since the situation is not described in EN 50160, various interpretations are possible. Unified legal definitions would be useful for finding an optimal solution between the data duplication level and monitors' density. To conclude, in this paragraph two issues directly influencing monitors allocation have been mentioned; however, there are more indirectly related problems related to efficient monitoring (neither mentioned nor solved in EN 50160) which requires unification of approaches and legal definition: time synchronization errors, voltage sag indexes (IEEE Std 1564 research field), damage to equipment assessment, voltage sag hysteresis (according to the definition in IEC 61000-4-30; do not confuse with the ferromagnetic hysteresis loop of a transformer core), assessment of voltage sag burst (voltage sags row with short pause which threshold time must be defined and can be caused by either external triggers (e.g., tree branches) or various commutations, a typical example being the automatic circuit recloser operation).

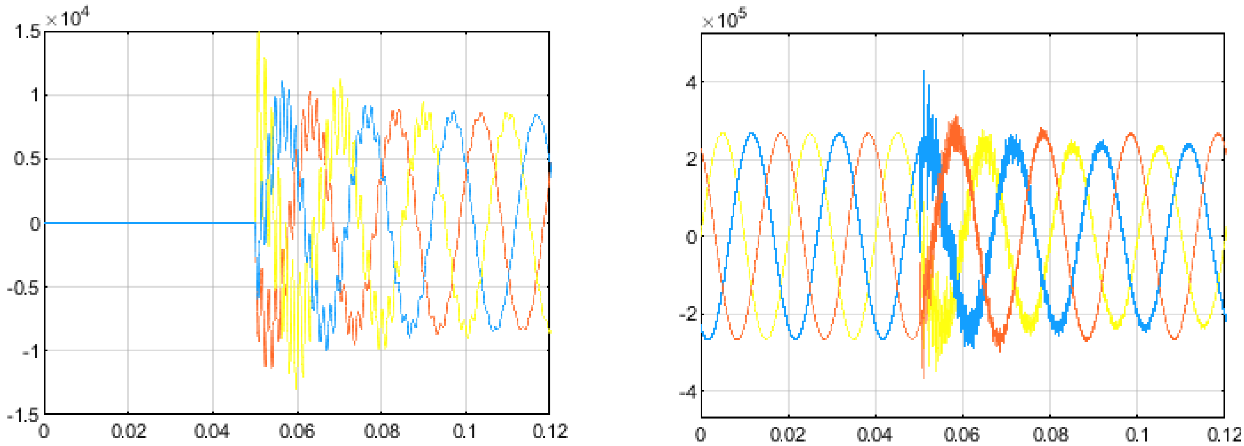
In Figure 5, two simulation examples of faults in the Lithuanian DSO grid are given: in Figure 5a—phase-to-ground voltage of single phase-to-ground fault in 10 kV grid (the most frequent type of fault), in Figure 5b—phase-to-ground voltage of two-phase fault in 35 kV. The nature of the process is influenced by many factors, one of them (important)—neutral mode: the Lithuanian MV grid operates in either isolated or compensated neutral mode. The grid scheme and a more detailed description of scenarios are given in Appendix A. Despite being the most frequent, neither these faults nor phase-to-ground voltage are included in EN 50160, since they almost have no influence on phase-to-phase voltage. The standard encompasses only symmetrical phase-to-phase voltage sag which is the rarest fault. Phase-to-phase supply assessment is important for three-phase loads; however, single-phase loads are influenced by phase-to-ground voltage. Moreover, since phase-to-ground fault in MV grid does not propagate through transformer (including to the LV grid), the proposed amendments would not be disastrous for the grid operator, and will contribute to a great leap forward in the development of PQ monitors allocation strategies. Noteworthy, in the given examples a significant phase-shift (and phase unbalance) is seen at the beginning moment of short-circuit. This could become a reason for the loss of synchronization between monitor and grid, which obviously means PQ data loss (including fault event). Many synchronization loss flags were found during the Lithuanian PQ campaign. Remote monitoring and higher DRF could help to solve this problem, and the detailed description and focus on communication issues will be provided in the next subchapter.



(**a**) (**b**)

Figure 5. (**a**) Phase-to-ground voltage in the beginning of 10 kV line where single-phase short-circuit occurs; (**b**) phase-to-ground voltage in the beginning of 35 kV line where two-phase short-circuit occurs (blue and yellow curves of short-circuited phases coincides after the fault). Significant phase-shift and unbalance are seen at the beginning moment of both faults (after 0.05 s). The simulation has been performed with model of chosen region of Lithuanian power system.

In the future, complex approaches must be applied for PQ situation assessment—it is important to monitor the full list of events because there are strong interconnections among them. It can be clearly seen from the given simulation examples. In Figure 5a, one phase-to-ground power supply interruption triggers voltage swells, zero sequence unbalance, and phase unbalance. It is noteworthy that, despite zero sequence component and phase unbalance being measured and controlled by protective relays, in EN 50160, these PQ events are not seriously regarded as serious. Let us examine the relation between voltage sags (Figure 5) and transients (Figure 6). In Figure 6a, a process of commutation overvoltage in 10 kV line is shown, a higher short-circuit frequency leads to a higher number of voltage sags, and consequently to higher number of commutations. In Figure 6b, two-phase-to-ground short-circuits occur in one end of 330 kV 100 km line, and cause the oscillations in the opposite end of the line (see Appendix A).



(**a**) (**b**)

Figure 6. (**a**) Phase-to-ground voltage transient (after 0.05 s) caused by 10 kV power line commutation (switching on); (**b**) Phase-to-ground voltage oscillations in 330 kV 100 km length power line end (busbar), where strong generation presents, caused by two-phase-to-ground short-circuit at the other end of the same line (after 0.05 s). Sampling time is 10^{-6} s. The simulation has been performed with model of chosen region of Lithuanian power system.

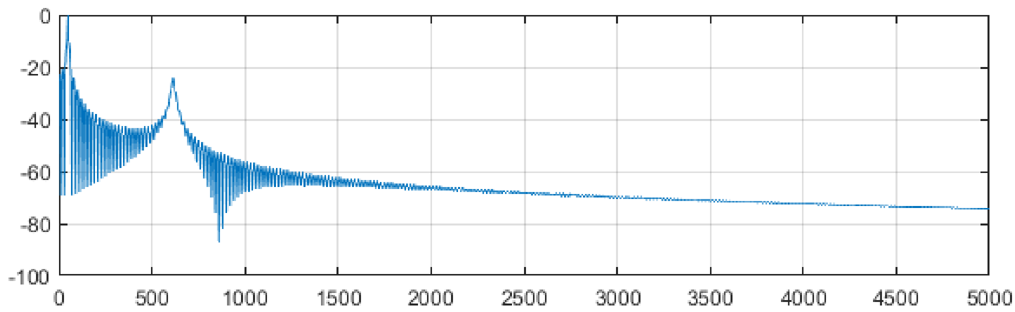
The authors do not give enough attention to device types and measurement requirements. Those dimensions must be added to future allocation strategies: cost-efficient selection of criteria should be ensured by considering monitor type (its features and technical characteristics), PQ events target group (individually for each monitor type regarding propagation mechanism), voltage level, electrical power system features, technical condition of substation, remote communication aspects, national legislation, policy (including responsibility sharing, penalties), etc. Let us discuss one of the most important monitor characteristics—sampling frequency. It highly correlates with the price. Obviously, a high sampling rate is required for fast processes and transients monitoring. In addition, a higher sampling rate is important for precise waveform extraction which can be used in the future, in advanced algorithms such as wavelet transform.

The classification of voltage transients is proposed and their typical characteristics are given in IEEE Std 1159; we prefer the IEEE standard to the insufficiently informative EN 50160 and EMC standards. Voltage transients are classified into two main groups—impulsive and oscillatory. Impulsive transients are classified into nanosecond, microsecond, and millisecond: their typical (rise) time constants—5 ns, 1 µs, and 0.1 ms, typical duration—less than 50 ns, 50 ns–1 ms, more than 1 ms, respectively [3]. Spectral content of impulse transients cannot be determined due to the Heisenberg uncertainty principle; thus, time constants are given instead of spectral content. Oscillatory transients are classified into low, medium, and high frequency. Typical characteristics: spectral content of low frequency oscillations is up to 5 kHz, duration—0.3–5 ms, magnitude—0–4 p.u.; medium frequency oscillations—5–500 kHz, 20 µs, 0–8 p.u.; high frequency oscillations—0.5–5 MHz, 5 µs, 0–4 p.u. [3].

