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A Case Study on Power Quality in a Virtual Power Plant: Long Term Assessment and Global Index Application

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Abstract: The concept of virtual power plants (VPP) was introduced over 20 years ago but is still actively researched. The majority of research now focuses on analyzing case studies of such installations. In this article, the investigation is based on a VPP in Poland, which contains hydropower plants (HPP) and energy storage systems (ESS). For specific analysis, the power quality (PQ) issues were selected. The used data contain 26 weeks of multipoint, synchronic measurements of power quality levels in four related points. The investigation is concerned with the application of a global index to a single-point assessment as well as an area-related assessment approach. Moreover, the problem of flagged data is discussed. Finally, the assessment of VPP's impact on PQ level is conducted.

Keywords: virtual power plant (VPP); power quality (PQ); global index; distributed energy resources (DER); energy storage systems (ESS); power systems; long-term assessment

1. Introduction

In recent electrical power networks, the number of renewable energy sources (RES) and energy storage systems (EES) have continuously increased. Thus, different approaches to controlling them have appeared, such as microgrids and virtual power plants (VPP) [1,2]. Generally, VPPs are autonomous units equipped with effective power flow control systems. VPPs consist of different elements that are connected to the distribution network. The indicated elements are generators, loads, and energy storage systems [2]. Coordinating the work of the entire VPP is a difficult and demanding task.

The operation of VPPs may be analyzed in different areas. This article is related to power quality (PQ) issues in VPP. Thus, Table 1 presents the current research directions concerning VPPs and PQ. The literature investigation is based only on articles published in the last 5 years.

Table 1. Current research trends concern virtal power pland (VPP) and power quality (PQ).

Current Research Trends Concerning VPP	
optimal active and reactive power scheduling	[3–12]
network voltage control by renewable energy sources integrated	[13–18]
power flow control and analysis	[19–24]
frequency control issues with VPP support	[25–31]
Electric energy storage (EES) sizing, localization and management in VPP	[32–37]
playing a role in energy market	[38–48]
energy management in a VPP	[49–58]
real case study analysis	Denmark [59], Germany [60], Ireland [61], Greece [62], United Kingdom [63], China [64], South Korea [65], India [66], Australia [67].
Current Research Trends Concerning PQ	
development of PQ measurement devices and systems	[68–74]
data mining of PQ measurements	[75–84]
global power quality indices	[85–93]
detection and classification of voltage events	[94–102]
vehicle-to-grid (V2G) impact on PQ	[103–111]

The possibility of a simple assessment of a virtual power plant's impact regarding power quality was the main focus of this paper. The articles that concern PQ issues in VPPs are indicated in this paragraph. The first example is an article [112] which introduces VPP as vehicles to facilitate the cost-efficient integration of distributed energy sources (DER) into the existing power system. The article also presents case studies that demonstrate the application of the concepts on a test system. The result of the system performance includes energy efficiency, power quality, and security. The authors of [113] propose extensions of the IEC 61850 standard to enhance the interaction between the VPP controller and the DER. The article presents the implementation of VPP communication and control architecture in a real case. The investigated case concerns the PQ recorders' issues and demands in accordance with IEC 61850. The authors of [114] attempt to provide a suitable framework for harmonizing the operations of different units of VPP. The authors indicated that decisions and the generation of profit, although complying with the required power quality levels and physical network constraints, are an important element of VPP strategies. The authors of [115] present simulations of a situation with a VPP during an islanded grid with a thermal power plant for baseload. The indicated VPP consists of 200 MW wind power, 100 MW photovoltaic power, and +/− 250 MW pumped storage. The article presents different control strategies of the storage plant to highlight the impact of VPP on power quality. The authors of [116] consider the coordinative operation problem of multi-energy VPP. The bi-objective dispatch model was established for the optimization of the performance of multi-energy VPP in terms of economic cost and PQ. A real case study was performed on Hongfeng Eco-town in Southwestern China. The authors of [117] consider VPP management with priority requirements optimized by the compromised method. The operation optimization model of the virtual power plant was formulated as the fuzzy multiple objective optimization problems. This optimization problem considers the satisfaction of both customers and suppliers, system stability, PQ, and costs with operation limitations. The proposed method was applied in a test system. However, in the literature, there is a lack of research that presents the assessment of PQ in different units of VPP. Thus, this article investigates PQ measurements in long-term performance.

This article presents a case study of analyzing a real VPP that operates in Poland. The investigated VPP consists of a fragment of both low-voltage (LV) and medium-voltage (MV) distribution networks. The VPP consists of a hydropower plant (HPP), a photovoltaic system (PV), and energy storage systems (ESS). In this article, only the part of this VPP is analyzed which is concerned with the 1.25 MW HPP and associated 0.5 MW ESS. The investigation is based on power quality measurements that were obtained synchronically in five measurement points, which are HPP, ESS, associated MV line, and two LV loads. The duration of the measurements was from 1 May 2020 to 28 October 2020. Therefore, the observable period of time was 26 weeks—182 days. For the indicated time period and measurement points, the assessment of PQ was realized using the global value. The single parameter of a single measurement point for such a long period of time demands analysis of a huge dataset. Thus, this global index approach was used. Moreover, since the measurement points are connected in one network, the proposition of common analysis was proposed. The analysis of how to use the flagging concept was indicated for multipoint measurement. Another element of the analysis was to indicate the different working conditions of the VPP. Fifty of them were indicated concerning HPP and EES working schedule. Then, the comparison of the indicated working conditions was realized using the global index.

