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# Effect of Power Quality on Production Reliability and Stability of Water Treatment Plant at Vodovod-Osijek

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**Abstract:** Power quality issues are pervasive in most industries. The system operator and the network user are responsible for the power quality at the point of common coupling (PCC). Since a water treatment plant must operate continuously, a reliable and continuous power supply of satisfactory quality is necessary in accordance with HRN EN 50160:2012. Additionally, the electromagnetic feedback of load consumption on the power grid must be within the permitted values prescribed by the Distribution System Grid Code (Official Gazzete nos. 74/18, 52/20). The low-voltage power grid of the “Nebo Pustara” water treatment plant contains sensitive electric and electronic loads. As such, the loads require a power supply of satisfactory quality. Moreover, these loads have non-linear voltage/current characteristics and as such negatively affect power quality. In order to prevent the effects of poor power quality on the water treatment plan operation and to reduce the impermissible effect of non-linear loads on the power grid, the “Nebo Pustara” power sub-station was outfitted with a PQube3 power quality analyzer. This paper presents the results of the power quality analysis. Additionally, the paper details the actions taken in the user and distribution power grid to increase effect production reliability and stability of the water treatment plant and water supply, with the aim of reducing the negative effect on plant operation and equipment and also reducing the impermissible feedback of non-linear loads.

**Key words:** power quality, water for human consumption, production reliability and stability of water treatment plant and water supply, Nebo Pustara, PQube3

## 1. Introduction

Water supply is an essential service and integral to urban area and infrastructure. Water infrastructure cannot function properly and efficiently without other urban infrastructure, such as a good quality power supply [1]. The water supply system of the city of Osijek sources raw (underground) water from the “Vinogradi” well field. The raw water is transported to the “Nebo Pustara” water treatment plant, where it is conditioned prior to being distributed to end customers via the water supply network. Conditioning is necessary as the raw water does not meet the drinking water regulations. Excessive iron, manganese, arsenic and ammonia are removed from the raw water through the process shown in Fig. 1.

The water treatment plant is a large power consumer. Given that it must operate continuously, and considering the adverse socio-economic impact of prolonged plant outages, the plant requires a reliable supply of electricity [1].

The “Nebo Pustara” plant is powered by a medium-voltage distribution network from two different sources. The connection at the “Nebo Pustara” transformer substation, comprises two 10/0.4 kV transformers connected in parallel. The transformers’ secondary side is connected to the low-voltage switchgear facility that powers the entire water treatment plant, including the laboratory and wastewater administration building (which are located outside the water treatment plant circuit). The two diesel generators connected to the low-voltage switchgear facility serve as an uninterruptible power

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supply (UPS) system, as well as a reactive power central compensation system (Fig. 2).

