Investigation of Power Quality in a Hybrid Power System- The case of Paros Island Complex

Athanasios Safacas*‡, Dimitrios G. Giaourakis*, Savvas Tsotoulidis**, Konstantinos Kaousias***, Stefanos Kokkinelis***

*Electromechanical Energy Conversion Laboratory, Electrical and Computer Engineering Department, University of Patras, Greece

**Siemens AG, Process Industries and Drives, Large Drives, Research and Development, Werner-von-Siemens-Straße 1, 80333 Munich, Germany

***[3]Hellenic Electricity Distribution Network Operator S.A.(HEDNO), LeoforosSyggrou 98-100, Athens

(a.n.safacas@ece.upatras.gr, dgkiaourakis@ece.upatras.gr, stsotoulidis@ece.upatras.gr,K.Kaousias@deddie.gr, s.kokkinelis@deddie.gr)

‡Corresponding Author; Athanasios Safacas, Electromechanical Energy Conversion Laboratory, Electrical and Computer Engineering Department, University of Patras, Greece, Tel: +30 2610996894, Fax: +30 2610997367,a.n.safacas@ece.upatras.gr

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Abstract-This paper examines the power quality of the nine islands complex in Aegean Sea (Paros island complex), which are connected to each other by submarine cables. The power supply of this island complex is provided by a power station (DIESEL) of nominal power 79.43 MW and by renewable energy plants (6 wind farms totalling 13.960 kW) and 34 photovoltaic stations totalling 2982.745 kW, which are located in the islands of the complex. Due to the structure of the power generation and distribution system in this island complex, it has been considered necessary to study the power quality, which is affected mainly by the connection and disconnection of renewable energy sources as well as the physical characteristics of these sources. The influence of variations in the power parameters of the renewable sources and the harmonic content of electrical quantities were critical issues to be investigated at two selected locations for reasonable time intervals. The assessment of the power quality was done in accordance with the international standards and mainly according to the standard EN 50160. The DRANETZ measurement system recorded the attributable power / energy of the renewable sources and corresponding time plots were formed for the time periods of measurements. Also, interruptions and reconnections of the renewable sources with the grid have been recorded. It was found that all the standard principles have been met and taking into account the experience of the system operator, it had been concluded that the power quality of the island complex's system was satisfactory. The aim of this investigation was to extract useful information about the power quality and to show how somebody has to work in practice to evaluate the power quality.

Keywords: Hybrid power system; island complex Paros (Greece); Measurements; International Standards; Evaluation of power quality.

1. Introduction

Nowadays, the production of electricity from renewable natural sources is the most important factor in reducing greenhouse gas emissions, which has the effect of changing the climate of the planet. Moreover, some countries strive to reduce energy costs and energy dependence on external suppliers, as well as to reduce harmful emissions. For these perspectives, all countries around the world are planning or have already deployed strategies for enhancing the exploitation of renewable energy sources (RES - wind, solar, hydroelectric, geothermal, etc.) by implementing mature technologies with satisfactory success. Especially, EU has set three key objectives for 2020, known as the "20-20-20" targets: 20 percent reduction in the greenhouse gas emissions relative to 1990 levels, 20 percent of the energy consumed should be derived from renewable sources and finally the EU energy efficiency should be increased by 20 percent. In [1], extensive information on the prevailing global renewable energy situation is provided. Statistical investigations indicate an impressive increase in installed power and its share of energy production, with an increasing trend. In selected bibliographic sources [1] − [10], [47] some typical cases of application of renewable energy sources are presented to highlight the current trends for the integration of renewable energy sources in the energy production energy mix. Papers [11] − [22], [43]-[47] deal with research work conducted by Universities and research centres focusing on special operation problems of electric energy systems incorporating renewable energy sources. These works highlight the issues of power quality, high harmonic content, dynamic phenomena from the interconnection of RES to the grid along with the necessary control strategies. In [23] and [24], state of the art of the renewable energy sources technology and adopted strategies are thoroughly reviewed. Especially, work [24] appoints the Strategic Energy Plan (SET – plan) of the European Union for the next decades (2020, 2050) providing "a framework to technologies".

The position of the European Union, as expressed by its responsible bodies [25], is that the SET has set ambitious targets for research and innovation to reduce costs and improve the efficiency of energy systems by applying new technologies to the tackling the problems of climate change. At the same time the SET aims to moderize industrial and economic structures for the benefit of citizens. The European Commission Vice – President has reported that the gross domestic product (GDP) has increased by 50% since 1990, and emissions have fallen 22%, a fact which implies the success of decoupling the limiting of emissions from the economy-development. It is also noted that the future climate change can cause much more than has been caused in 2008. From the above analysis, it can be easily concluded that developments in technology and in the renewable energy economy are following a significant upward trend throughout the world.

2. The Electrification of the Islands

In countries with many islands, such as Greece, ensuring the availability of electricity on the islands is a particular problem. Mainly, the use of liquid fuels for the operation of conventional units (generators powered by internal combustion engines [26] (Diesel- Heavy Fuel Oil /Light Fuel Oil) is the solution for providing electricity. The financial cost in this case is high and pollutant emissions are inevitable. The solution to connect the islands to the country's electricity grid via submarine cables is very expensive. Instead, the installation of renewable energy plants, mainly wind and photovoltaic farms, and combining renewable energy with conventional units is a feasible solution that can also contribute to EU 2020 targets. It is clear that wind and solar energy are facing the known serious problem of discontinuity and of inevitable fluctuations, which are inherent in the nature of these energy sources. Addressing this problem by storing energy at times when natural conditions favor the generation of electricity without the possibility of simultaneous consumption, is a challenge for researchers and designers of technical storage systems, but it is considered practically unenforceable nowadays, because of the high cost. So, the creation of an energy system that comprises conventional units and RES (wind parks, photovoltaic stations) is presented as the realistic solution.

In this paper authors examine the case of an island complex in the Aegean, which includes the islands of Naxos, Paros, Antiparos, Koufonissi, Schinousa, Ikaria, Ios, Folegandros, which are connected electrically with submarine cables. This study was based on the collaboration of Hellenic Electricity Distribution Network Operator S. A. (HEDNO) with the Laboratory of Electromechanical Energy Conversion of the University of Patras. The aim was to investigate the power and voltage quality in the autonomous electrical system of Paros with high RES penetration according to the Standards and the operation of a thermal power station on Paros Island, the high wind power production and the operation of photovoltaic stations.