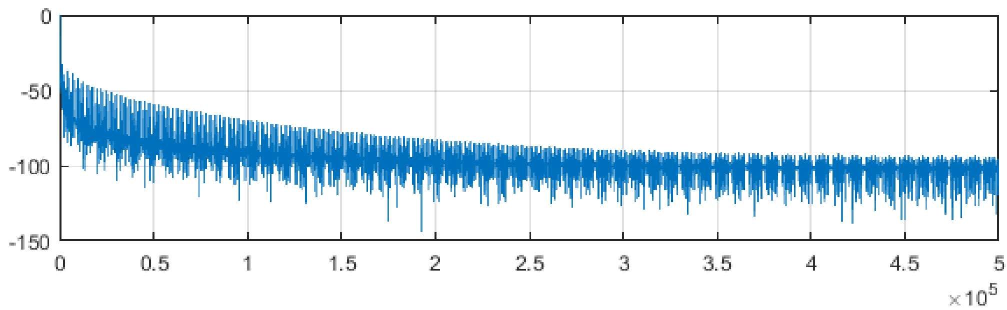
In addition, in Figure 7, spectrum calculations of Figure 6 transients are presented. Two spectral components of commutation process are clearly seen in Figure 7a: fundamental grid frequency and free oscillation frequency of the transient examined. According to IEEE Std 1159, this transient is treated as a low frequency oscillation. On the contrary, the peaks are not seen in Figure 7b. There are various and scarcely determined reasons for such occurrence: limitations due to the Heisenberg uncertainty principle (either an oscillation is too short or transient is impulsive), spectrum aliasing (simulation sampling frequency is too low for transient), impact of spectral leakage determined by window function (in given example, rectangular window is used), noise influence, higher grid impedance for higher frequency components, features of measurement circuit, etc. Along with FT, other methods will potentially be used in the future for short signals, for example, short-time Fourier transform. Currently, only free oscillations monitoring seems to be massively solvable in practice through a prism of sampling frequency (at least partly), since it does not require unrealizable sampling. Many analyzers, along with casual parameters monitoring, have separated a high sampling frequency short-memory channel. However, since a very high sampling rate is required for impulses, limitations regarding the dynamic range of casual PQ monitor remain: according to IEEE Std 1159, the typical magnitude of oscillations is up to 8 p.u., but the nature of impulses is not well studied; thus, it is hard to predict the real values. It is noteworthy that the free oscillations frequency, including the process in Figure 6a, in the electrical circuit is inversely proportional to the product of inductance and capacitance; therefore, the minimum requirement can be defined with the following equation (after applying Nyquist–Shannon sampling theorem):

$$\frac{f_s}{2} \geq \frac{1}{2\pi\sqrt{LC}}, \tag{6}$$

where f_s—sampling frequency; L—inductance; C—capacitance.



(**a**)



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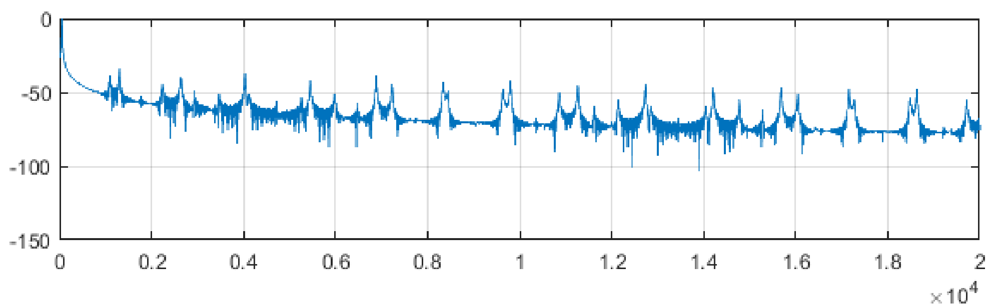

(**c**)

Figure 7. (**a**) Spectrum of voltage transient of Figure 6a: clear peaks at 50 Hz (0 dB; fundamental frequency) and 615 Hz (−24 dB; transient frequency); (**b**) Spectrum of voltage oscillations of Figure 6b; (**c**) Spectrum of voltage oscillations of Figure 6b: focus on 0–20 kHz band. Since all three phases spectrums are almost similar, a single curve is given.

All the mentioned issues with transients are directly related to PQ monitors' allocation strategy, and in the future dealing with those issues will lead to the introduction of new nodes selection criteria. Some examples: (1) high commutation frequency zones; (2) high lightning probability regions (based on long-term meteorological data); (3) focus on selected surge arrester operation; (4) investigation of displacement of surge arresters and overall overvoltage mitigation strategy (i.e., mutual effect of all devices); (5) focus on critical and vulnerable loads; (6) investigation of impact on grid equipment, for example, insulators. It is possible that separate special monitors for transient monitoring will be used in the future, but the problem will remain the same—optimization between quantity of monitors, their features and coverage, and price. In addition, measurement transducer issues (such as inappropriate magnitude and phase frequency response) will remain a limiting factor.

The future structure of PQ monitoring application is given in Figure 8. Firstly, in comparison with Figure 1, the measurement transducer block is split into two parts. Broadband transducers (with appropriate frequency response) will be designed for high sampling monitors which will output high-precision waveform and broadband spectrum. For example, precise waveform input is required for the wavelet transform tool which can be used in predictive maintenance applications (e.g., impact on insulators evaluation). Secondly, the allocation strategy is strongly dependent on monitor type and its PQ target group. Thirdly, interoperability with all Smart Grid application must be reached in order to achieve the most efficient solutions (including both technical and economic aspects): penalties for grid pollution, compensations, expenditure saving, calculations of CAPEX and OPEX, etc. In Figure 8, most Smart Grid applications (systems) examples are based on terminology used in IEEE Std P2030 [5,27]: supervisory control and data acquisition—SCADA, demand side management—DSM, substation automation—SA, meter data management—MDM (the term closely related to AMI—advanced metering infrastructure), asset management—AM, transmission lines monitoring—TLM (the term closely related to DLR—dynamic line rating), PM—predictive maintenance, DMS—distribution management system, OM—outage management, EV—electric vehicle, WASA—wide-area situational awareness, DG—distributed generation. After integration with other systems, artificial intelligence (AI) algorithms will be used to deliver solutions for many purposes: history and data storage (e.g., impedance database), data classification and statistics (including political reports), compliance verification, legislation and amendments, decision making and their correction, assessment methodic and management strategy correction, machine learning (supervised, semi-supervised, unsupervised, reinforced) and software updates, forecasting, maintenance planning, grid automation commands (including "self-healing"), demand side response planning, etc.

Currently, the suitability of many algorithms for PQ evaluation has not been sufficiently investigated and it remains an open research field with traditional methods such as FT modifications for signal components filtering (discrete Fourier transform—DFT, fast Fourier transform—FFT, short-time Fourier transform—STFT), and newer methods for data processing and specific features extraction, for example, Kalman filter—KF, wavelet transform—WT, discrete Stockwell transform—DST, Hilbert–Huang transform—HHT, Gabor transform—GT, time–frequency representation—TFR, chirp z-transform—CZT, space-phasors—SP, morphology method—MM, slant transform—SLT, Teager energy operator—TEO, principle curves—PC, spectral kurtosis—SK, amplitude and frequency demodulation—AFD. KF is applicable for the high accuracy evaluation of harmonic signal amplitude, phase angle, and frequency in case of noise presence, and together with other methods (e.g., discrete WT, fuzzy expert system—FES) can be used for data PQ deviations identification and classification. In addition, WT can be used for data compression, noise reduction, to extract various signal array characteristics such as amplitude, mean, standard deviation, probability density function, entropy, etc. ST is an extension of either WT or STFT with varying window length, and can output better time–frequency representation of the signal. HHT is a combination of empirical mode decomposition and Hilbert transform, and suitable for nonstationary signal processing. GT is an advanced signal processing tool which it is possible to apply for short duration transient analysis. Furthermore, many AI methods are also appropriate: well-known neural networks—NN (multilayer, radial basis function, probabilistic), support vector machine—SVM, fuzzy c-means—FCM, k-nearest neighbor algorithm—k-NN, hidden Markov model—HMM. For instance, a combination of fully informed particle swarm and adaptive probabilistic NN can be employed for PQ disturbances' identification, when ST and time–time transform (extension of ST) are used for probabilistic NN training. FCM, DWT-based SVM and many other techniques can be used for PQ disturbances' classification [28].