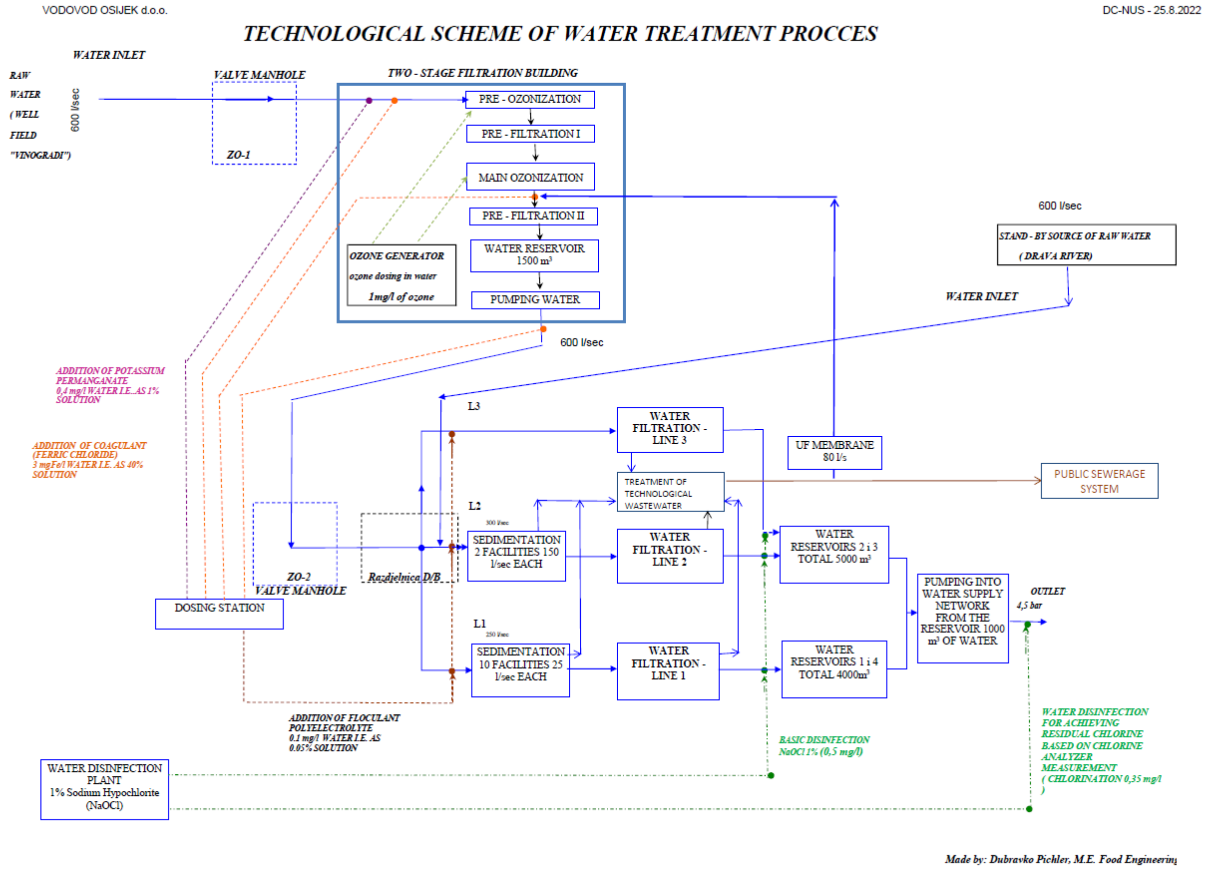

**Fig. 1** Technological scheme of water treatment process Vodovod-Osijek d.o.o.

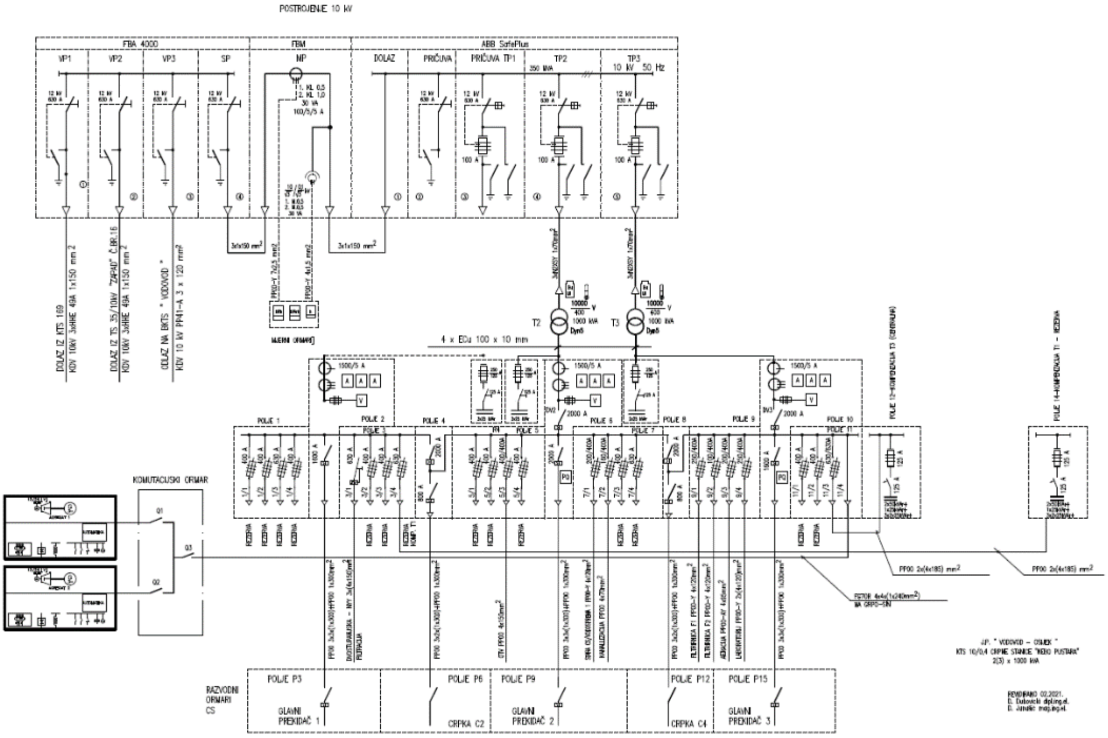

**Fig. 2** Single-line diagram of the “Nebo Pustara” transformer sub-station.

The electrical loads that are supplied from the transformer substation include: induction motors (for driving centrifugal pumps, air compressors and electric valves) driven with or without frequency converters, ozone generators, process-control computers, switching–control equipment, measuring-process equipment and desktop computers. Voltage distortion exceeding the limit under EN 50160 may disrupt the load operation in turn threatening the stability of the water production technological process. Certain critical loads, such as process-control computers and programmable logic controllers (PLC), are powered by on-line UPS devices, which protect them from power outages [2]. As the said loads are inductive and non-linear, they affect power quality [3]. The increased number of critical loads outages (such as centrifugal pumps and ozone generators) in the first half of the 2020 and 2021 reduced the production reliability and stability of the "Nebo Pustara" water treatment plant. This led to a detailed analysis of electrical installation of the water treatment plant as well as of the power quality parameters.

## 2. Power Quality

Power quality issues are pervasive in most industries. Owing to their varied symptoms and intensity, they are not always easily recognized. A complete analysis of power quality is usually applied only where the plant is experiencing extreme difficulties caused by poor power quality [4]. The optimal mitigation of such issues requires a blend of custom solutions. This entails the identifying of the problem, considering potential solutions, and selecting the best option [5]. Power quality is a characteristic of the electricity at a certain point in the power grid, observed against reference technical parameters determined on the basis of experience in analyzing the state of power networks [6].

Power quality is the combination of power supply continuity and supply voltage quality. Supply voltage quality in power system substations is determined by the overall interaction between all system elements, such as generation units, transmission and distribution lines, transformers and consumers. It is reduced by permanent disturbances (frequency changes, voltage changes, harmonic distortion, interharmonics distortion, flicker, voltage unbalance), and discrete disturbances in the power network (voltage dips, switching overvoltage, transient overvoltage and signaling voltages). The limit for these parameters is defined in EN 50160. In Croatia, the feedback effect of electrical installations on the power network must comply with Distribution System Grid Code (OG nos. 74/18, 52/20).

This paper will analyze the effect of voltage changes, voltage dips and voltage harmonic distortion on production reliability and stability of a water treatment plant. Parameters remained within the permissible limits according to EN 50160 were excluded from the analysis.