Firstly, an accurate study of the structure of this electrical system (production units, electrical interconnections etc) has been conducted and then the results obtained from specific measurements of the electrical quantities for a typical period of time have been analyzed. The data provided by HEDNO [26] has been evaluated by the qualitative characteristics of the system variables (resulting from the measurements) using international standards. Finally, the evaluation results along with extensive assessment have provided an overview of the actual status of the investigated autonomous grid of Paros islands complex in terms of power quality. Furthermore, it has been evaluated if this grid is harmonized with standards requirements and critical information for system operation has been indicated in order to obtain optimal electrical energy.

3. Description of the Autonomous Electrical System of the Island Complex of Paros

The autonomous electrical system of the island complex of Paros consists of nine interconnected islands (Paros - Naxos - Ios - Sikinos - Folegandros - Antiparos - Koufonissi - Schinoussa - Iraklia). The special features of this system are the underwater connections between the islands, the operation of a single thermal power station on Paros Island (79.43 MW), the notable wind power generation and the operation of many photovoltaic stations.

Figure 1 shows the islands' complex and the submarine electricity network [26] and the characteristics of the transport lines (P-22 − P-35) with the corresponding colors.

Figure 2 shows the location of the transmission lines on the islands of Paros – Antiparos (single line network plan).

Regarding the RES installed in the complex of Paros Tables I and II show the technical features of the installed wind farms (quantity, installed capacity and connection point to the grid) and the total installed capacity of photovoltaic stations per island.

It is noted that the output of wind farms is regulated through set-points. Two wind farms are controlled from a central SCADA system while each of the remaining three wind farms is controlled from a dedicated SCADA system. All SCADA systems are located in the Thermal Station control room.

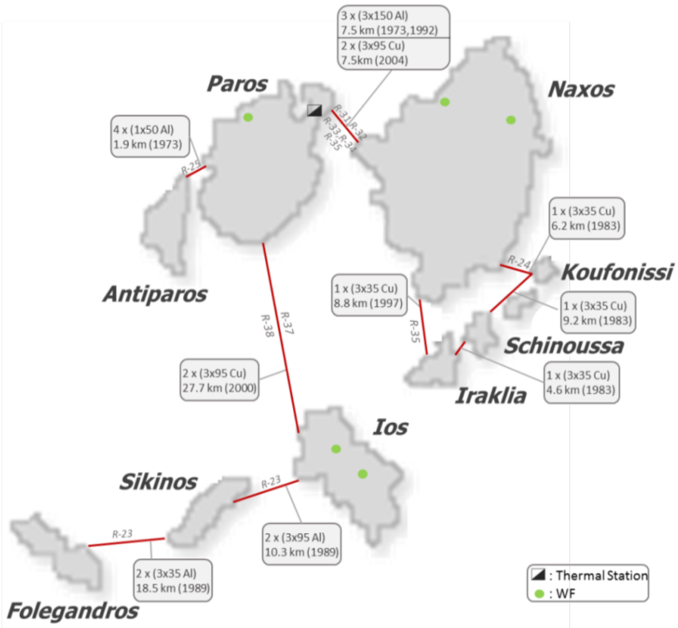


Fig. 1. Paros Electric Power System with the locations of the production plants [26].

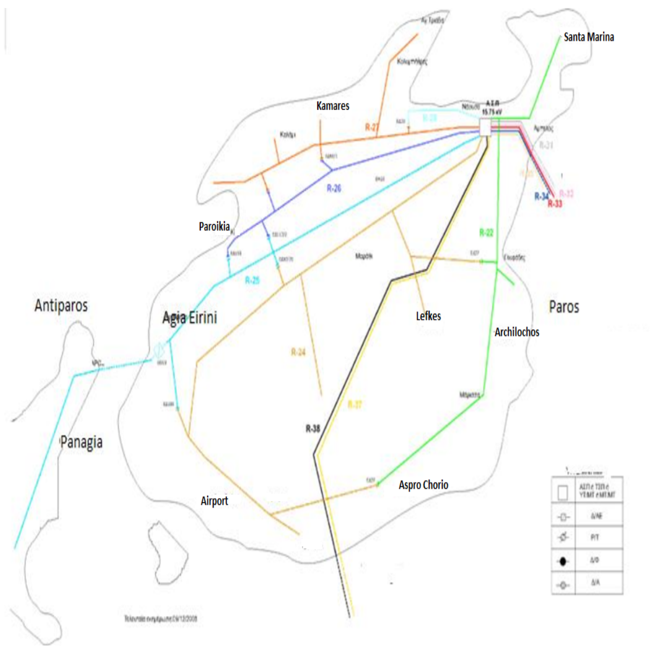


Fig. 2. Single line voltage network diagram of the islands of Paros - Antiparos [26].

Table 1. Installed wind farms in the Paros complex.

Quantity	Island	Installed Capacity[kW]	Line
1	Paros	3000	P-27
1	Naxos	7560	P-23, P-24
1	Naxos	1200	P–23
1	Ios	600	P-22
1	Ios	600	P-22
Total		**13.960**	

Table 2. Installed photovoltaic stations in Paros complex.

Quantity	Island	Total Installed Capacity[kW]	Line
13	Paros	1.294,36	P-22
17	Naxos	1.449,59	P-23, P-24, P-25
1	Antiparos	99,64	P-25
1	Schinoussa	19,8	P-35
2	Ios	119,355	P-22
Total		**2.982,745**	

In general, high instantaneous penetration rates of wind power affect power quality, causing voltage and frequency disturbances as well as harmonics to the grid.

The concentrated installation of wind farms on specific medium voltage lines and at a great distance from the thermal power plant, as well as the operation of wind farms located in Naxos and Ios, combined with submarine cables and the relatively high penetration of renewable energy may cause particular disturbances in the network. These disturbances may be due to the effects of high penetration of energy from renewable sources and could affect both the local network and the whole system.

The Paros Complex has distribution lines at 15 kV voltage level, and there is no transmission network there.