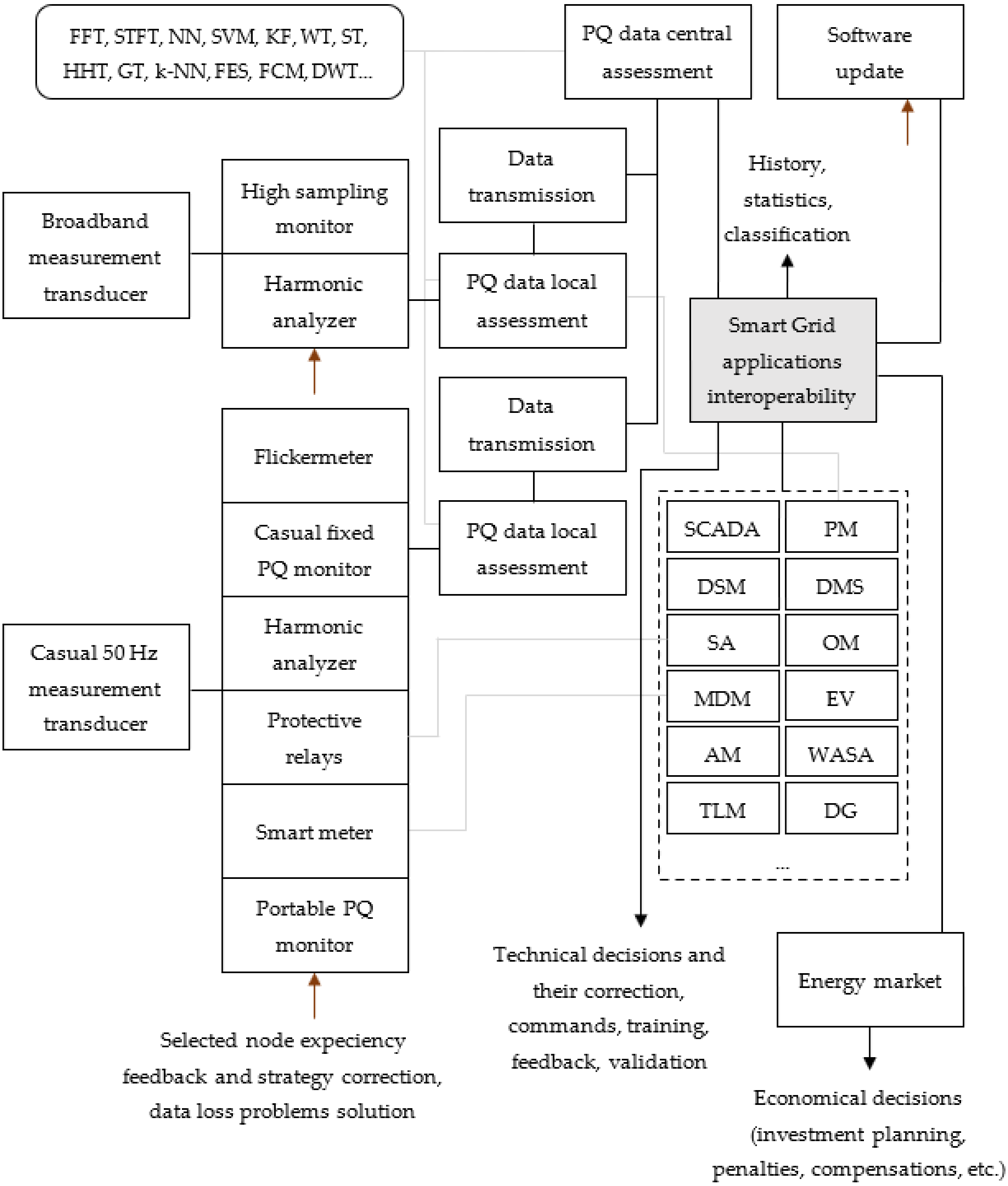

Figure 8. Perspective block diagram of a remote PQ monitoring process.

In regard to PQ monitors' allocation, from the literature review, it is seen that none of the above-mentioned AI methods have been applied in [6–24] or included in standards guidelines (see Chapter 2): for example, in [7], the branch-and-bound algorithm is used (Figure 2); in [16–18], matrix operations which are based on Ohm's law; in addition, some classical statistical methods have been proposed. Each method has its own advantages and disadvantages. For example, the advantage (perhaps the only one) of the branch-and-bound algorithm is the provision of an optimal solution (basing on input data), but the increase in task amount by 1 unit doubles the convergence time (in the case of [7]—see Figure 2); thus, in order to avoid enormous computational times, the task must be strictly defined (limited) considering capabilities of modern computers.

In our opinion, the main reasons for the absence of AI in reviewed papers are described in this subsection. First of all, the further development and approach unification of PQ evaluation methods together with technical progress of PQ-measuring devices capabilities are the prerequisites for further progress in PQ monitors' allocation strategies. In the future, the monitoring aim and general strategy will be selected by a human (interested party) but AI algorithms will deal with the remainder of the task—determine required quantity, monitoring places, and will prioritize them. Feedback signal along with various information flows will be used for decision making, for example, to determine the expediency of the selected node and evaluate displacement need. Some examples of possible situations:

- Situations based on meteorological data in a specific part of a country: an expected increase in solar and wind parks generation, and levels of harmonics and flickers, respectively; annually expected thunderstorms and lightning (in May–June) or just wind storms, ice formation risk, high humidity (e.g., conditions which can intensify corona discharges);
- Situations regarding grid operation and maintenance: planned maintenance works in substations (power transformer disconnection from grid), a high number of operational commutations expected, changed grid topology, frequent protective relays triggering, hardly accessible locations;
- Grid research and condition monitoring: research of PQ mitigation strategy or specific equipment, research of impact on grid equipment, predictive maintenance, excellent PQ situation in monitor coverage zone;
- Situations regarding technological processes and customers' loads: expected intensive manufacturing mode (risk of outages, risk of production spoilage and quality drop), expected frequent electric motors starting (the cause of voltage sags), newly installed sensitive equipment, critical technological process (e.g., fire-fighting pumps, nitrogen loop for chemical inerting, cooling loops in nuclear power plants, nuclear waste repository, oil refinery), customers' complaints and surveys;
- Other technical issues: weak communication signal, signals interference, unavailable optical fiber, redundancy of analyzers in a region (due to unknown reasons), allocation algorithm limitations, errors or coefficient changing, etc.;
- Political initiatives, economic evaluation, compliance verification and other legislative reasons, insurance policy, marketing, education, and science popularization.

As mentioned previously, IEEE Std 1159 treats more phenomena as PQ events including the focus on electric current and EMC issues. Currently, many authors try to focus only on EN 50160 since it introduces some regulation and is simpler for large-scale application. In contrast, only IEEE Std 519 sets limit values for the harmonics, and IEEE Std 1159 gives only general information and recommendations (including some threshold values); however, the documents can be applied only to the case of the North American grid (i.e., it is significantly different from European systems: for example, frequency is 60 Hz, low phase-to-ground voltage—120 V, low phase-to-phase voltage—240 V). To conclude, amendments and sophisticated focus on IEEE Std 1159 are possible after the elimination of uncertainties in EN 50160 and IEC 61000-4-30. These documents require serious amendments which have not been made since legislative year. Some aspects can be eliminated immediately, some require more research and technical progress.