### *2.1 Voltage Dips*

According to Baggini, voltage dip is an unexpected reduction of the voltage at a particular point of a power system to a value below a specified dip threshold (according to EN 50160, a value between 90% and 1% of the declared nominal voltage), followed by its recovery after a short period of time [5]. Voltage dips usually last between 10 ms and 1 min. The depth of a voltage dip is defined as the difference between the minimum RMS voltage during the dip and the declared voltage [7]. According to Kalea, 10 to 1000 voltage dips are allowed annually [3]. Voltage dips can be caused by internal (originating in the user installation) or external sources (originating in the power system network). The most common external source is a short circuit within the power supply system. Other external sources include power oscillations in certain power network nodes (caused by switching on and off power system elements and outages of power system elements). The most common internal source is the direct switching on of induction motors connected to the end of a long supply line, and switching on of large loads that can produce large currents (similar to short circuit currents) within the system [5]. Voltage dips cause electrical loads to operate with limited efficiency or even fail. Depending on the size of disturbance, overly frequent voltage dips may cause on equipment degradation. Protective equipment is used for certain loads, which switch off the load in the event of voltage dip of a certain amount. Voltage dips affect a wide range of equipment. They may cause data and parameter loss, damage to IT and other electronic equipment [8], and unwanted operation of switching equipment and relays [9]. Voltage dips may also affect electromagnetic torque and withdrawal of larger currents in induction motors, thus aggravating the disturbances [5]. In control circuits of frequency converter, voltage dips may affect the speed or torque control of the induction motors or cause commutation failure [10]. Critical loads (such as IT equipment and PLCs) are usually powered by an on-line UPS systems, and thus protected from this type of disturbance. In water treatment plants, the most adverse effect voltage dips are manifested as the outage of distributional centrifugal pumps driven by frequency-controlled induction motors. This event leads to a time change of fluid flow rate, which in turn causes pressure oscillations in the pipeline due to the movement of water in the pipeline. This may create a water hammer, which may damage the pipelines and the water supply network. Further, outages of various loads (such as ozone generators or microprocessor systems) that are not powered by an on-line UPS systems require time for cancelling errors, and may cause the loss of the set parameters, which extends the devices' recovery time.

### *2.2 Voltage Changes*

The supply voltage in public low-voltage network between phase and neutral conductors is 230 V (±10%) and phase to phase voltage is 400 V (±10%) according to EN 50160. Increases or decreases of the root mean square (RMS) voltage are the most common consequences of switching on and off a larger load in a certain part of the network. Standard EN 50160 requires that 10-minute mean values of RMS voltage of the supply voltage be within 10% of the nominal voltage value during 95% of the time in the course of one week. Thus, the voltage in a low-voltage network with a nominal voltage of 230 V, must remain between 207 V and 253 V 95% of time during one week. Voltage changes can be slow or fast. A smaller RMS voltage on power busbars may increase the depth of rapid voltage changes that are caused by various transients. In turn, they may ultimately cause voltage dips, as well as increase the current in the electric installation [11].

### *2.3 Voltage Harmonics Distortion*

A harmonic is a component with a frequency that is an integer multiple of the fundamental frequency [5]. Voltage harmonic distortions are generally the result of higher current harmonics caused by equipment with non-linear voltage/current characteristic such as power electronic devices, IT equipment, electronic equipment, magnetic core equipment like transformers, induction motors etc. According to EN 50160, 10-minute mean RMS voltage value are observed in 95% the time during a one-week period. Certain higher harmonics within that period have different individual limit values, e.g.: the 2nd harmonic has 2% value of the fundamental harmonic, 3rd harmonic 5%, 4th harmonic 1%, 5th harmonic 6%, 7th harmonic 5%, etc. The total harmonic distortion factor (THDv) of the supply voltage (calculated by taking into account all harmonics up to the 40th order) must not exceed 8% of the nominal voltage. Harmonic distortion should also remain below the limit to prevent excessive injection of harmonics into the power grid.

While not necessarily instantly noticeable, over time, the effects of harmonic distortion can produce major consequences. At its most extreme, harmonic distortion can lead to parallel and series resonance, which may damage and/or failure of a part of the plant equipment. Moreover, an excessive current can cause additional losses that lead to a reduction of the life cycle of plant equipment, false operation of protective and switching devices, negative effects on frequency converters, faulty operation of certain measuring instruments etc. [5].

Due to the type of loads and network configuration changes caused by connecting new facilities and various switching manipulations in accordance with technological process and energy needs, power quality parameters at the “Nebo Pustara” the water treatment plant must be monitored continuously to avoid potential breakdowns and other adverse effects on production reliability and stability of water treatment plant.

## 3. Influence of Voltage Changes and Voltage Dips on Industrial Equipment of the “Nebo Pustara” Water Treatment Plant

In the first half of 2020, the “Nebo Pustara” pumping station saw a significant number of frequency-controlled centrifugal pump outages (Fig. 3).

The outages were caused by pressure oscillations in the pumping station delivery pipe (Fig. 4). The red curve shows regular outlet pressure under normal operation.