4. Effect of Renewable Energy on the Electrical System of the Paros Complex

The impact of wind farms and photovoltaic stations on not only the total electric network of the nine islands but also the local sections of the network is investigated by acquiring and post-processing power quality measurements at the front-end of wind farms and photovoltaic stations(i.e. Point of Common Coupling – Power Public Corporation). At specific network locations, higher harmonics, flicker, voltage and frequency changes have been recorded continuously over long periods of time.

Measurements regarding the total autonomous system, which refer to both power dissipation and contribution from renewable energy sources, are presented below. Figure 3 shows the time plot of the total demand for power and the contribution of RES per hour for the period from 8/11/2010 to 11/02/2012. The increased demand during the summer months (June-July-August) is obvious.

Calculations have been made to determine the percentage contribution of RES for the duration of the aforementioned period and the results are shown in Figure 4, where the permissible penetration percentage of 30% is exceeded.

By correlating Fig. 3 and 4, we can easily see the time frames with maximum and minimum demand, as well as the maximum and minimum penetration rate from RES. Figure 4, the permissible penetration percentage of 30% (the well-known limit) is exceeded. Figure 4 shows the percentage change in energy penetration from RES during change 23/12/2011 to approximately 07/12/2012 per hour. The maximum and minimum percentile intervals from RES have been found to be critical and marginal cases, for which the investigation of the power and voltage quality of the network under study is worth examining. Numerous measurements have been conducted and the corresponding time series has been recorded with maximum, minimum and medium percentage penetration of RES energy. Figure 5 shows the total demand and RES contribution for a typical day (21/04/2011). Figure 6 shows the total demand and RES contribution for a day when RES penetration exceeded 30% (28/10/2011). These measurements confirmed the well-known phenomenon of stochastic creation of RES, which depends on the location and climatic conditions in wind farms and photovoltaic stations.

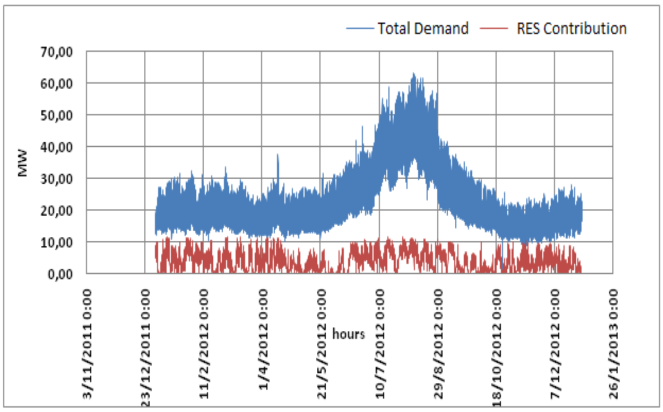


Fig. 3. Hourly measurements of total demand (blue curve) and RES contribution (red curve) for the period 08/11/2010 to 11/02/2012.

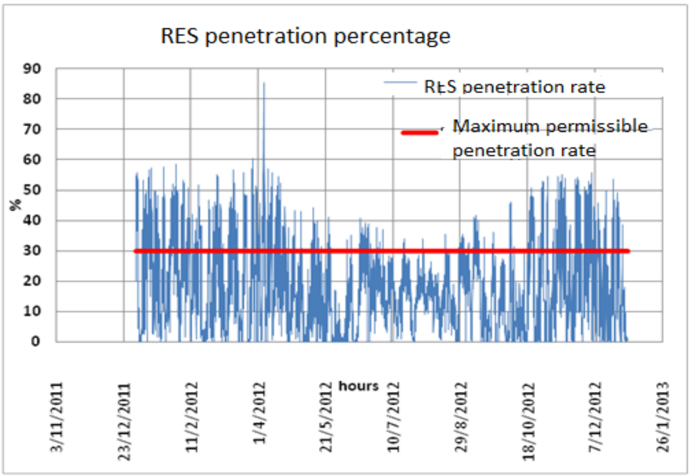


Fig. 4. Percentage penetration of RES per hour between 23/12/2011 and 07/12/2012.

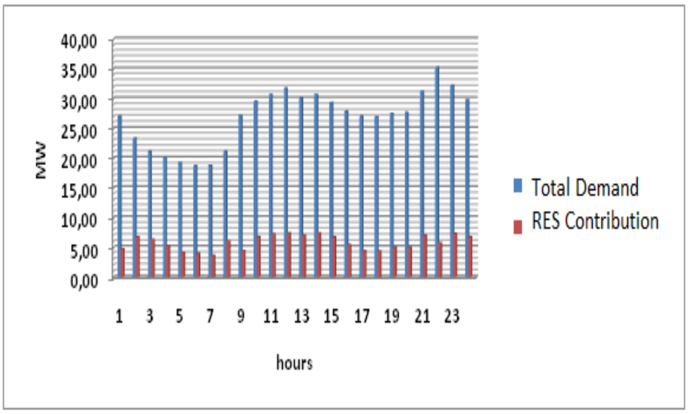


Fig. 5. Total demand and RES contribution for a typical day (21/04/2011).

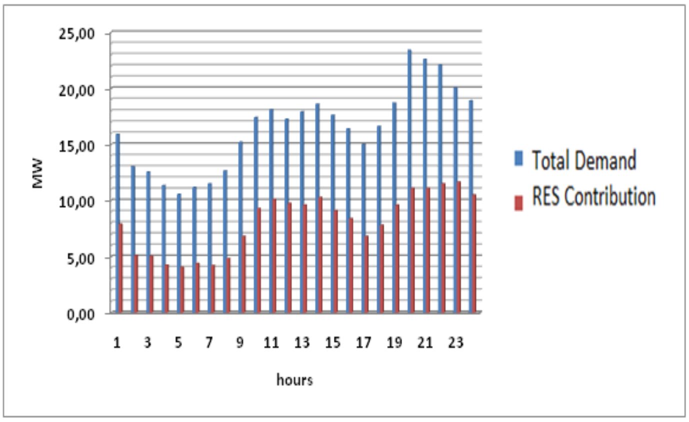


Fig. 6. Total demand and energy contribution from RES for a day when penetration exceeded 30% (28/10/2011).