4.2. PQ—Part of Smart Grid and Its Communication Network

Earlier, PQ was not seriously regarded in traditional power systems planning: the attention should have been given to more fundamental problems such as generation planning, energy demand forecasting, and evaluation of stability and reliability. Nowadays, technological progress opens new opportunities: PQ monitoring enables better situation observability which will consequently update comprehension and give rise to new ideas. Deeper experience in the understanding of the nature of PQ will not only update PQ assessment methodology but also will tighten the requirements for power systems planning. Currently, power systems are facing big changes in a broader context, and renewable energy generators together with new types of loads based on power electronics become not only emission sources but also vulnerable elements to PQ phenomena. Therefore, PQ evaluation is becoming crucially important at the beginning stages of electrical grid planning through a prism of sustainable development. However, currently, PQ monitoring application is also not highlighted or at least mentioned in many papers oriented to Smart Grid research, for example, in [27,29]. Moreover, as previously referred to, PQ application is not involved in IEEE Std 2030 [5]—the most sophisticated Smart Grid guideline. On the other hand, energy policy attempts to attract attention to PQ. For example, the CEER 6th Benchmarking Report [30] highlights the importance of voltage monitoring and regulation in the chapter "Voltage Quality", and affirms that PQ is becoming "an increasingly important issue due to, among other things, the increasing susceptibility of end-user equipment and industrial installations to voltage disturbances." In addition to earlier given examples of new grid polluters types, rapid load switching (for energy-saving purposes) is mentioned in the document.

The future concept of electric power system planning is presented in Figure 9: PQ evaluation is incorporated into the beginning stages along with traditional stages (such as energy balance, stability, and reliability estimation) required for a new investment project. Deep knowledge in the field of PQ will lead to grid-designing methodic updates, and enable efficient allocation of PQ mitigation devices in order to maximize their individual and mutual effect. Efficient PQ monitors' allocation will allow not only the tracking of all PQ events propagation path (which is important for development of a mitigation strategy) but also to inspire more complex research for the distributed-element model of electrical grid, for example, transient wave reflection from surge arrester. Similar to the case of PQ monitors, there are many types of PQ mitigating devices with their own characteristics. For example, synchronous condenser, static synchronous compensator (STATCOM), or static VAR compensator (SVC) can be used for voltage sags' mitigation; however, each type has its own unique features such as energy, latency, and voltage level, thus the mitigation will be selective (i.e., will depend on voltage sag characteristics—voltage, duration, depth, energy, rise time, etc.). Obviously, additional CAPEX is required for PQ mitigation planning but it highly correlates with risk reduction, OPEX minimization, losses minimization, and profit maximalization. In addition, grid development and relevant decisions will remain being highly influenced by many external factors—for example, policy, macroeconomics, environment protection, participants' skills.

Information and communication technologies (ICT) is a relatively new and important layer converting traditional electric power system to a smart system. On the one hand, ICT will solve many problems and add new functionality, on the other hand it will bring new challenges. A new layer in PQ monitors' allocation strategy must be considered with the advance in ICT. Criteria will be related to optic fiber availability in a substation, reference signal received power (for cellular communication), or other aspects of signal propagation, EMC limits, and hygiene norms; in addition, the required investments for infrastructure, bandwidth licenses, and bills for communication services. However, from our point of view, the best example of remote PQ monitoring is given in [24], in which many communication problems were encountered with less than 50 monitors.

According to IEEE Std 2030, each investigation (in the field of ICT) should be started from the analysis of data flow characteristics, and a classification table is proposed for this purpose. The table with an insignificant expansion for PQ application is presented in Table 7, since the table and the approach has not been met in the PQ literature. A "Data aggregation" row is added to the table since it is important for PQ: despite PQ events being expected at every moment, they should be aggregated into larger time intervals, which is directly related with data packet structure. A tight requirement for the delay is not needed, but the accuracy of time synchronization (monitors synchronicity) is very important for avoiding excessive PQ events counting as voltage sags in [20]. PQ data are transmitted from the end-node to the hub; thus, the application works in unicast mode. Currently, PQ data are only informative, but later, after amendments in legislation, they will become more critical. Despite low requirements for data provision reliability, PQ analyzers' resistance is necessary to both intentional EM interference (IEMI) and high-altitude EM pulses (HEMP). Currently, security issues, such as unauthorized access, are not critical. Later, security issues will gain an importance for legal disputes. Moreover, if the PQ system is integrated, for example, with relay protection and automation, the strictest requirements for data security must be introduced (to ensure correct grid operation, prevent cyberattacks).

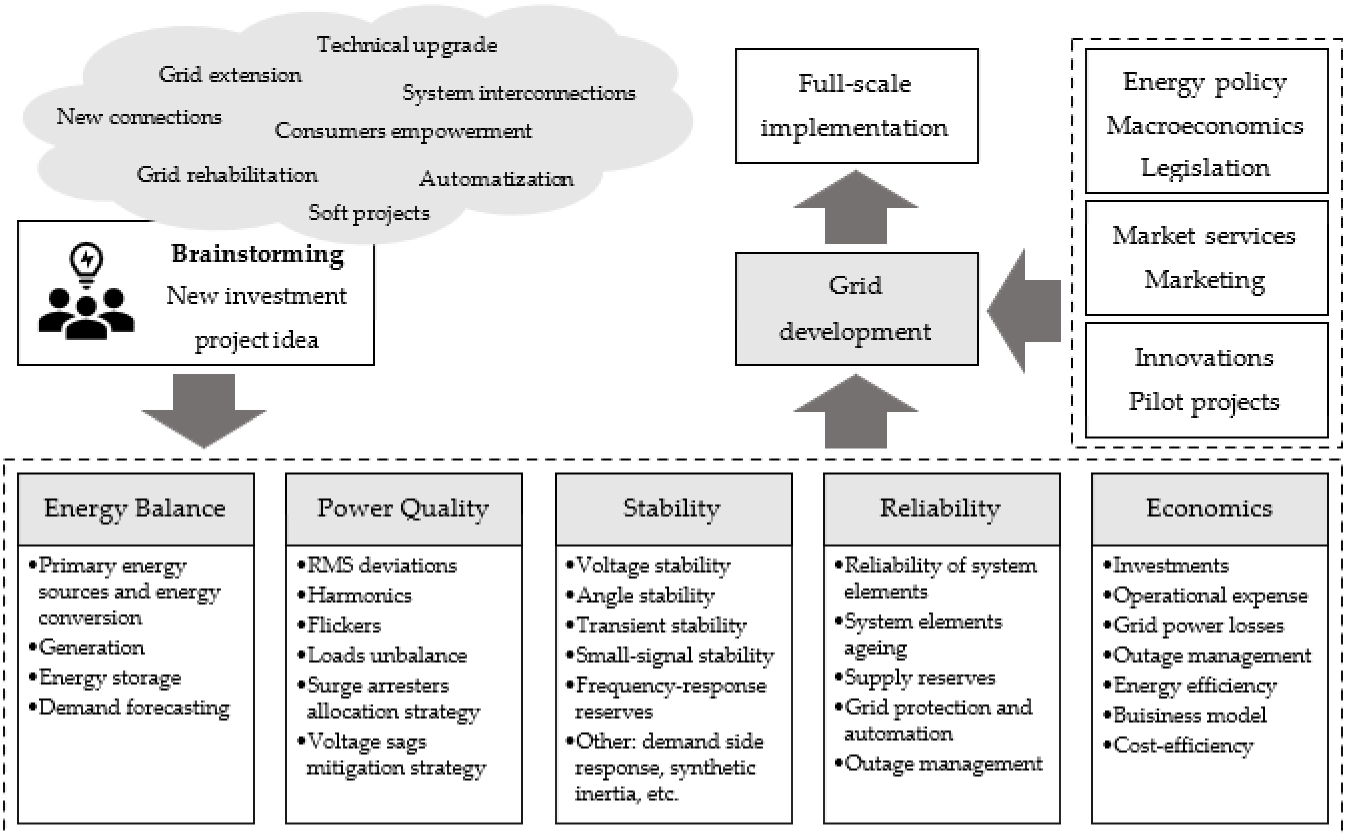

Figure 9. Extension of traditional power grid planning and development concept: PQ layer incorporation is essential to sustainable development.