To summarize the contributions of this article:

- It contains the analysis of multipoint, synchronic, and long-term power quality data;
- PQ assessment is realized for both single-point and area-related approaches;
- Flagging concept is discussed for both single-point and area-related approaches;
- PQ assessment is realized using the global index approach;
- Different working conditions of the VPP are defined, investigated, and compared in terms of power quality.

To obtain indicated contributions, the article is organized into five sections. In Section 2, the investigated virtual power plant is presented. Section 3 presents results concerning the use of the global index for PQ assessment of each measurement point; different working conditions of the investigated VPP; analyzing the application of the flagging concept for the area-related approach; using the global index for the assessment of different working conditions of the VPP in both single-point and area-related approaches. Section 4 presents a discussion of the obtained results. Section 5 indicates the conclusions.

2. Methodology and Research Object Description

The investigation presented in this article concerns PQ issues in VPP. The proposed approach concerns the application of the global index. Thus, the selection and customization of the global index for VPP issues are presented in Section 2.1. Then, the description of the investigated VPP localized in Poland is presented in Section 2.2. Finally, the specific working conditions of single VPP elements are indicated in Section 2.3.

2.1. Global Power Quality Index

As a current trend in PQ issues, the global index was indicated. Thus, in this article, there is a proposition to use one such index. Aggregated data index (ADI) [86,87] was selected. The used index consists of five classic 10-min PQ parameters, such as:

- frequency—f,
- voltage—U,
- short term flicker severity—P_{st},
- asymmetry factor—k_{u2},
- total harmonic distortion in voltage—THDu,

And additional parameters that are responsible for the enhancement of the sensitivity of the index:

- an envelope of voltage deviation obtained by the difference between the maximum and minimum of 200-millisecond U values identified during the 10-min aggregation interval,
- a maximum of the 200-millisecond value of THDu, similarly identified in the 10-min aggregation interval [86,87].

Indicated parameters refer to the demands of the standard IEC 61000-4-30 [118]. Three-phase values are reduced to one using the mean value of them. All factors that are included in the ADI are based on the differences between the measured 10-min aggregated power quality data and the recommended limits of the selected standard. Therefore, the differences are expressed as a percentage in relation to standard limits. However, to customize the proposed index to VPP issues, the authors decided to exclude frequency. It is known that local changes do not impact frequency. Therefore, to conduct an assessment of VPP, impact on local area frequency was omitted. The calculations of ADI were performed on raw PQ measurement data using Excel software.

2.2. Investigated VPP

The indicated virtual power plant in this article is based on a fragment of the distribution network in Poland [119,120]. It is supplied by two stations of 110/20 kV. The indicated stations are connected to a 110 kV electrical power system. However, in this article, only a certain area of one substation is investigated. The 20 kV network fed from the station is an overhead cable network. The 20 kV network fed from the second station is mainly an urban cable network. The 20 kV network has earth fault current compensation. Connected to the VPP are a 1.25 MW HPP and a 0.5 MW battery ESS, both of which are connected to a medium voltage level.

The simplified scheme of the selected fragment of the VPP area is presented in Figure 1. It consists of a 20 kV distribution network with a hydropower plant (HPP) and an energy storage system (EES) connected with the HV/MV substation by MV line (MV_L). HPP and ESS are connected to the same node of the network. Furthermore, two additional low voltage loads are indicated: LV_L and LV_HE. LV_L is connected with the indicated MV associated line. LV_HE is connected with the node of the HPP and EES. The localization of power quality recorders (denoted as "R") is also indicated in Figure 1. Due to this, the HPP and EES are connected to one node and their PQ recorders use the same voltage transformer. In further research, they are treated as one point, indicated as MV_HPP&EES.