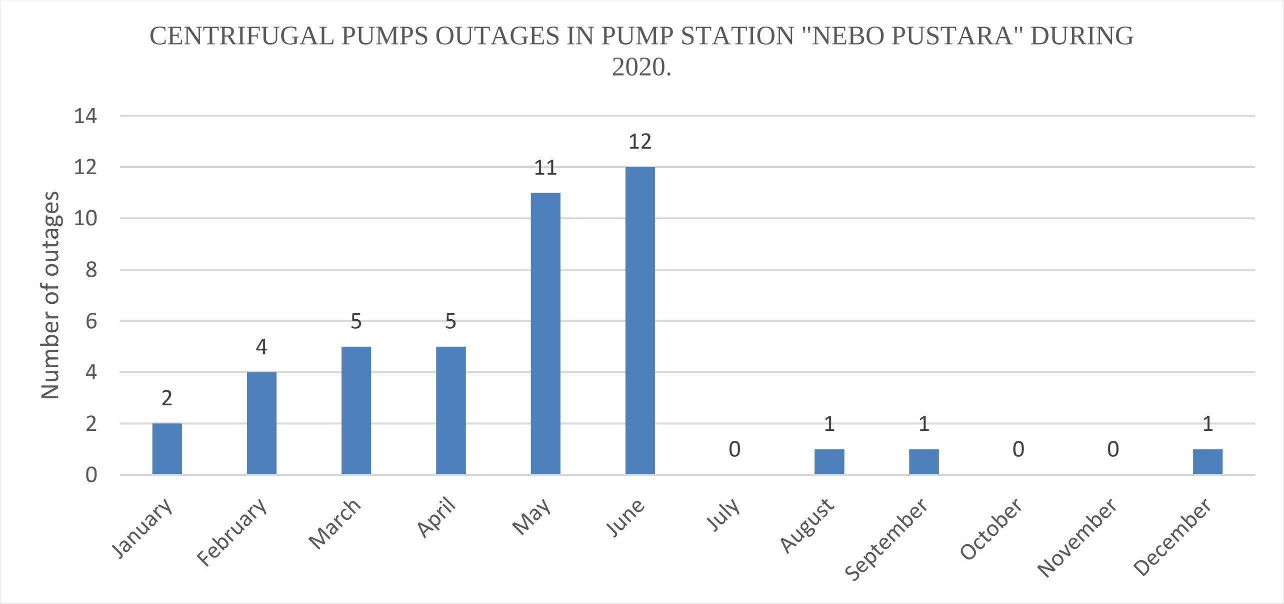

**Fig. 3 Pump outages at the “Nebo Pustara” pumping station during 2020.**

The “Nebo Pustara” pump outages were sporadic and did not correlate with any process manipulation in the water production facility. Pumps outages were assumed to have been caused by voltage dips originating in the power grid. Considering that the transformer substation power quality was not monitored at the time, the depth and duration of voltage dips were impossible to determine. The spike in pressure outages in May and June significantly reduced the reliability and stability of the water supply to the network, and required remedying. Considering the voltage quality tolerance of the centrifugal pumps’ frequency converters, as well as the absence of a human machine interface (HMI) error prompt from the frequency converter following the outage, the issue was remedied by monitoring the phase control relay. The function of the relay (which is located in the control circuit of the centrifugal pumps frequency converter) is to stop the frequency converter following a phase failure. Monitoring was carried out by connecting the trigger pulse counter to the phase control relay. Upon pump failure, the counter recorded the triggering of phase control relay, thus confirming the relay’s excessive sensitivity to voltage dips. Ultimately, the centrifugal pump outages were significantly reduced (Fig. 5) by replacing the phase control relay with a one with adjustable amplitude and sensitivity-trigger time, as suggested by Baggini [5]. Relay replacement was made in July.