5. Power Quality – Standards for Electrical Variables, for Electromagnetic Compatibility and Flicker

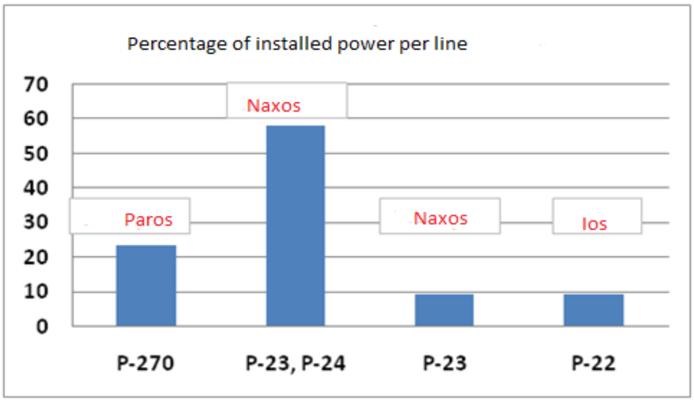
The ideal condition (in terms of power quality) in an electrical system would be if the waveform of both voltage and current would be sinusoidal. The reality, however, is completely different, because both the production systems and the consumer side have technical devices that distort the sinusoidal waveform of voltage and current. As it is known, photovoltaic sources produce a Direct Current (D.C.) voltage which, by means of electronic power converters, is converted into alternating but substantially different from the sinusoidal waveform. Furthermore, different types of consumers cause non-sinusoidal currents, such as the various controlled electric drive systems. From that perspective, a necessity has arisen for constituting specific legislation and standards ensuring high quality operation of electricity generation, transmission and operation systems and to pay particular attention to the quality of electrical power. Particularly in continental country where wind farms and photovoltaic stations are installed and operate in collaboration with thermal or hydropower plants, the necessity to examine power quality is absolutely imposed. Thus, the following international standards [16, 27, 28, 29,] constitute the basis for the establishment and operation of power generation systems containing RES, such as the island complex of Paros in Greece: IEC 61000, IEC 61000-1-1, IEC 61000-1-2, IEC 61000-2-1, IEC 61000 -2-2, IEC 61000-3-2, IEC 61000-3-3, IEC 61000-3-4, IEC 61000-3-5, IEC 61000-3-7, IEC 61000-4-7, IEC 61000-4-15, IEC 61000-4-30, IEC 61508, IEC 61400-21, IEC 61557-252-11, DIRECTIVE 2006/95/EC "Electrical equipment design for use within certain Voltage Limits", IEC 1547.2, IEC 1453, IEC 868,IEC 868-0,IEC 725.Byexploiting the aforementioned standards, the power quality of an electrical network can be evaluated.

6. Determination of the Appropriate Locations on Paros Island Interconnection to Monitor the Power Quality – Measurements

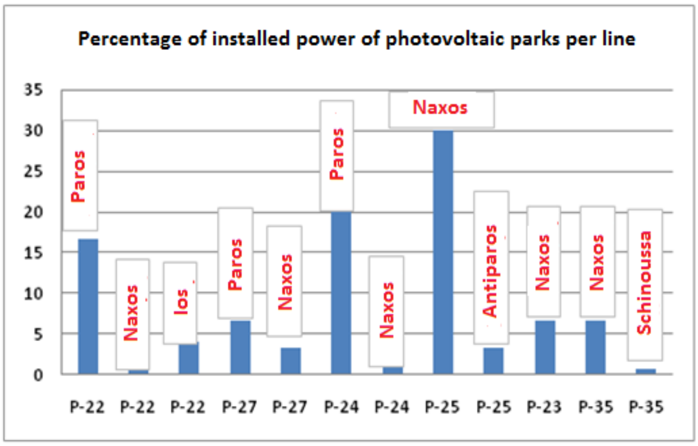
In the context of the assessment of the power quality of the network under consideration, the appropriate locations for the installation of surveillance and measurement equipment of certain operational parameters, which offer power quality information, should be identified. The number of points where measurements had to be made for an ideal recording would be very big. However, this would require enormous amount of measurement equipment with high cost, so a solution had to be sought to reduce the number of surveillance points, without risking lack of critical information taken in account the experience of the system operator. Thus, two points were considered as the most technically correct for reliable measurements. For this purpose, a statistical study was carried out to determine the geographical distribution of RES units with the highest penetration. The selection of points for conducting measurements has been based on the following criteria:

- Geographical distribution of installed wind farms and photovoltaic production.
- Number of submarines cables.
- Lines with the highest frequency of occurrences based on historical data.
- Highly charged power lines.

It should be noted that the centralization of power plants from RES on certain medium voltage lines and at a great distance from the thermal power station coupled with high RES penetration can cause particular disturbances in both the local and the whole electric grid. In this direction, it was necessary to determine the percentage of installed wind farms per line as to the total installed wind power and also for the photovoltaic stations. Figures 7 (a) and 7 (b) show the percentage of installed wind farms per line, based on the total installed wind power, and respectively for photovoltaic stations.



(a)



(b)

Fig. 7.a) Percentage of installed wind farms per line in relation to all installed wind power plants, b) similarly for photovoltaic stations.

We can see that for photovoltaic stations the maximum rate is 33.4% regarding the line P-25. Using available data for the years 2011 and 2012 possible time periods where RES penetration exceeds 30% of total demand can be identified. Based on these data, two points (1 and 2) were proposed for the installation of power quality analyzers in order to carry out measurements for the autonomous electric system of the island complex of Paros (installation took place on 7/10/2013). Figure 8 shows points 1 and 2.

7. Process and Means of Monitoring Electrical Power and Development of Appropriate Software for the Analysis of the Findings from the Measurements

For the study of power quality, in general, the following should be considered (according to [37]):

1. Surveillance period. It should be noted that planning a power quality survey is easy when a problem has already

occurred and so there is relevant experience about the event. However, it is difficult to determine the length of time for surveillance before the problem occurs, probably using some smart approach through forecasting methodologies.

2. Geographical location of the surveillance. This is necessary to obtain valid results.

3. Type of instruments. The choice of appropriate equipment should be made taking into account the monitoring time, the type of disturbances to be investigated and the possibilities of the transfer of information.

4. Type and number of electrical operating parameters to be measured. It is logical to measure all indicators related to the quality of power for a general evaluation. However, in specific cases, there must be measured specific parameters as defined by international standards.

5. A method of organizing and processing of the recorded data. After the desired measurements, the analysis of the data aiming on the evaluation of the power quality in the investigated electricity network shall be followed.