A Smart Grid communication network is classified into three main coverage areas: wide area network (WAN), neighborhood area network (NAN), and home area network (HAN). In addition, many specific groups can be derived: low power wide-area network (LPWAN), industrial area network (IAN), local area network (LAN), etc. [27,29]. It is obvious that PQ monitoring is s WAN application where the data rate from the end-node should be reduced with feature extraction in the stage of local analysis (see Figure 1). Feature extraction is an important factor to lower requirements for ICT and avoid channel jamming. Table 8 summarizes bandwidth and coverage of main ICTs which are suitable for Smart Grid applications, and contributes to the clarification that data rates must be diminished as much as possible in the case of a massive monitoring system. Main WAN alternatives with high data rates are as follows: WiMAX—1 Gbps (802.16 m), cellular network (e.g., HSPA+—168 Mbps in downlink and 22 Mbps in uplink, LTE-Advanced—1 Gbps in downlink and 500 Mbps in uplink), and fiber optics—1–40 Gbps typical. According to [27], some fiber optic pilot projects have been executed with terabytes or petabytes bandwidths; however, high cost is a key factor limiting the usage of power optics. In the case of [24], 4G LTE has been selected for WAN; however, cellular service can be expensive. LPWAN technologies—LoRa or NB-IoT—can be applied when it is possible to reduce bandwidth to 20–50 kbps. Obviously, the whole list (given in Table 8) is applicable to designs of PQ communication network: WAN ICTs are suitable to be utilized in a backhaul network, the alternatives—for lower-in-hierarchy levels such as backbone and LAN. To conclude, in order to enable massive remote monitoring and increase the number of ICT alternatives, all possible measures must be taken in order to lower data transmission requirements (including the most important, the data rate).

Table 7. Proposed definitions of PQ data flow: current situation and perspective.

Data Characteristic [1]	Classification/Value Range [2]			
(1) Data use category:	To be determined by interested party: PQ data			
(2) Reach:	meters (feet)	**kilometers (miles)**		
(3) Information transfer time:	<3 ms	3 ms–10 s	10 s–minutes	**hours**
Data occurrence interval	**milliseconds**	seconds	minutes	hours
Data aggregation	seconds	minutes	**hours**	**days**
Method of broadcast	**Unicast**	Multicast	Broadcast	All
Priority	**Low**	Medium	High	
(4) Latency:	Low-low (<3 ms)	Low (<16 ms)	Medium (<160 ms)	**High** (>160 ms)
(5) Synchronicity:	**Yes**	No		
(6) Information reliability:	**Informative**	Important	Critical	
Availability	**Low** (limited impact)	Medium (serious impact)	High (severe impact)	
Level of assurance	**Low**	Medium	High	
HEMP, IEMI	**Hardened, yes**	Hardened, no		
(7) Data volume: [3]	bytes	kilobytes	megabytes	**gigabytes**
(8) Security:	**Low** (limited impact)	Medium (serious impact)	High (severe impact)	
Confidentiality	**Low** (limited impact)	Medium (serious impact)	High (severe impact)	
Integrity	**Low** (limited impact)	Medium (serious impact)	High (severe impact)	
Availability	**Low** (limited impact)	Medium (serious impact)	High (severe impact)	

[1] IEEE Std 2030 table is extended with addition of "Data aggregation" row. [2] Legend: bold text—either final or current feature; normal text (black)—perspective feature (in many cases—to ensure smooth integration and compatibility with other Smart Grid applications), invisible text (grey)—rejected option. [3] From single end-node. Depends on data processing and feature extraction strategies.

Table 8. The list of main ICTs and their features for Smart Grid applications [27,29,31–35].

Group	Technology	Bandwidth	Coverage
Wireless HAN	ZigBee	250 kbps at 2.4 GHz; 40 kbps at 915 MHz; 20 kbps at 868 MHz	10–75 m (30 m indoor)
	Wi-Fi	802.11b: 11 Mbps at 2.4 GHz; 802.11a and 802.11g: 54 Mbps; 802.11n: 600 Mbps	Max 250 m (100 m indoor)
	Bluetooth	Max 1 Mbps	Class 1—100 m; Class 2—10 m
	Z-Wave	40 kbps at 868 MHz (Europe); 250 kbps at 2.4 GHz	100 m (30 m indoor)
	6LoWPAN	250 kbps at 2.4 GHz; 40 kbps at 915 MHz; 20 kbps at 868 MHz	200 m

Table 8. *Cont.*

Group	Technology	Bandwidth	Coverage
Wireless LPWAN	LoRa	0.3–50 kbps at 868 MHz (Europe)	10–15 km (3–5 km in urban area)
	NB-IoT	200 kbps downlink, 20 kbps uplink	10 km (1 km in urban area)
	Sigfox	100 bps (140 uplink messages per day limit, 4—downlink)	40 km (10 km in urban area)
Wireless WAN	WiMAX	72 Mbps in 48 km radius, 100 Mbps in 10 km radius, max 1 Gbps (802.16m) at 2–66 GHz	
	Cellular	2G and 2.5G: up to 250 kbps (2G GSM—14.4 kbps); 3G HSPA+: 22 Mbps uplink, 168 Mbps downlink; 4G LTE: 86 Mbps uplink and 326 Mbps downlink (for 20 MHz bandwidth with 4x4 MIMO); 4G LTE-Advanced: 500 Mbps uplink, 1 Gbps downlink (for 70 MHz bandwidth with 4x4 MIMO), 1 Gbps uplink, 3.3 Gbps downlink in 10 km radius; 5G: larger than 1 Gbps expected	
Wired	PLC	BB-PLC: 200 Mbps at 1.8–250 MHz; NB-PLC: 800 kbps at 3–500 kHz	Does not propagate through transformer
	DSL	VDSL2 (ITU-T G.993.2): 10 Mbps for 500–750 m; G.fast (ITU-T G.9700 and G.9701): 1 Gbps for 500 m	
	Ethernet cables	100 Base-Tx (802.3u): 100 Mbps; P802.3bs: 200 Gbps and 400 Gbps (1 Tbps is expected in the near future); Cat 8: up to 40 Gbps for 30 m for 2 GHz bandwidth; Cat 7: 10 Gbps for 100 m for 600 MHz bandwidth (Cat 7A—1 GHz)	
	Optical	Up to 100 Gbps (1–40 Gbps typical)	AON: 80–100 km (typical); PON: 10–20 km (typical)

On the one hand, the ICT layer will bring new challenges, for example: grid network designing and planning issues, data transfer errors, cybersecurity, reliability reduction (since monitoring system will become more complicated), etc. On the other hand, the ICT layer will be beneficial. Firstly, it will simplify and accelerate data collection from a vast amount of PQ monitors—time, human, and transport resources will be saved. Secondly, less memory will be required in end-nodes (due to central data storage), but legislation defining minimum history storage time must be introduced. Thirdly, a great leap forward will be achieved in data loss avoidance and decrease in required DRF (which means a lower number of monitors). Therefore, optimal PQ monitors' allocation strategy is important not only for primary resources saving (such as monitor cost) but also for economy in ICT layer—CAPEX and OPEX saving, bandwidth reduction, and channel jamming prevention, data flow optimization in order to simplify data processing.

In Figure 10, an example of measurements of data loss is given: three phase-to-ground voltage arrays have been lost (from 3 March 2020 to 6 March 2020) during PQ measurement campaign in a 35 kV grid belonging to Lithuanian DSO ("Energijos skirstymo operatorius", AB). Measurements were non-remote, consequently it was impossible to immediately detect the data loss. In the future, data loss can be crucial for legal disputes about responsibility and penalties (between grid operators, regulator, consumers, and other parties), correct grid logic and operation (situation assessment, predictive maintenance, smooth and correct interoperability with other systems—"self-healing", relay protection, outage management, etc.), reporting for statistical or political purposes. In our case, the corrupted weak array is the loss of legal value, since according to EN 50160, weak duration data are required for compliance verification of supply voltage RMS, negative sequence unbalance, and other events. During the project, many problems have arisen with only a few monitors; thus, a huge technological leap forward must be made in anticipation of massive installation.