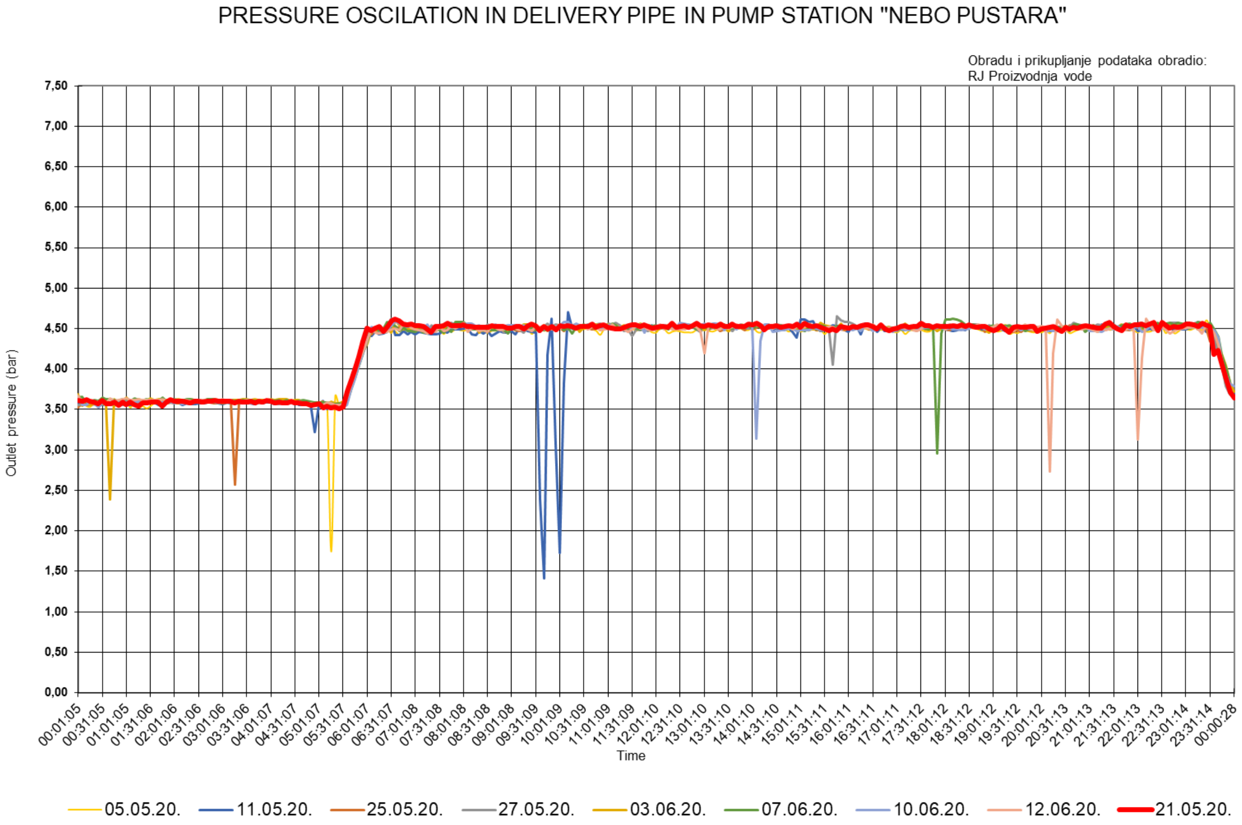

**Fig. 4** **Pressure failures at the “Nebo Pustara” pumping station.**

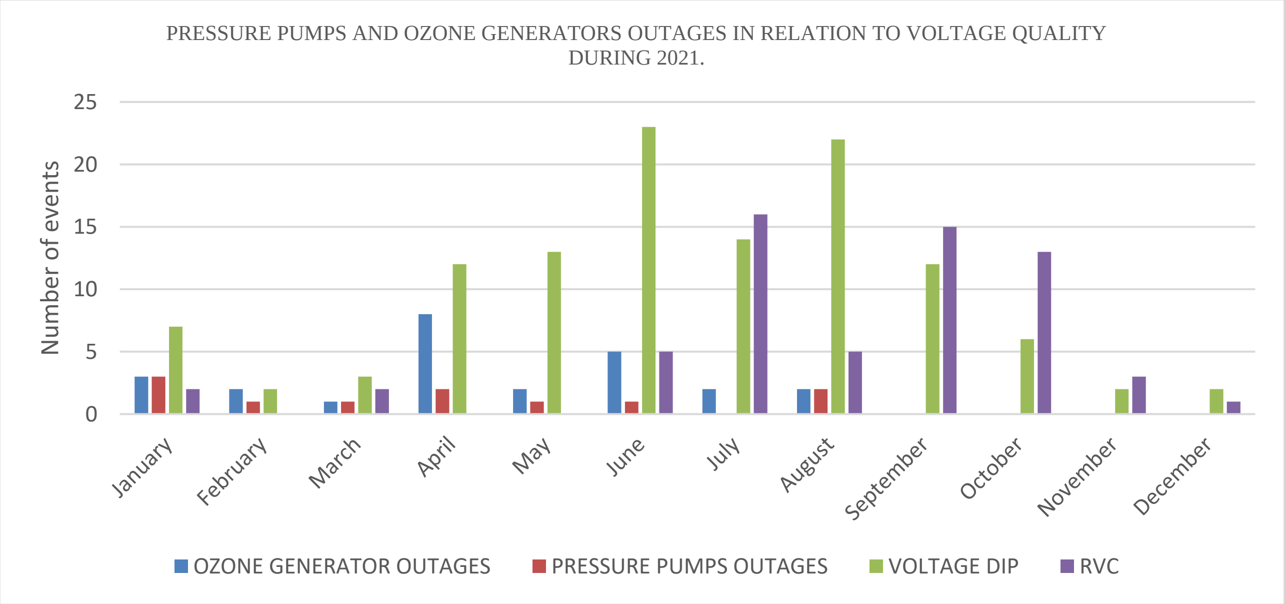

**Fig. 5** **Pump failures at the “Nebo Pustara” pumping station, and ozone generator failures at two-stage filtration facility in 2021 in relation to voltage quality.**

The subsequent addition of new facilities (one such being the two-stage filtration building) and new critical loads (such as the ozone generators) increased the need for constant power quality monitoring. Noting the insight gained from the above-described situation, to continuously monitor power quality parameters, the PQube 3 power quality analyzer was installed on the low-voltage busbars in the "Nebo Pustara" transformer substation. The distribution of outages of the centrifugal pumps (in the pump station) and the ozone generators (in the two-stage filtration facility) caused by voltage dips in 2021 is shown in Fig. 5, along with voltage dips and rapid voltage changes (RVC) events. A rapid voltage change (RVC) is a type of voltage fluctuation defined as a quick transition in r.m.s. voltage occurring between two steady-state conditions, and during which the r.m.s. voltage does not exceed the dip/swell thresholds [13].

As Fig. 5 shows, the first half of 2021 saw a noticeable number of centrifugal pump and ozone generator outages. The larger number of ozone generator outages was ascribed to the remoteness of the "Nebo Pustara" transformer substation from the ozone generator power supply point. Identical adjustable phase control relays were used in ozone generators control circuits and centrifugal pumps control circuits. The analysis performed using the PQube 3 analyzer showed that the voltage dip cause was external. Specifically, the voltage dips were surmised to be originating in the power grid given the correlation between the current and the voltage during the event, and considering that they were sporadic and did not correlate to water production plant operations and management. The analysis of the voltage conditions in the water treatment plant power network, as performed with a power quality analyzer, revealed a voltage lower than the nominal, albeit within the limit under EN 50160. The average RMS line voltage in the observed period was 385.1 V, or 96% value of the nominal value according to the EN 50160. On June 23rd, in cooperation with the distribution system operator (HEP-ODS d.o.o.), voltage correction was performed in the network feeder transformer substation by switching the transformer tap to a higher position and increasing the transformer ratio. This yielded the nominal RMS voltage on the low–voltage busbars in the "Nebo Pustara" transformer substation. The switching of the transformer tap to a higher position and the subsequent voltage are shown in Fig. 6.