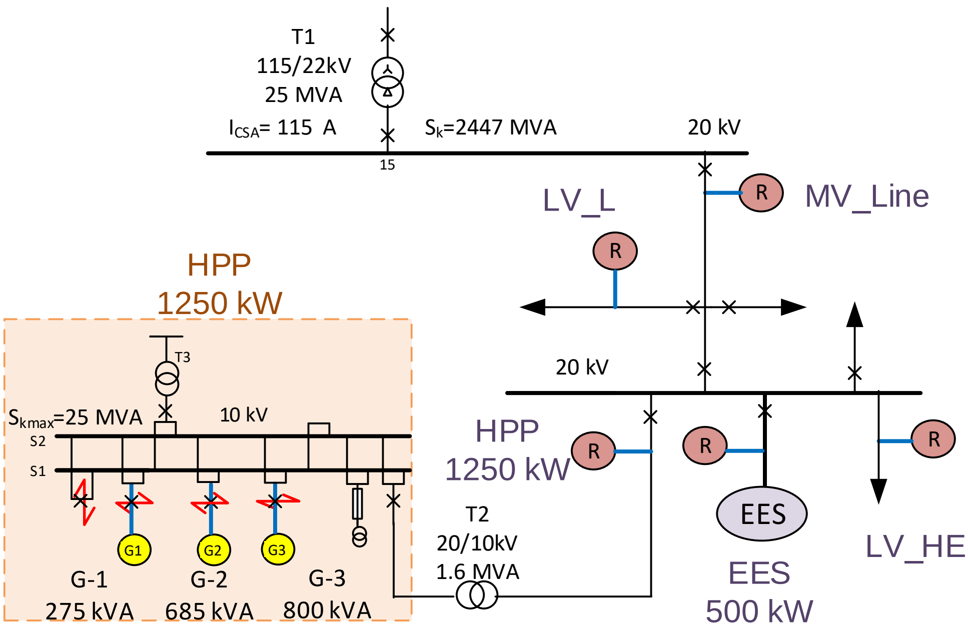

Figure 1. Investigated part of VPP with the placement of PQ recorders.

2.3. Different Working Conditions of Virtual Power Plant (VPP)

To investigate the working conditions of the VPP, different working conditions of the HPP and EES were considered. Regarding the HPP, three different working conditions were considered:

- not working—active power level equal to 0 or equal to own consumption;
- working at a part power—active power higher than own consumption but lower than 1 MW;
- working at a maximal power—active power higher than 1 MW.

Regarding EES, five different working conditions were indicated:

- not working—active power level equal to 0 or equal to own consumption;
- a low power charging—charging power higher than 40 kW and lower than 200 kW;
- a high power charging—charging power higher than 200 kW;
- a low power discharging—discharging power higher than 6 kW and lower than 200 kW;
- a high power discharging—discharging power higher than 200 kW.

The values are based on working circumstances that were discussed with the power distribution company during the VPP settlement.

3. Results

This section presents the results of the investigation of PQ issues in VPP. In Section 3.1, the global index application is presented. The case is realized for EN 50160 [121] demands and realized for each measurement point separately. Section 3.2 analyzes the occurrence of different working conditions of the investigated VPP. Then, in Section 3.3, the flagging concept is applied in accordance with standard IEC 61000-4-30 [114]. Additionally, the cross-analysis between event occurrence in different measurement points is conducted. Finally, Section 3.4 presents the assessment of the indicated working conditions of the VPP using the global index for both single-point and area-related approaches.

3.1. Application of Global Power Quality Index for Single Measurement Points

This section presents the application of ADI to a long-term comparison of power quality level. As indicated in Section 2.1, VPP frequency is omitted so the frequency importance rate was set as 0. Standard EN 50160 [121] was selected to obtain global values. The applied limits based on EN 50160 [121] are presented in Table 2.

Table 2. Limit values of standard EN 50160 [121] used for the global index.

Parameter	Value
U_{limit}	10% of U_d
Pst_{limit}	1.0
$ku2_{limit}$	2%
$THDu_{limit}$	8%

U_d—declared value of voltage.

For such defined ADI, the assessment of PQ level was conducted for all four measurement points (Figures 2–5). Moreover, to enable easier analysis, green-yellow-red colors were included in the figures:

- green for ADI ≤ 0.5;
- yellow for 0.5 < ADI ≤ 1;
- red for ADI > 1.

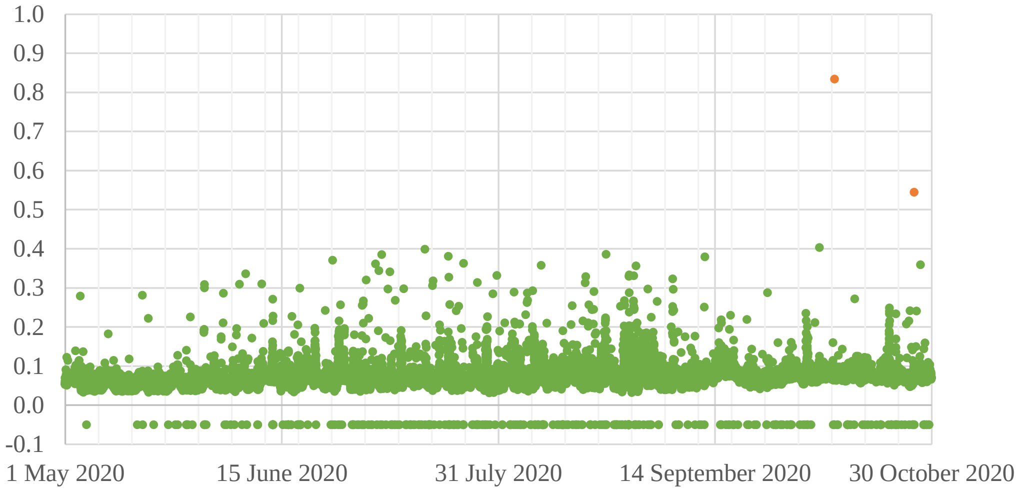

Figure 2. Global power quality index changeability for MV_Line.