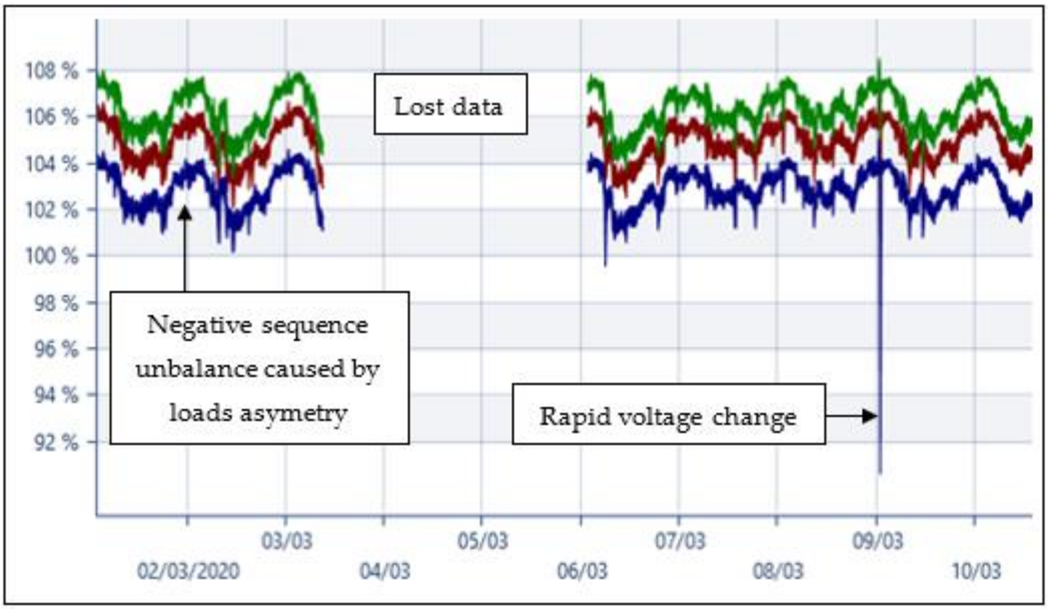

Figure 10. Phase-to-ground voltage array loss in 35 kV node during PQ measurements campaign in Lithuanian power system. Weak array (necessary for EN 50160 assessment) had been corrupted.

4.3. Case Study: PQ Monitoring System Development in Lithuania

This subchapter presents the stages of PQ monitoring system development by Lithuanian DSO ("Energijos skirstymo operatorius", AB) including monitors' allocation criteria, campaign size, duration, economics, communications, and integration with other systems. The concept is presented in Figure 11. Stage I encompasses smart meters with PQ functionality linking to MDM with 3G GPRS communication, PQ analyzers (IEC 61000-4-30 class A) installation, and connection to the PQ data system with fiber optics (according to the agreed allocation plan). Stage II encompasses both relay protection and fault management systems integration to SCADA/DMS, and MDM system interconnection with PQ data system. SCADA/DMS integration to PQ data system is going to be implemented in Stage III.

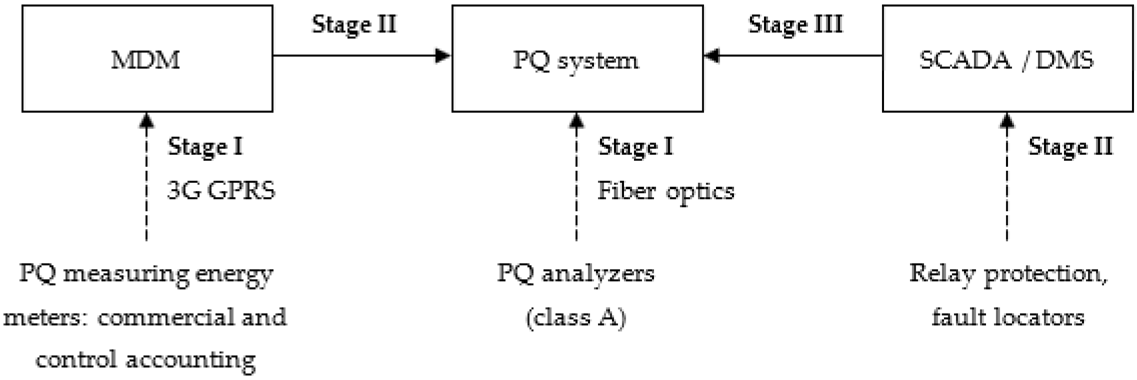

Figure 11. Development stages of remote PQ monitoring system in Lithuanian DSO grid.

Lithuanian monitors' allocation strategy is presented in Figure 12. PQ analyzers (550 units) are going to be installed in all HV/MV substations during Stage I (maximum term is 2–3 years, including procedures of public tenders), CAPEX—2.8M EUR (budget year: 2021). In addition, the stage involves PQ-measuring energy meters' installation for households. Stage II is parallel with Stage I; the duration is 3–5 years: monitors are installed in MV substations (preferentially in 35/10 kV) where optical fiber is available. If optical fiber is unavailable, smart meters with PQ functionality and GPRS will be installed in addition to fixed non-remote monitors (250 units). Both devices will be installed on secondary winding, CAPEX—1.3M EUR. In Stage III, remote PQ monitoring must be ensured in every MV substation: PQ analyzers will be integrated to PQ system along with optical fiber advance. In addition, the stage encompasses MV switching stations if optical fiber is available, else—PQ smart meter installation.

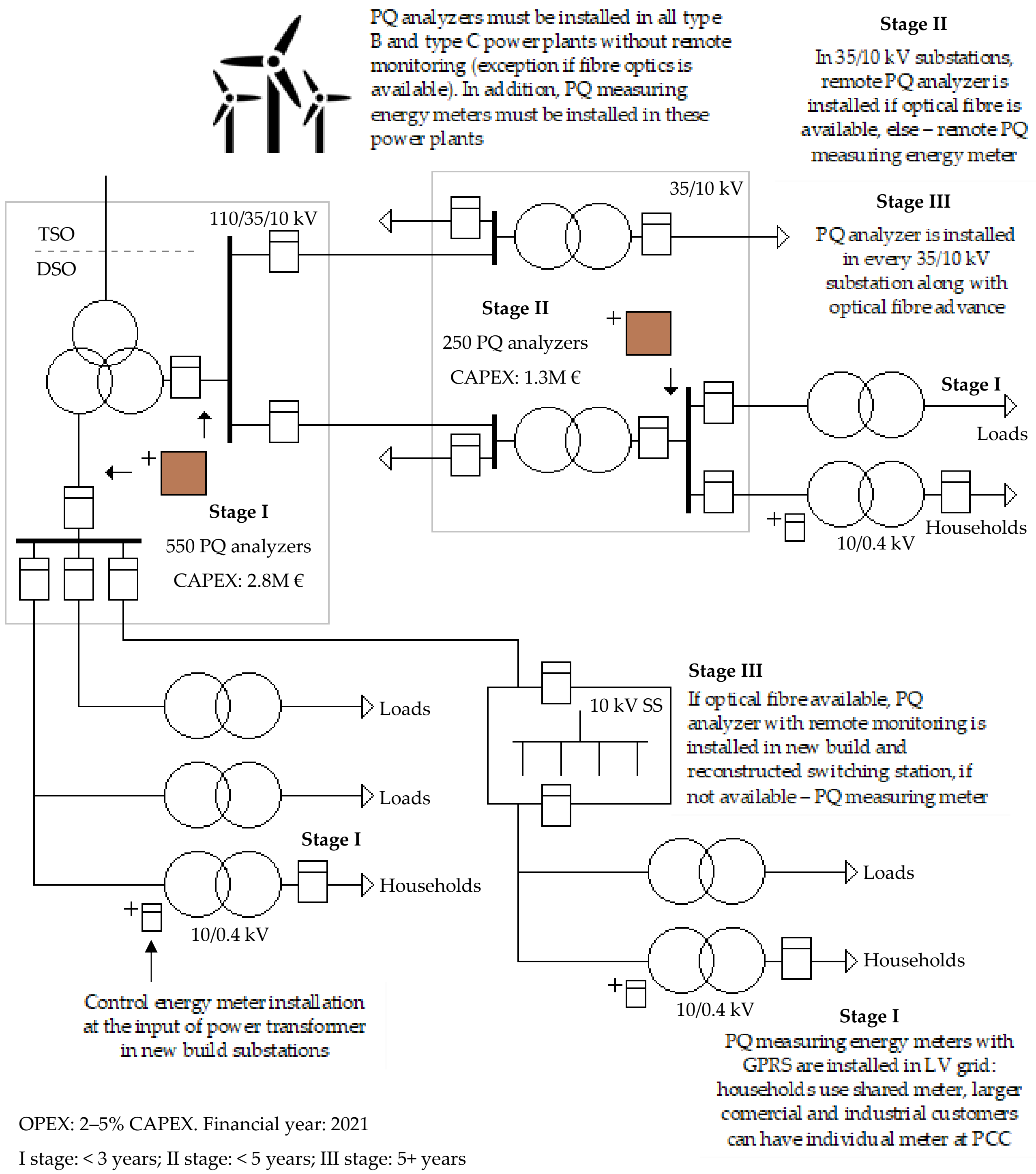

Figure 12. PQ monitors allocation strategy and other details about the development of remote PQ monitoring system in Lithuanian DSO grid.