According to the international standard EN 50160, the basic characteristic variables to be measured and within which the power quality assessment can be conducted are: a) changes in the nominal supply frequency, b) variations in the amplitude of the nominal supply voltage, c) transient phenomena, d) flicker, e) asymmetry of phase voltage, f) harmonics, g) intermediate harmonics, h) sinking and voltage interruption.

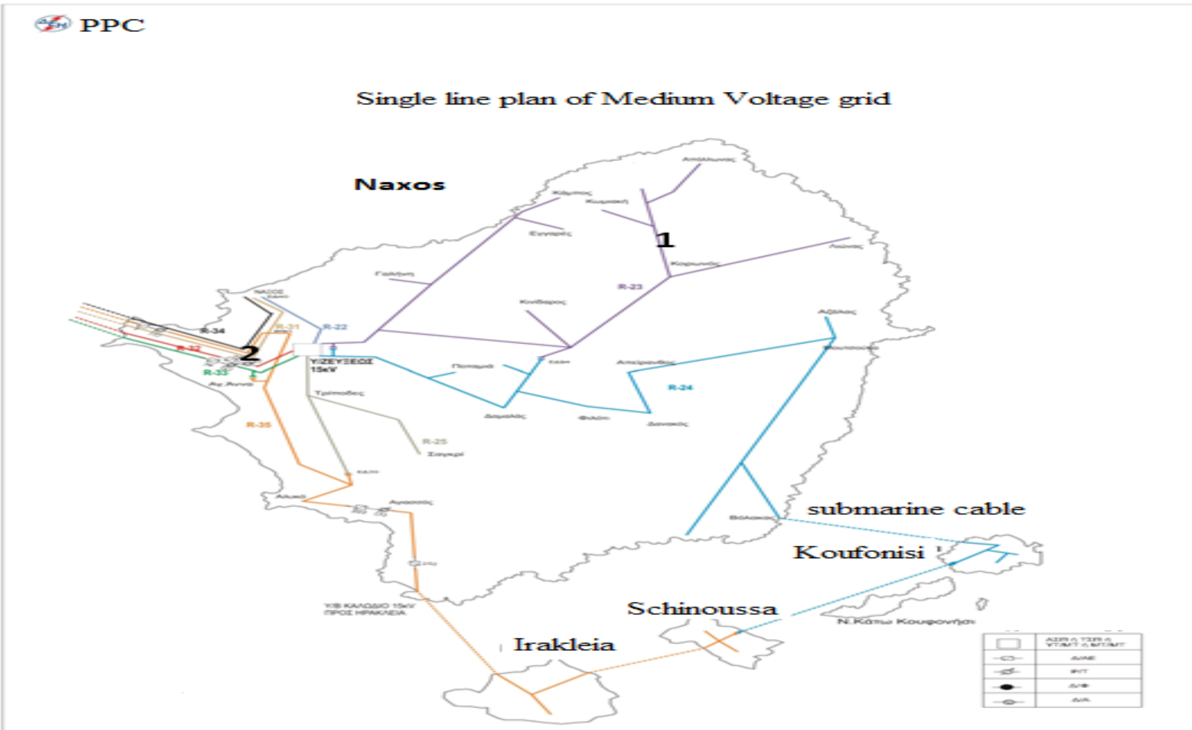


Fig. 8. Single line network design of Naxos showing the points (1 and 2) of the energy analyzer installation.

Point 1: Line P-24, latitude 37.111.616, longitude 25.549.188.

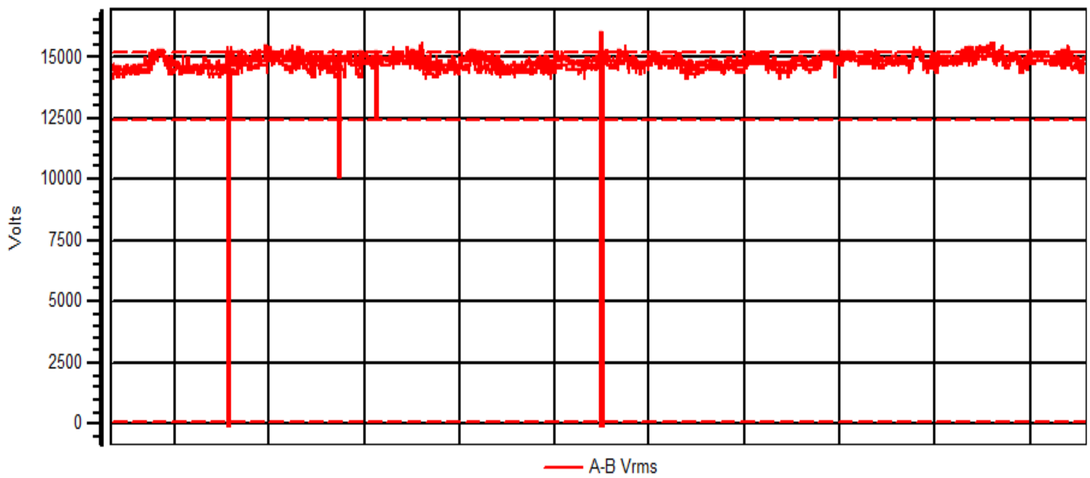
Point 2: The analyzer was connected in the secondary transformer winding of line P-33, which is used for internal service, on the low –b voltage side. For this point there was the capability for tele-surveillance and remote control of the analyzer, while at the other point the data were extracted locally and then send to the research team every week.