The decrease in voltage dip depth (which is evident from the higher RVC/voltage dip ratio) allowed outages of the above-mentioned loads to be reduced to a minimum, even in the summer months that usually see an increase in voltage dips. The increase voltage dips and RVC events in summer months coincides with higher loads on the power grid [12]. The classification of voltage events before and after voltage correction, i.e., before and after transformer tap switching is shown in Tables 1 and 2.

As the above tables show, the distribution of voltage dips remained similar before and after voltage correction, the occurrence of RVC events increased significantly, as shown in Fig. 5. Had voltage correction not been performed, the depth of voltage dips may have increased, and the events shown in Tab. 2 would likely be distributed differently (some events would be classified in lower rows) which in turn could have triggered further outages of the respective loads and caused other negative effects of voltage dips.

## 4. Effect of Total Harmonic Distortion on Industrial Equipment of the "Nebo Pustara" Water Treatment Plant

In November 2020, a transformer in the "Nebo Pustara" transformer substation was disconnected from the parallel operation, since only one transformer was sufficient in regard to the engaged power from the power grid. The PQube 3 analyzer detected a level of voltage total harmonic distortion ($THD_v$) exceeding the EN 50160. The $THD_v$ increasing trend in the week following the transformer disconnection is shown in percentage value per phase in Fig. 7.

The THDv patently exceeds the 8% limit (marked red) during the day the period heavy in non-linear load use (frequency converter of centrifugal pumps, IT and electronic equipment). THDv value in the week following the transformer disconnection is shown in Table 3. Distortions occurred in all three phases, as shown in Table 3. Maximum THDv was 11% (in the L3 phase).

The dominant harmonics with the most significant impact on THDv in the observed period are shown in Table 4.

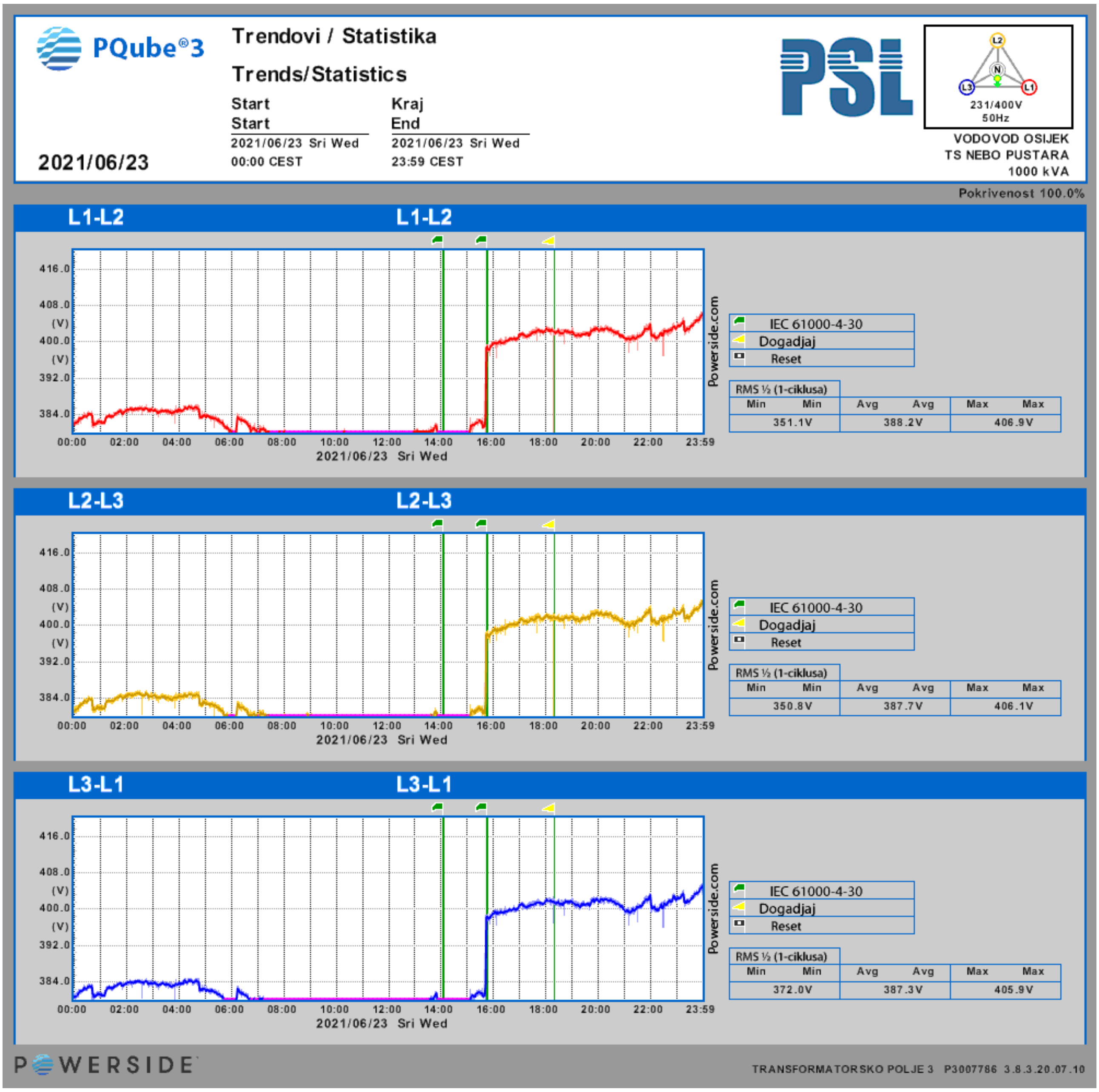

Fig. 6 Voltage diagram at the moment of lifting transformer tap changer.