Work priority is determined by substation ranking, a newly mentioned concept in this paper. Ranking can be reviewed as a new intermediate allocation category which stands between AI algorithms and abstract non-quantitative criteria. The advantage of ranking is simplicity (i.e., ratio determination without complex mathematics, algorithms). In the general case, a ranking approach does not require scientific software such as MATLAB, or Microsoft Excel can be a sufficient tool for task implementation. The disadvantages are as follows: ranking is not a multidimensional approach, only the main parameters can be considered, and adequacy depends on researcher competence. The proposed substations ranking has been based on transformer load and nominal power as follows:

$$P_1 = \frac{P^1{}_i}{\max\{P^1{}_i\}}, \tag{7}$$

$$P_2 = \frac{P^2{}_i}{\max\{P^2{}_i\}}, \tag{8}$$

$$P_3 = \frac{P^3{}_i}{\max\{P^3{}_i\}}, \tag{9}$$

$$\text{Score} = \begin{cases} w_1 P_1 + w_2 P_2 + w_3 P_3 \\ \sum_{i=1}^{3} w_i = 1 \end{cases} \tag{10}$$

where $P^1{}_i$—average yearly apparent load of a transformer; $\max\{P^1{}_i\}$—apparent load of the largest DSO transformer; $P^2{}_i$—relative apparent load of a transformer; $\max\{P^2{}_i\}$—relative apparent load of the largest DSO transformer; $P^3{}_i$—nominal power of a transformer; $\max\{P^3{}_i\}$—nominal power of the largest DSO transformer; w_i—weights.

In addition, remote PQ energy meters are installed in all type B and type C power plants with a non-remote PQ analyzer (see Figure 12). In the case of fiber optics' availability, a remote PQ analyzer is installed with a non-remote PQ energy meter.

Guidelines for portable monitors are also included into the strategy. It has been estimated that 15–30 portable PQ monitors are required in total at the initial stage of PQ system development (2–4 monitors per department). These monitors will be used for both customers' complaints and nodes research upon DSO decision. The recommendations were partially influenced by the survey presented in [36], where the total number of respondents is 114: 64% DSOs, 30% TSOs, and 6% of companies which operate both systems; 5 responses came from Africa, 30—Americas, 8—Asia, 61—Europe, and 10—Oceania. In general, DSOs have more PQ monitors—both portable and fixed—than TSOs (Figure 13). Some additional information about the most common responses which are noteworthy: 83% of respondents highlighted the importance of monitor compliance with standards, 70%—selected customers' complaints as the monitoring aim (86% DSOs).

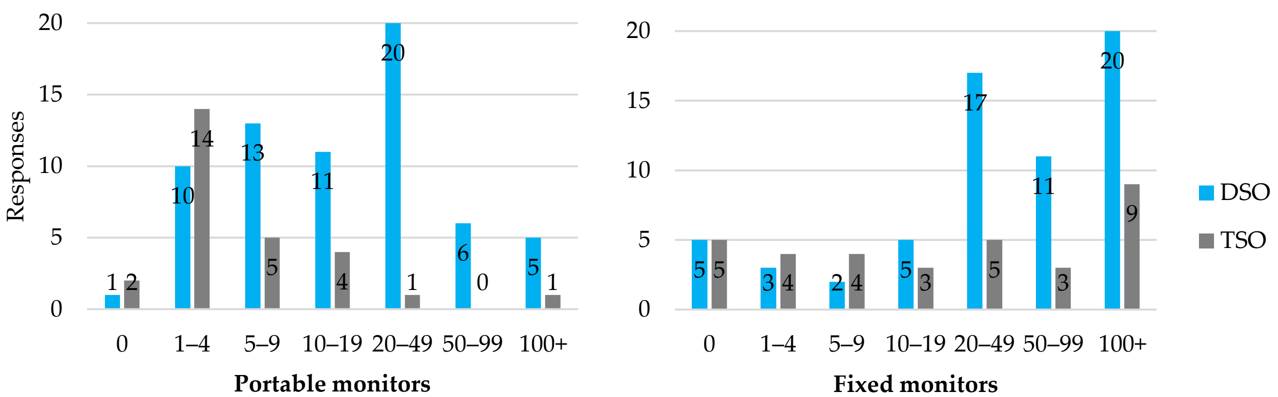

Figure 13. Number of responses regarding PQ analyzers in the possession of grid operators in 2013. The total number of respondents is 114. The median value of portable monitors is 9 units, the median value of fixed PQ monitors—45 [36].

In addition, high sampling analyzers are recommended for atmospheric transients' monitoring: the estimated number for the initial stage—7 units. The priority is given to the municipalities with higher lightning probability. The available historical weather data are given in [37] (see Figure 14): the territory of Lithuania is divided into two zones regarding annual thunderstorm duration—up to 40 h and more than 40 h.