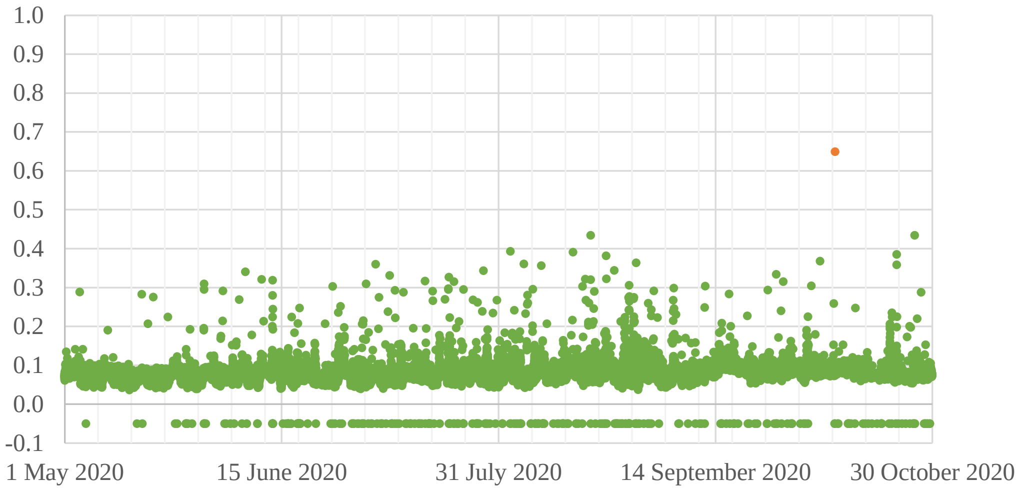

Figure 3. Global power quality index changeability for MV_HPP&EES.

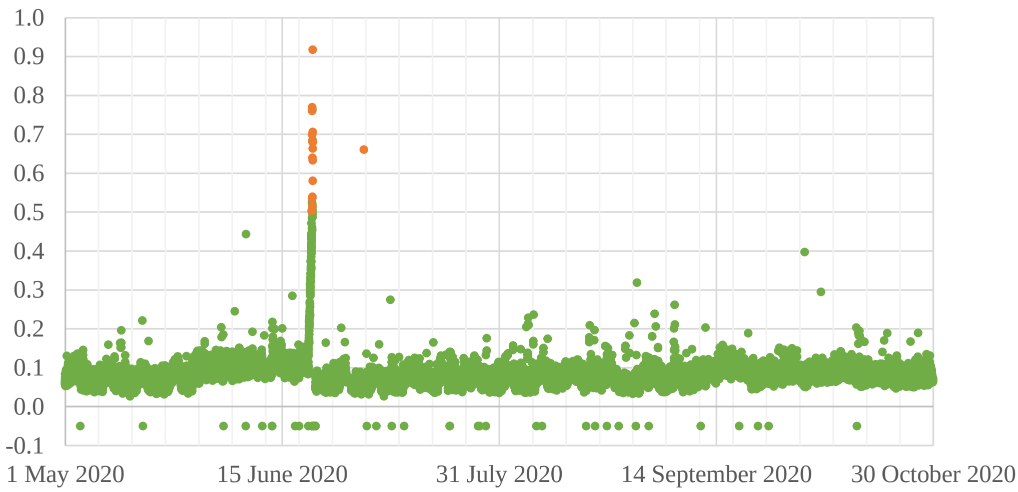

Figure 4. Global power quality index changeability for LV_HE.

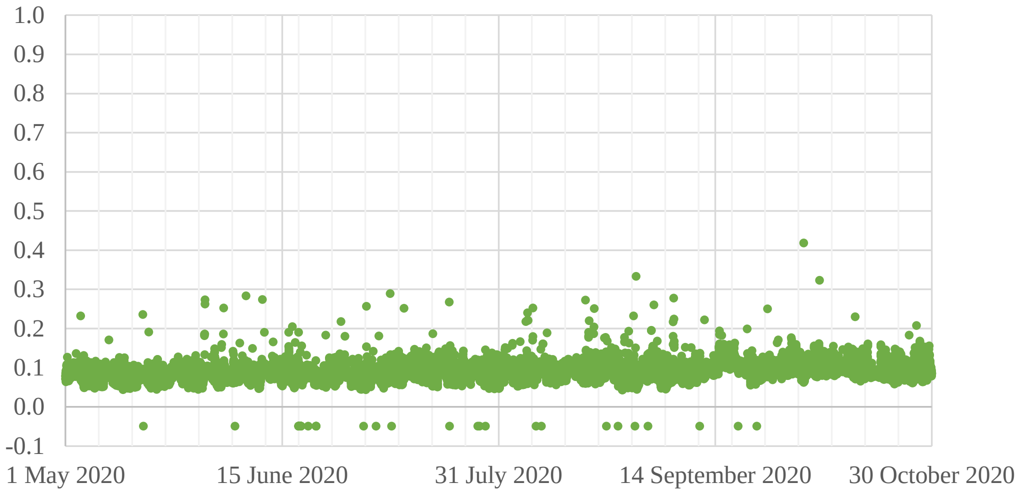

Figure 5. Global power quality index changeability for LV_L.

In the analysis, the time when voltage events occurred was excluded. The event data exclusion was based on the flagging concept of standard IEC 61000-4-30 [118]. Flagged data are represented as "virtual" value of ADI equal to −0.05. A deeper consideration of these voltage events is presented in Section 3.3. To summarize ADI levels for selected points in the selected 26 weeks of measurements, Table 3 was prepared. The results indicated that the highest level of power quality level (the lowest ADI) was in the MV_Line and the lowest level of power quality (the highest ADI) in LV_L.