**Table 1** **Voltage events classification before voltage correction.**

| Limit Voltage u [%] | Duration t [ms] | | | | | |
|---|---|---|---|---|---|---|
| | 10 ≤ t ≤ 200 | 200 < t ≤ 500 | 500 < t ≤ 1000 | 1000 < t ≤ 5000 | 5000 < t ≤ 60000 | t > 600000 |
| RVC | 4 | | | | | |
| 90 > u ≥ 80 | 39 | 3 | - | - | - | - |
| 80 > u ≥ 70 | 6 | - | 2 | - | 2 | - |
| 70 > u ≥ 40 | 6 | - | - | - | - | - |
| 40 > u ≥ 5 | 2 | - | - | - | - | - |
| 5 > u | - | - | - | - | - | - |

**Table 2** **Voltage events classification after voltage correction.**

| Limit Voltage u [%] | Duration t[ms] | | | | | |
|---|---|---|---|---|---|---|
| | 10 ≤ t ≤ 200 | 200 < t ≤ 500 | 500 < t ≤ 1000 | 1000 < t ≤ 5000 | 5000 < t ≤ 60000 | t > 60000 |
| RVC | 56 | 1 | | | | |
| 90 > u ≥ 80 | 39 | 1 | - | 1 | - | - |
| 80 > u ≥ 70 | 10 | - | - | - | - | - |
| 70 > u ≥ 40 | 5 | 1 | - | - | - | - |
| 40 > u ≥ 5 | - | - | - | - | - | - |
| 5 > u | - | - | - | - | - | - |

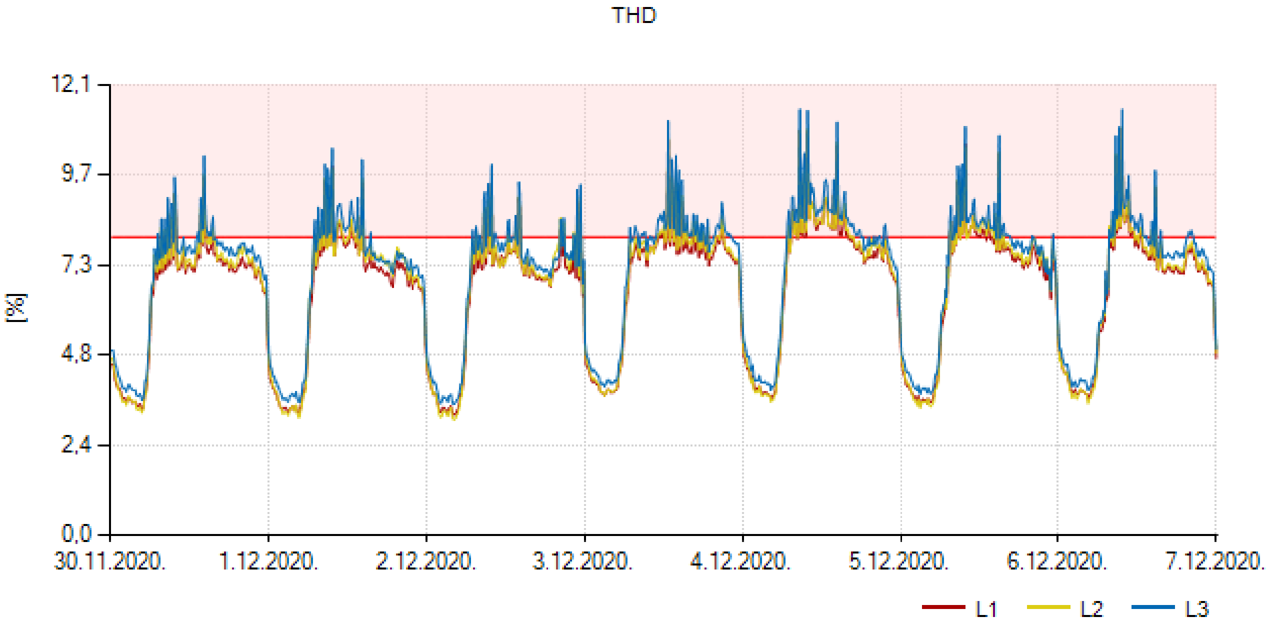

**Fig. 7** **THD values after switching off the transformer during a 1-week monitoring period.**

The dominant harmonics are usually originating from frequency converters and electronic equipment. Despite the installed line reactors at frequency converters line side for harmonic mitigation, THDv was of significant value. The power quality analysis using PQube 3 showed that the THDv increase and limit-exceeding higher harmonics were caused by the disconnection of the second transformer (by two). This led to a doubling of the total impedance of the transformation point in the user's power network. The

**Table 3** **THD value analysis after switching off the transformer during the 1-week monitoring period.**

| *Requirement* | **Measured L1 THD** | **Measured L2 THD** | **Measured L3 THD** |
|---|---|---|---|
| *95% of the time: THD ≤ 8%* | **3.55% ~ 8.74%** | **3.48% ~ 8.80%** | **3.83% ~ 9.19%** |
| *Requirement* | **THD 1 out of limits** | **THD 2 out of limits** | **THD 3 out of limits** |
| *95% of the time: THD ≤ 8%* | **17.20%** | **20.50%** | **31.80%** |
| | **Min** | **Avg** | **Max** |
| **THD L1** | 3.22% | 6.64% | 10.94% |
| **THD L2** | 3.11% | 6.74% | 10.96% |
| **THD L3** | 3.52% | 7.01% | 11.43% |