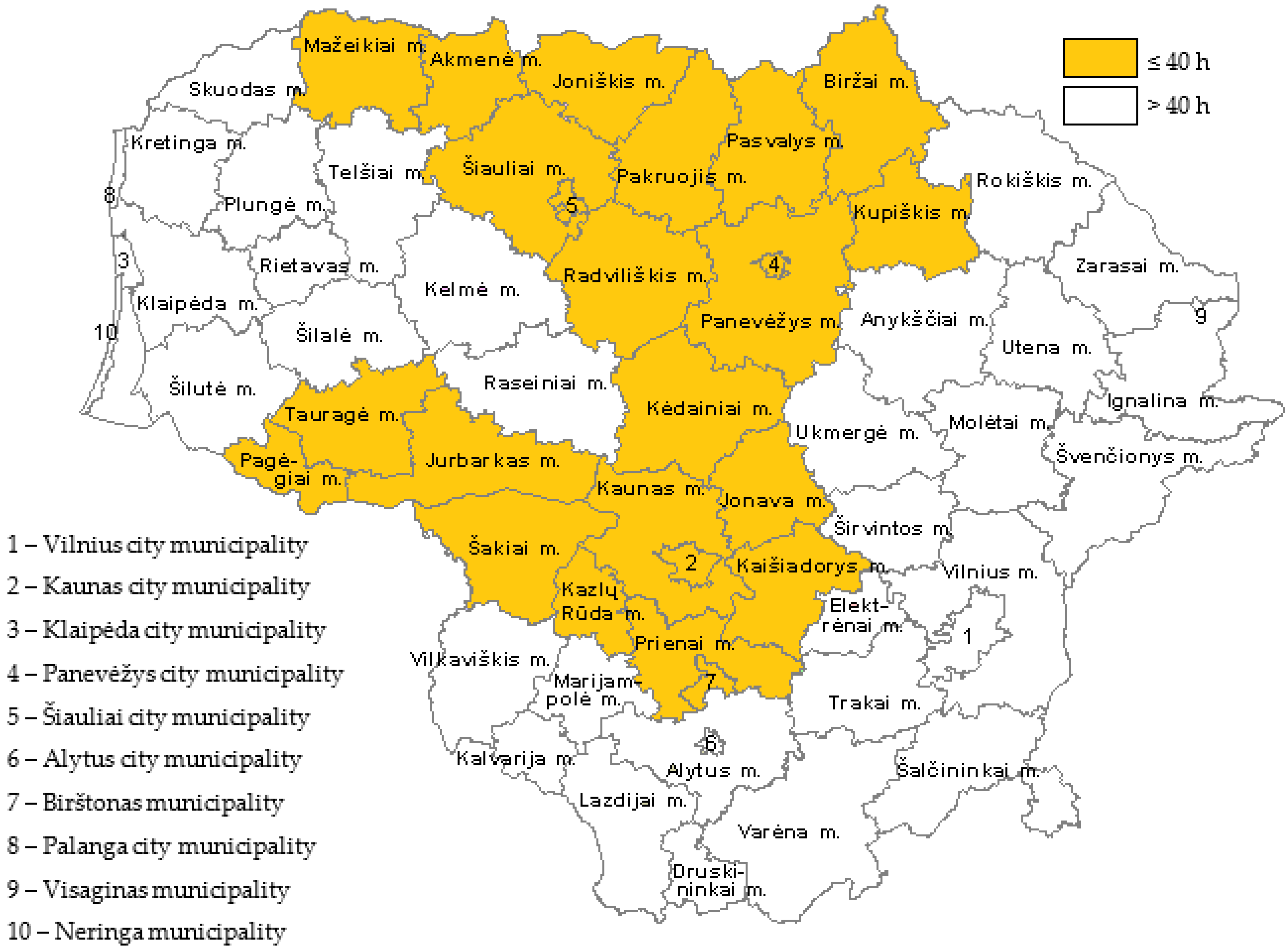

Figure 14. Expected annual thunderstorm duration in municipalities of Lithuania [37].

5. Conclusions

The main factor promoting PQ monitoring is legislation supplemented by customers' complaints and energy policy. The main PQ standards in the world are: IEEE Std 1159-2019 which currently provides the best guidelines (and includes some recommendations about monitors' displacement), and EN 50160:2010 which does not provide guidelines but sets limit values for a part of the PQ events list. Nowadays, since traditional power systems are facing vast changes and transforming to Smart Grid, PQ legislation does not correspond to modern needs. Currently, worldwide development of PQ monitoring systems is in the initial stages: in order to create conditions for efficient PQ monitors' allocation, besides the additional technical progress needed, solutions and unified approaches to many fundamental issues are essential. A clear and forward-thinking strategy of further research avenues is essential for progress acceleration: according to our findings, primary directions could be a development of organizational monitoring structure (steps, layers), and PQ physics investigation; secondary—PQ target group determination (limitation) for the specific monitor type considering other relevant layers and factors (e.g., grid voltage, propagation mechanism of disturbance, research aim, load type); tertiary—measurement engineering, AI algorithms, ICT, etc. Results, decisions, agreements should reflect in the standards amendments (as unified, universal approach).

To conclude, the main highlights of this state-of-the-art review about PQ nodes selection strategies are summarized:

- Research can be strictly divided into theoretical and practical, and the final allocation result will depend on the objective and PQ target group. According to the proposed criteria classification, the most common criteria selected in theoretical papers is short-circuits and residual voltage evaluation, and in practical papers they were the monitoring of all selected-type substations or busbars, and customers' complaints. In the future, the allocation strategy must have a layered architecture; currently, authors do not pay much attention to the differences between various monitor types and their features: the PQ target group, applicable voltage level, measurement characteristics (e.g., sampling, frequency response), etc.
- In theoretical studies, algorithms are usually tested on small size (up to 123 nodes) test systems—IEEE, CIGRÉ, and Brazilian. In addition, only one example of a large test was found—the EPRI Ckt5 2998-node test. In practical studies, the proposed strategies are used on larger grids since they do not use any algorithm-based approach, and in general, use up to 600 monitors. In the case of the most massive examples (with 3500 and 12,000 monitors), the authors acknowledged that the installation was costly, and more efficient decisions should have been taken. In the future, monitors quantity optimization will be essential not only for CAPEX and OPEX but also for ICT aspects—reduction in bandwidth and simpler data processing.
- Currently, PQ physics is not sufficiently studied, and the remaining open questions inhibit the development of a measurement methodology and prerequisite aspects for allocation strategy. For example, special attention should be paid to the following PQ subjects: propagation, indexes (features extraction), assessment of voltage sag burst, impact on equipment (both short-term and long-term), voltage sag mitigation efficiency of power plants, etc. All PQ phenomena are interdependent, but authors often limit their approach to a specific target group (e.g., to balanced voltage sags) and skip the remainder of the list. It is the only way to start (also considering the previously mentioned small test grid size) in anticipation of a unified approach, a universal complex methodology, and AI utilization; thus, the development is now at the beginning stage. Extensive experience in this field will probably result in an efficient PQ mitigation strategy designed at the initial stages of grid planning, reducing possible risks in project cost-efficiency evaluation, contributing to Smart Grid development and its applications' interconnection—in other words, effective decision making and excellent PQ assurance is an essential part of sustainable development.
- In the Lithuanian DSO grid, approximately 800 PQ analyzers (mostly with optical fiber communication) are going to be installed on the MV side—in most HV/MV or MV/MV substations, in all type B and type C power plants. The installation priority is determined by ranking—a newly introduced approach which lies between AI and abstract non-quantitative criteria (frequently used and reviewed in papers). The proposed ranking methodology is based on transformer nominal power and loading. In addition to fixed monitors, PQ-measuring Smart Meters (with 3G GPRS) will be utilized in the LV grid, 15–30 portable monitors are required in response to customers' complaints, and the priority is given to municipalities with higher thunderstorm probability for high sampling analyzers. PQ system integration with MDM and SCADA/DMS is expected in more than 5 years.

Author Contributions: Conceptualization, V.L. and V.R.; methodology, V.L., V.R., D.N. and G.K.; software, V.L., V.R., D.N. and G.K.; formal analysis, V.L., V.R., D.N. and G.K.; investigation, V.L., V.R., D.N. and G.K.; resources, V.L. and V.R.; data curation, V.L.; writing—original draft preparation, V.L., V.R., D.N. and G.K.; writing—review and editing, V.L., V.R., D.N. and G.K.; visualization, V.L.; supervision, V.R., D.N. and G.K.; project administration, V.L. and V.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Lithuanian Energy Institute.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

A chosen fragment of Lithuanian power system which is used for simulations to support some statements regarding the PQ phenomena is shown in Figure A1. Simulation is performed with MATLAB/Simulink. Four scenarios have been created: two-phase-to-ground short-circuit at the end of 330 kV 100 km line, two-phase-to-ground short-circuit in the beginning of 35 kV line, 10 kV line commutation, and the most frequent fault—single-phase short-circuit in 10 kV line. The Lithuanian MV grid operates in either isolated or compensated neutral mode, HV grid—earthed via a separator (some separators are disconnected to reduce a ratio of short-circuit current). More detailed structure and data cannot be provided due to data confidentiality issues.

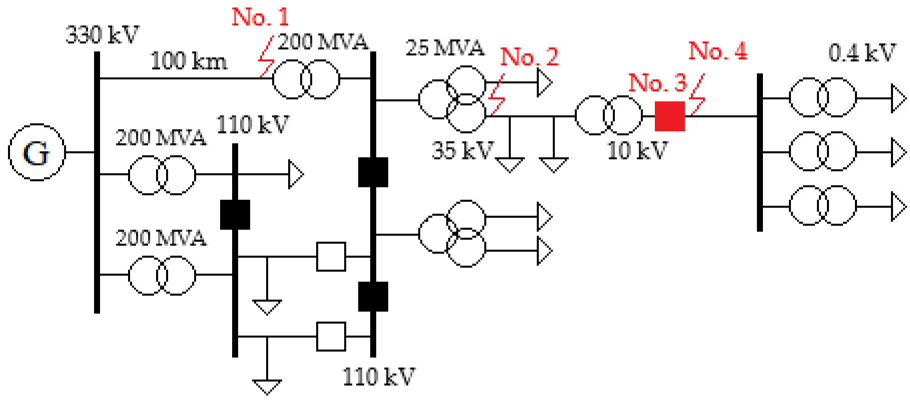

Figure A1. Chosen fragment of Lithuanian power system for PQ events simulation: scenario No. 1—two-phase-to-ground short-circuit at the end of 330 kV 100 km line; scenario No. 2—two-phase-to-ground short-circuit in the beginning of 35 kV line; scenario No. 3—10 kV line commutation; scenario No. 4—single-phase short-circuit in 10 kV line.

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