Table 3. Limit values of standard EN 50160 [121] used for the global index.

Measurement Point	Number of Flagged Data	Mean Value of ADI
MV_Line	327	0.069
MV_HPP&EES	294	0.080
LV_HE	111	0.077
LV_L	47	0.087

During the time domain change in ADI level in LV_HE, a specific period was selected. In long-term assessment, it is challenging to verify the phenomena of this working condition. Therefore, the time shortage to 4 days that were connected with this working condition is presented in Figure 6. It can be observed that the PQ problem is noticed only in LV_HE, so this working condition is not connected with the impact of VPP. However, it is worth noticing that after a continuous (even linear) increase in ADI, a long event time in the LV_HE measurement point was indicated. In this article, in depth analysis of the reason for this working condition is omitted but this is a very interesting topic for future research.

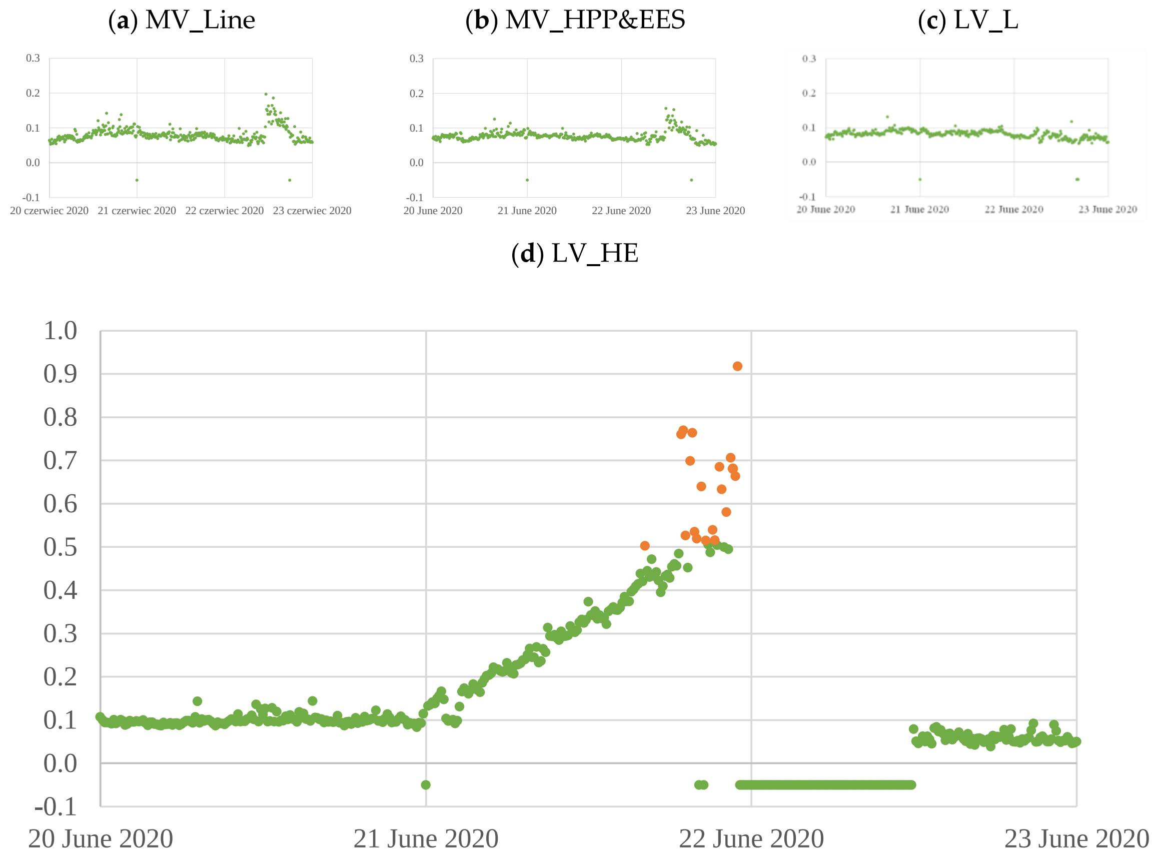

Figure 6. Specific working conditions observed in the level of ADI for measurement point (**a**) MV_Line, (**b**) MV_HPP&EES, (**c**) LV_L, (**d**) LV-HE.

3.2. Indication of the VPP Different Working Conditions

Based on information about HPP and EES possible operation indicated in Section 2.3, the investigated VPP working conditions are as follows:

- "0"—HPP is not working and ESS is not working;
- "1"—HPP is working partially and ESS is not working;
- "2"—HPP is working at maximal power and ESS is not working;
- "3"—HPP is not working and ESS is discharging at low power;
- "4"—HPP is working partially and ESS is discharging at low power;
- "5"—HPP is working at maximal power and ESS is discharging at low power;
- "6"—HPP is not working and ESS is discharging at high power;
- "7"—HPP is working partially and ESS is discharging at high power;
- "8"—HPP is working at maximal power and ESS is discharging at high power;
- "9"—HPP is not working and ESS is charging at low power;
- "10"—HPP is working partially and ESS is charging at low power;
- "11"—HPP is working at maximal power and ESS is charging at low power;
- "12"—HPP is not working and ESS is charging at high power;
- "13"—HPP is working partially and ESS is charging at high power;
- "14"—HPP is working at maximal power and ESS is charging at high power.