**Table 4** **Dominant harmonics after switching off the transformer during the 1-week monitoring period.**

| Harmonic | EN50160 | L1 - N | L2 - N | L3 - N |
|---|---|---|---|---|
| | | 95% value | 95% value | 95% value |
| H5 | 6.0% | 6.220% | 6.267% | 6.637% |
| H7 | 5.0% | 5.051% | 5.050% | 5.152% |
| H11 | 3.5% | 3.446% | 3.535% | 3.758% |
| H13 | 3.0% | 3.822% | 4.057% | 3.700% |

higher-current harmonics generated by the non-linear loads of the water production plant create higher harmonics voltage drops on the dual impedance of the transformation point. The transformation point impedance increase caused higher voltage harmonics to also increase. Following the analysis, the second transformer was switched on in parallel operation mode, which halved the transformation point impedance. In turn, harmonic distortion fell below the limits set out in EN 50160. The THDv in the week following the switching on of the second transformer is shown in Fig. 8.

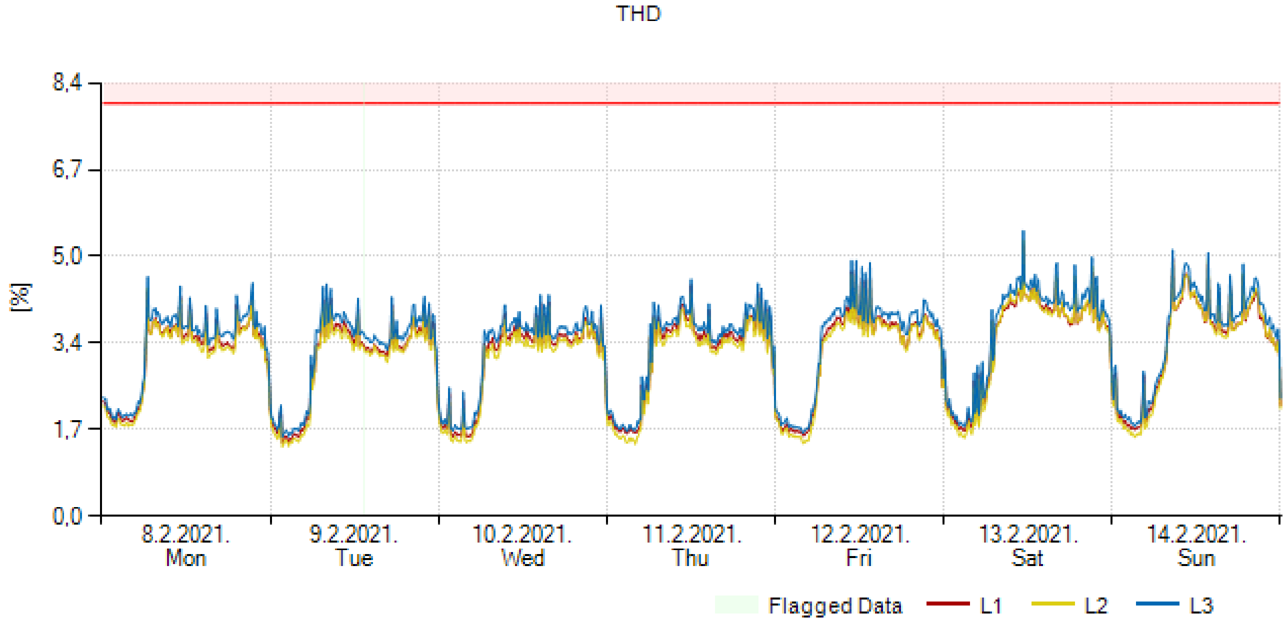

**Fig. 8** **THD after switching on the transformer during a 1-week monitoring period.**

Unlike voltage dips, the high THDv did not immediately affects the production reliability and stability of water treatment plant. Nevertheless, considering that it was measured at low-voltage busbars in the transformer substation, over time, the high THDv could have negatively affected all electric equipment fed from the respective transformer substation, i.e., to the user's electric installation and, in turn, to the complete plant. A correction was imperative. The high THDv did not produce a feedback impact on the power grid given that the current harmonics source did not increase. It was only the impedance of the user network that changed through the reconfiguration of the user's power network by means of disconnecting one transformer from parallel operation.

## 5. Conclusion

This paper discussed the cause and effect of voltage changes, voltage dips and voltage harmonic distortion on production reliability and stability of water treatment plant at Vodovod-Osijek d.o.o. Voltage dips produced immediate negative effects on plant operation. This was not the case with voltage harmonic distortion, which can prove very harmful if undetected for a longer period, even where only one harmonic is high. Affected most by voltage dips were the pump station and ozone generators. To track the power quality parameters in real-time and thus prevent the dips form affecting facility loads, the PQube 3 power quality analyzer was installed on low-voltage busbars in the "Nebo Pustara" transformer substation. The analyzer also tracked voltage harmonic istortion (which is only trackable through power quality monitoring).

Continuous power quality monitoring is essential, as shown by the present analysis of voltage changes, voltage dips and total harmonic distortion, including dominant higher harmonics and their influence on the production reliability and stability of the respective water production plant. Apart from monitoring, staff must also be properly trained in the area of power quality. Only with this two-pronged approach can power quality-related issues be identified timely and resolved optimally.

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