The electrical variables that need to be measured can be directly accessible in the case of medium and low voltage networks using voltage and current downgrading transformers. International organizations, IEC and CENELEC, have established standards for the design of measurement systems and the design of power quality monitoring instruments, such as DRANETZ PX5, which has been used in the present study. DRANETZ PX5 is an eight-channel instrument with high sampling and recording capability for very fast transient phenomena. It has a liquid crystal display (LCD ¼ VGA) and can record or display data from four voltage channels and four current channels at the same time. It is designed based on IEEE standard 1159 and ICE 61000-4-30 standards and provides high precision. It is used to identify if the measured variables are within the limits defined by European Standard EN 5016, which requires 95% of the measured values to be within predefined limits. In addition, this analyzer provides both the ability to record data and their ex-post statistical analysis in conjunction with software applications such as “DRAN VIEW”. The basic points that DRANETZ measuring system differs from SCADA system are the following [38-42]:

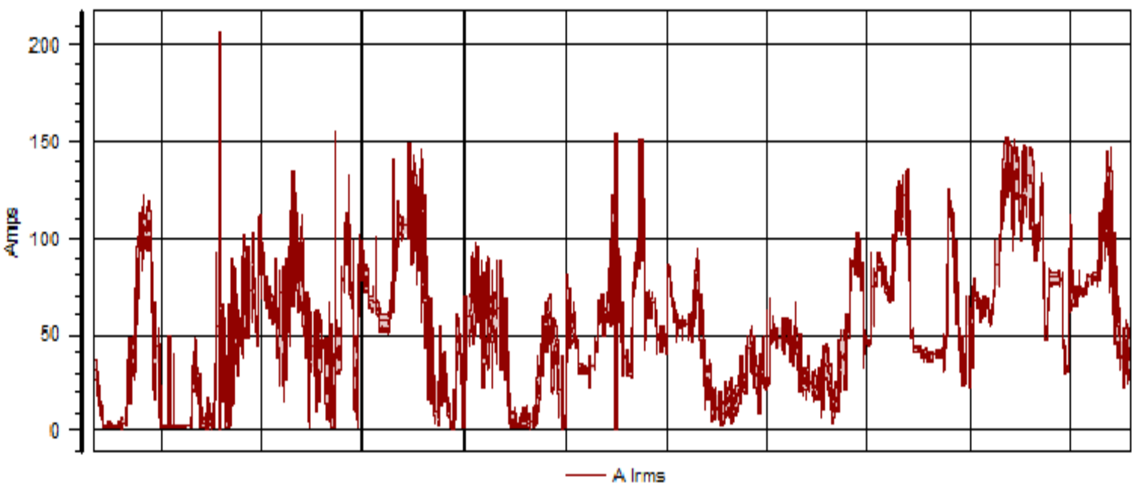
- DRANETZ is just a measuring and data recording system and is used for power analyzing. Its inputs are voltage and current measurements. On the other hand, SCADA system is a more complex system that among others it consists of a lot of measuring and data recording systems like DRANETZ.
- SCADA system offers to its users the ability to act (to interfere), when an event happens, in order to restrict its consequences on the system operation. This interference can also take place through automation systems that have been incorporated into SCADA system. On the other hand, DRAMETZ system can only record the corresponding event.
- If someone wants to depict and/or to process the data recorded by DRANETZ, DRANVIEW application must be used, while SCADA system offers the ability to process these data through its own software (there is no need for another application to be used).
- SCADA system has its own interface and it also is more user-friendly than DRANETZ.

8. Measurement Results

Two analyzers "DRANETZ PX5" have been used, one for each measurement point. The methods or control techniques used for power quality measures have been referred especially in [37] and in [38-42]. With the "DRANSET" program, each analyzer was parameterized, which involved electrical connection and any voltage and current measuring, as well as the storage of the operating parameters when these values were outside of predefined limits. The measurements have been stored whenever there is a deviation of the limits defined by the "DRANSET" program and the "DRANVIEW" program displays these events. The electrical parameter characteristics have been changed during the monitoring period of the power at the two selected points of the island complex, such as the collection and processing of the records through the “DRANSET” program. For the selected period, four electrical records (two for each measurement point) were obtained. Measurements at the point 1 have been taken place during the period 25/10/2013 to 15/11/2013, while at point 2 07/10/2013 to 28/10/2013 as well as during 07/11/2013 to 21/11 / 2013.



(a)



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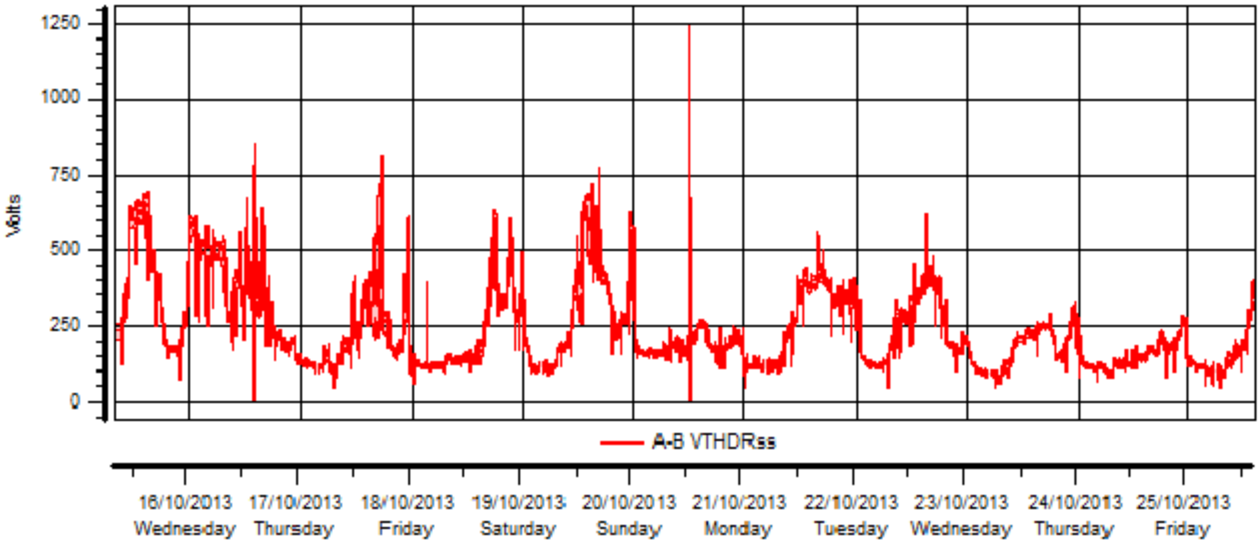
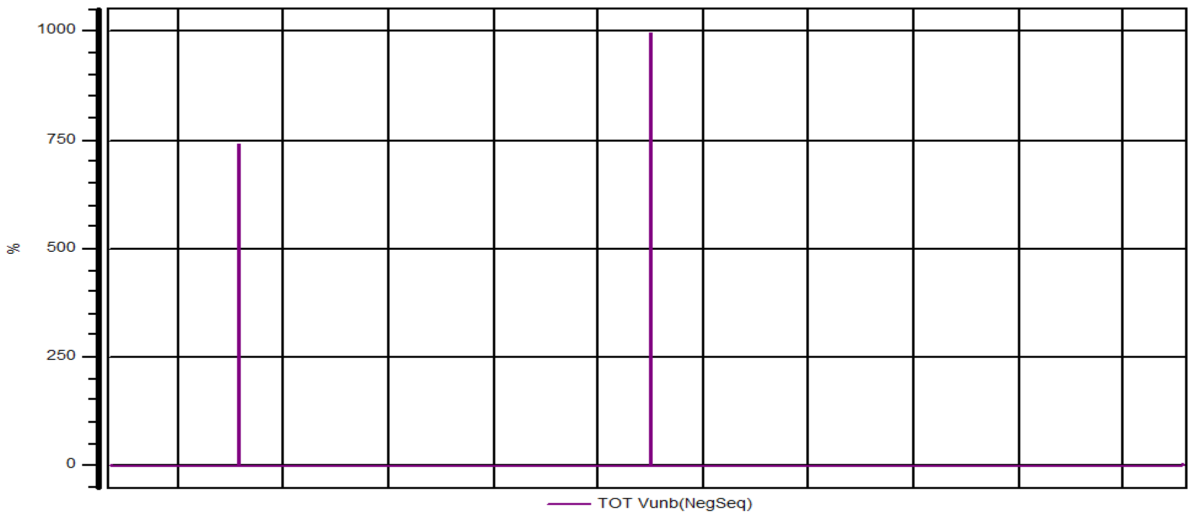