Initially, it was determined how long a given state of work occurred. The analyzed period of time was 182 days (26 weeks). Time aggregation of power quality data is 10 min, so the selected period is represented by 26,208 10-min data. However, due to the data coverage based on real measurements, synchronized 10-min data obtained from all points obtained were 25,069. Therefore, data coverage is 97.7%.

Detailed information on the number of 10-min data assigned to the working conditions is included in Table 4. Figure 7 also presents the occurrence of working conditions in the analyzed time period. It is worth noting that the state of operation 9 (HPP is not working and EES is charging at low power) and 12 (HPP is not working and EES is charging at low power) does not occur during measurements. This is because these working conditions were not permitted during the planning of the VPP. It also can be observed that the most common working conditions were "0" (HPP is not working and ESS is not working), "3" (HPP is not working and ESS is discharging at low power), and "2" (HPP is working at maximal power and ESS is not working).

Table 4. Duration of different working conditions.

VPP Working Condition	Number of 10-Min Data	Time of Working Condition Occurring as Percentage of Whole Time
0	9531	38.02
1	962	3.84
2	3382	13.49
3	8194	32.69
4	177	0.71
5	237	0.95
6	72	0.29
7	60	0.24
8	267	1.07
9	0	0.00
10	391	1.56
11	1538	6.14
12	0	0.00
13	127	0.51
14	131	0.52

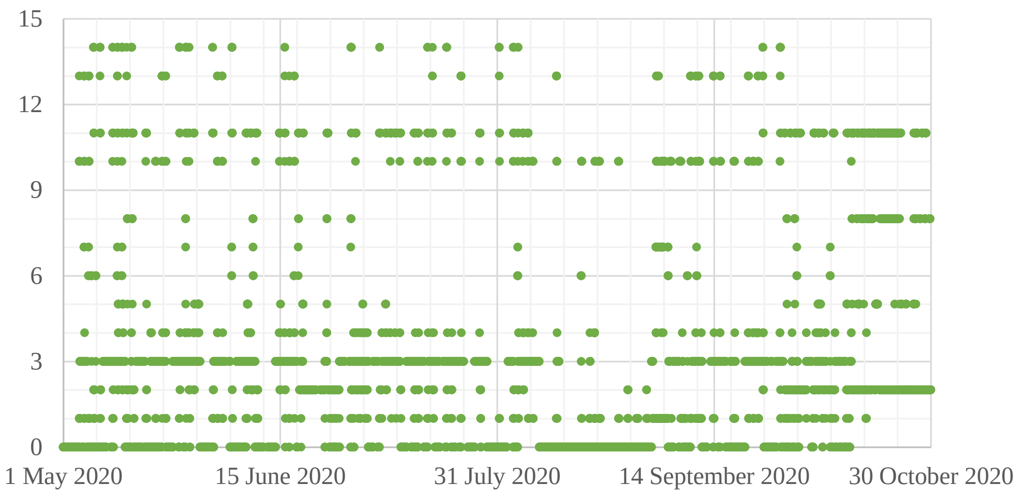

Figure 7. VPP working conditions in analyzed period of time.

3.3. Events Analysis as an Introduction to Area-Related Approach

In this section, the analysis of events occurring is performed. Generally, this is not a strict event analysis such as defining the type of event. The main aim of this subsection is to analyze how events impact the number of flagged data for both single- and multiple-point approaches. The flagging concept is introduced in standard IEC 61000-4-30 [118]. It indicates that if an aggregated value contains the time when an event occurred, these aggregated data must be flagged. This ensures that this problem is not counted twice as an event and as an extension of other parameter values.

For analysis of the number of flagged data, the flagged data matrix is proposed in Table 5. It presents the number of 10-min data that were flagged for single points and together on two measurement points. It can be observed that the highest number of flagged data was for the MV_Line and the lowest for the LV_L. It is also worth noticing that the majority of flagged data were common for MV_Line and MV_HPP&EES measurement points.

Table 5. Matrix of flagged data in analyzed measurement points.

	MV_Line	MV_HPP&EES	LV_HE	LV_L
MV_Line	327			
MV_HPP&EES	277	294		
LV_HE	15	15	111	
LV_L	17	29	10	47

The next step was to check how many of these common flagged data were indicated in more than two points. The results of this investigation are presented in Table 6. The results indicated that the general number of flagged data that are common for all measurement points is equal to 9.

Table 6. Limit values of standard EN 50160 [121] used to the global index.

Measurement Points	Number of Common Flagged Data
MV_Line + MV_HPP&EES + LV_HE	15
MV_Line + MV_HPP&EES + LV_L	17
MV_HPP&EES + LV_HE + LV_L	9
MV_Line + MV_HPP&EES + LV_HE + LV_L	9

The additional investigation included the concept of flagging for all measurement points treated together (area-related approach). This approach is based on set theory. Each measurement point is a single set of flagged data and the area-related value is a union of them all. Generally, the flagging for the whole period for all measurement points together was connected with the flagging of 457 10-min data. Then, the distribution of different working conditions (defined in Section 3.2) was realized. Presented in Section 3.4 is a comparative assessment of VPP working conditions. It is worth noticing that, due to the flagging concept, around 1.7% of data were excluded from the comparative assessment. Detailed results are presented in Table 7.