(c)

Fig. 9. Time plots of electrical variables for the point 1 during the period 15/10/2013 to 25/10/2013.



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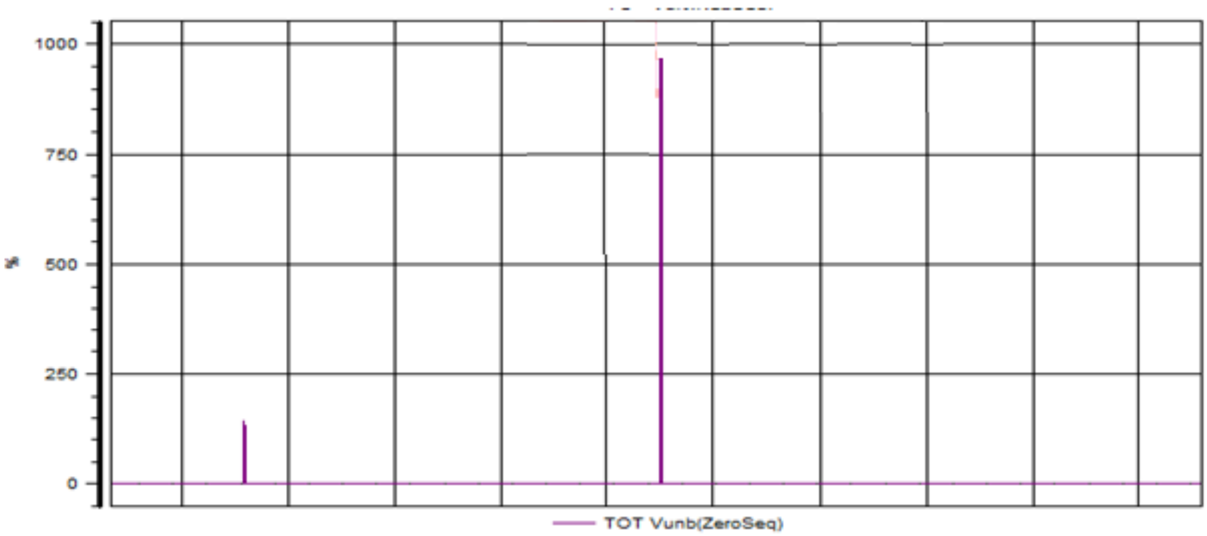