Table 7. Impact of flagging concept for area-related approach.

VPP Working Condition	Number of Data before Flagging	Number of Data after Flagging	Change in Percentage to the Number of Data before Flagging
0	9531	9373	1.7
1	962	951	1.2
2	3382	3247	4.2
3	8194	8092	1.3
4	177	175	1.1
5	237	235	0.9
6	72	71	1.4
7	60	60	0.0
8	267	264	1.1
9	0	0	-
10	391	389	0.5
11	1538	1501	2.5
12	0	0	-
13	127	127	0.0
14	131	127	3.1

3.4. Assessment of Different Working Conditions of VPP in Area-Related Approach

The next element of this research was the application of ADI to describe the working conditions of VPP indicated in Section 3.2. The analysis of ADI was realized separately for each of the four measurement points. The results are presented in Table 8. The assessment of the impact of individual working conditions of VPP (0–14) was related to the situation when both HPP and the associated EES are not working (working condition 0). Green was used to indicate conditions that are more positive in terms of quality in all measurement points, i.e., lower level of VPP. Additionally, a light green and light red color were introduced to compare the assessment of the ADI of individual measurement points. Light green was used for more favorable conditions and light red was used for worse conditions. The results indicated that working conditions 1, 3, 5, 6, 7, 10, 11, 13, 14 are more positive in terms of power quality than when working condition 0 occurs.

Table 8. Impact of flagging concept for area-related approach.

Working Condition of VPP	MV_Line	MV_HPP&EES	LV_HE	LV_L	Number of Data after Flagging
0	0.069	0.081	0.077	0.088	9373
1	0.067	0.074	0.068	0.084	951
2	0.075	0.077	0.083	0.087	3247
3	0.067	0.080	0.079	0.087	8092
4	0.063	0.077	0.074	0.085	175
5	0.067	0.073	0.082	0.088	235
6	0.065	0.078	0.072	0.085	71
7	0.071	0.080	0.069	0.085	60
8	0.076	0.079	0.074	0.093	264
9	-	-	-	-	0
10	0.065	0.072	0.067	0.083	389
11	0.071	0.075	0.071	0.086	1501
12	-	-	-	-	0
13	0.065	0.073	0.071	0.086	127
14	0.068	0.072	0.065	0.081	127
all	0.069	0.079	0.077	0.087	24,612

Green background—condition is more positive in terms of quality for all measurement points. Light green background—condition is more positive in terms of quality for single measurement point. Light red background—condition is more positive in terms of quality for single measurement point.

However, analysis of the number of data that represent each working condition indicated that some of them occur for a short period of time. Therefore, the next element of the research was to make a connection between them to obtain more numerous working conditions. Thus, the first connection was made for both conditions of HPP working (HPP is working partially and HPP is working at maximal power). Both were connected as a working condition, "HPP working". Moreover, working conditions that do not occur (9 and 12) are omitted. Therefore, the newly proposed working conditions are as follows:

- "20"—HPP is not working and ESS is not working;
- "21"—HPP is working and ESS is not working;
- "22"—HPP is not working and ESS is discharging at low power;
- "23"—HPP is working and ESS is discharging at low power;
- "24"—HPP is not working and ESS is discharging at high power;
- "25"—HPP is working and ESS is discharging at high power;
- "26"—HPP is working and ESS is charging at low power;
- "27"—HPP is working and ESS is charging at high power.

Then, the ADI level for these working conditions is presented in Table 9. Moreover, green/light green/light red colors are used. The results indicated that working conditions 24 and 27 are more positive in terms of power quality than when working condition 0 occurs.

Table 9. Impact of flagging concept for area-related approach.

Working Condition of VPP	MV_Line	MV_HPP&EES	LV_HE	LV_L	Number of Data after Flagging
20	0.069	0.081	0.077	0.088	9373
21	0.073	0.077	0.080	0.086	4198
22	0.067	0.080	0.079	0.087	8092
23	0.066	0.074	0.079	0.087	410
24	0.065	0.078	0.072	0.085	71
25	0.075	0.079	0.073	0.091	324
26	0.070	0.074	0.070	0.085	1890
27	0.066	0.073	0.068	0.083	254

Green background—condition is more positive in terms of quality for all measurement points. Light green background—condition is more positive in terms of quality for single measurement point. Light red background—condition is more positive in terms of quality for single measurement point.

Then, the next connections were made to obtain more numerous working conditions. This time, connection was made for the ESS at low power and a high-power charging/discharging, which is a new working condition that refers only to EES charging/discharging. Thus, the newly proposed working conditions are as follows:

- "30"—HPP is not working and ESS is not working;
- "31"—HPP is working and ESS is not working;
- "32"—HPP is not working and ESS is discharging;
- "33"—HPP is working and ESS is discharging;
- "34"—HPP is not working and ESS is discharging.

Then, the ADI level for these working conditions is presented in Table 10. Moreover, green/light green/light red colors are used. Finally, as a step in the area-related analysis of the investigated part of VPP, one value for all measurement points together was calculated. The value of the global index ADI for the common approach was calculated as a mean value of each measurement point. The results for single points indicated that working condition 30 is more positive in terms of power quality than when working condition 0 occurs. The results of this area-related approach indicate that, generally, there is no negative impact of the different working conditions of HPP and EES in long-term assessment (equal or lower value of ADI).

Table 10. Impact of flagging concept for area-related approach.

Working Condition of VPP	MV_Line	MV_HPP&EES	LV_HE	LV_L	Number of Data after Flagging	ADI for Area-Related Approach
30	0.069	0.081	0.077	0.088	9373	0.079
31	0.073	0.077	0.080	0.086	4198	0.079
32	0.067	0.080	0.079	0.087	8163	0.078
33	0.070	0.076	0.076	0.089	734	0.078
34	0.070	0.074	0.070	0.085	2144	0.075

Green background—condition is more positive in terms of quality for all measurement points. Light Green background—condition is more positive in terms of quality for single measurement point. Light red background—condition is more positive in terms of quality for single measurement point.

Finally, the investigated working conditions were reduced only to two cases:

- "40" when VPP is not working (HPP and EES are not working);

- "41" when VPP is working (HPP or EES is working).

The results are presented in Table 11. Therefore, the final statement is that VPP in long-term assessment has a positive impact on power quality assessment.

Table 11. Impact of flagging concept for area-related approach.

VPP Working Condition		ADI for Area-Related Approach
40	VPP is not working	0.079
41	VPP is working	0.078

Green background—condition is more positive in terms of quality for all measurement points.

4. Discussion

This article presents a case study analyzing a real VPP that operates in Poland. The investigated VPP consists of a fragment of both low-voltage (LV) and medium-voltage (MV) distribution network. Under investigation are the PQ measurements from five (four after reduction) different PQ recorders. The investigation is concerned with both MV and LV points. The duration of the measurements was 26 weeks (from 1 May 2020 to 28 October 2020).

The first element was an application of the global index ADI [86,87]. This index was successfully applied for the assessment of the multipoint measurement of the mining industry. Therefore, the authors also decided to apply this concept to the VPP. However, during the investigation, the frequency as a part of the global index was omitted because the VPP, even in maximum operational limits, has a negligible impact on frequency. The standard used to apply limits to the global value was EN 50160 [121]. The results indicated that the highest level of power quality (the lowest ADI) was in the associated MV line (MV_Line) and the lowest level of power quality (the highest ADI) in the LV measurement point that is associated with the MV line (LV_L).

During analysis of the changeability of the ADI, specific time periods of LV_HP were denoted. However, an analysis of only the global value enables us to conclude that the reason for such a situation is impossible. Thus, using one global index as a first stage to denote specific working conditions seems interesting. However, after indicating them, a deeper multiparameter assessment is still needed.

As the results concern long-term data, different working conditions occurred. In the first section of the article, the diverse technique was realized in the point of HPP and EES working. Therefore, fifteen different working conditions were indicated. Then, the assessment of PQ for each measurement point using ADI was realized. For the majority of cases, the positive impact of PQ was observed when VPP operated (working conditions 1, 3, 5, 6, 7, 10, 11, 13, 14 in comparison to 0). However, the majority of these working conditions were represented by a short period of time. Therefore, additional agglomeration of working conditions in terms of HPP and EES was realized. The final stage of agglomeration was when only two states occurred, which were when VPP is working and VPP is not working. Additionally, to compare this, the area-related value was calculated. This value was obtained as a mean value of ADI from all measurement points. The conclusion in the long-term approach indicated that the operation of VPP has a generally positive impact on power quality.

The authors are aware that analyzing a single-point assessment for single PQ parameters appears to be more valuable. However, for long-term assessment, this work is time-consuming. Moreover, the main purpose of the VPP is to obtain economic profits, and technical issues are often omitted. Therefore, the proposition of using the PQ global index seems interesting to extend the assessment of VPP in a long-term approach.

5. Conclusions

This article proposes the application of a global index to power quality issues in a virtual power plant. The proposed solution enables simplification of the assessment from many classical power quality parameters to one global value for each measurement point. However, on the other hand, including extremum 200-millisecond values of voltage and harmonics parameters is an extension of the classical approach. Thus, this approach simplifies the assessment and increases the range of used parameters during analysis.

The analysis of the global value changeability for long-term data was indicated as useful to the indication of specific conditions in terms of PQ. However, using this global value enables us to define the reason for this situation. However, it leads to the definition of the period of occurrence. Then, for this period, the classic multiparameter assessment may be realized to analyze the reasons.

This article also indicates the general impact of VPP working conditions on the PQ issue. Both single-point and area-related approaches were realized. The positive and negative results of both approaches were indicated. However, the most important conclusion is that, generally, VPP impact on the long-term performance of PQ issues was positive.

The future research directions are:

- research into using the global index for the identification and then assessment of short/specific working conditions of the selected VPP unit;
- applying data mining techniques to obtain less obvious relations that concern VPP operation and PQ level.

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