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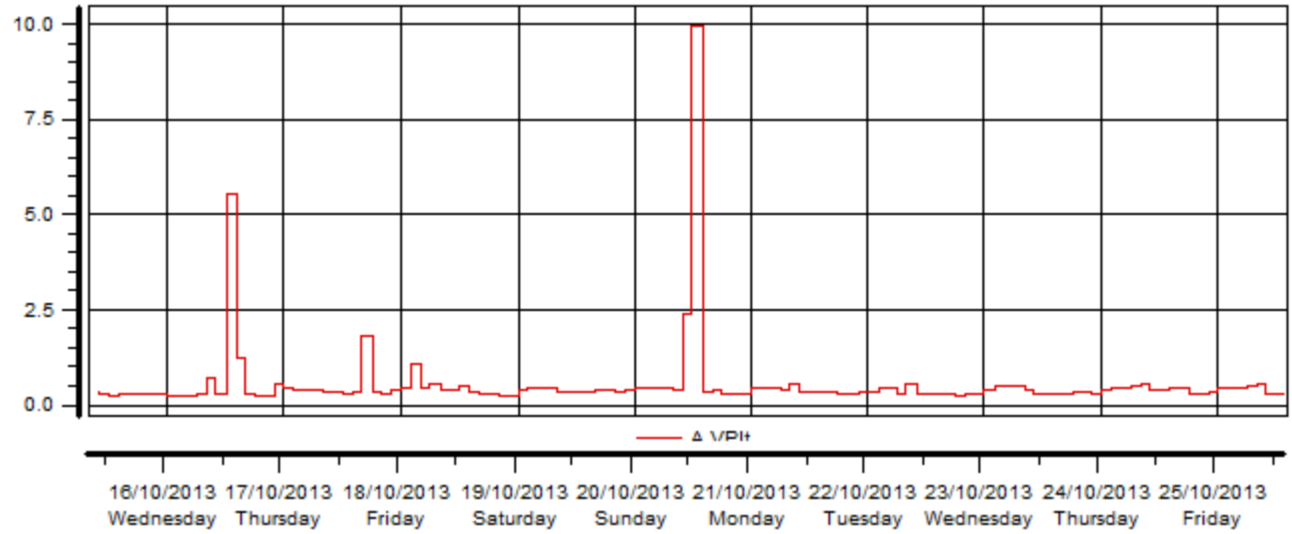
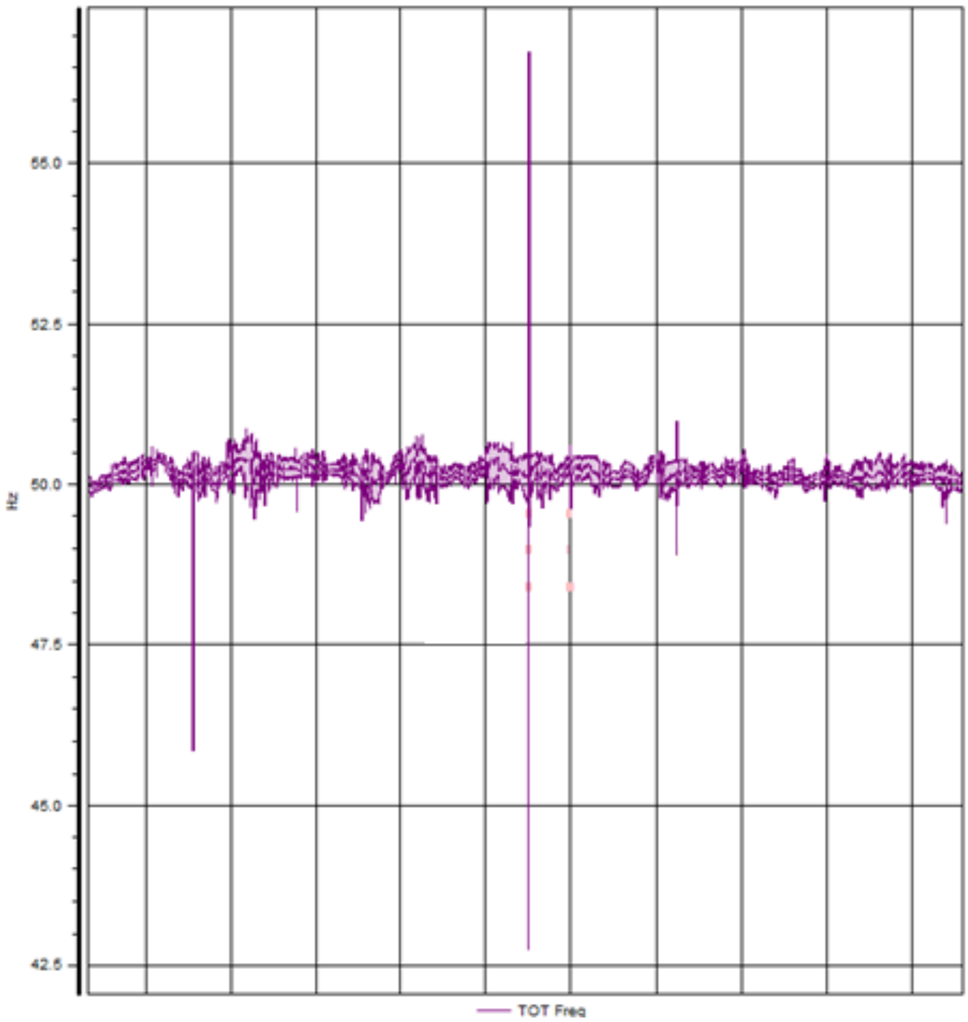


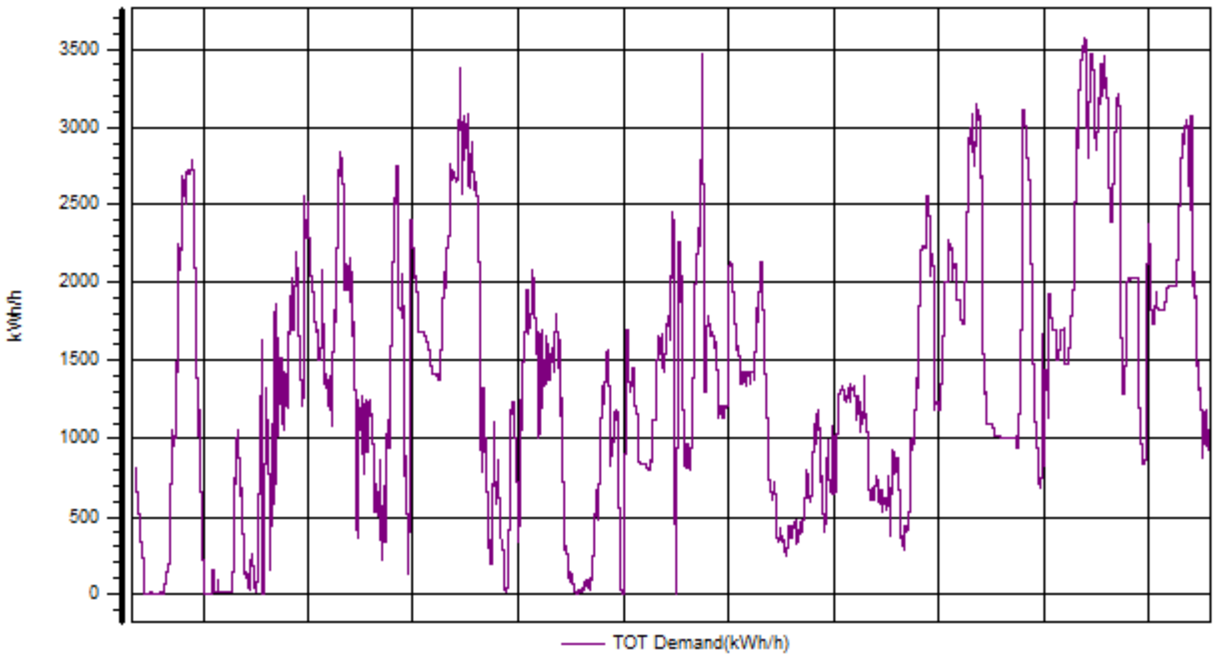
(c)

Fig. 10. Time plots of electrical variables in point 1 for the period 15/10/2013 to 25/10/2013.
(a) negative sequence percentage trend
(b) zero sequence percentage trend
(c) long-term index (PLT) for the flicker phenomenon.

Figure 11 shows the time series a) the frequency of the grid voltage, b) the actual power output and c) the energy offered in point 1 for the period 15/10/2013 to 25/10/2013.



(a)



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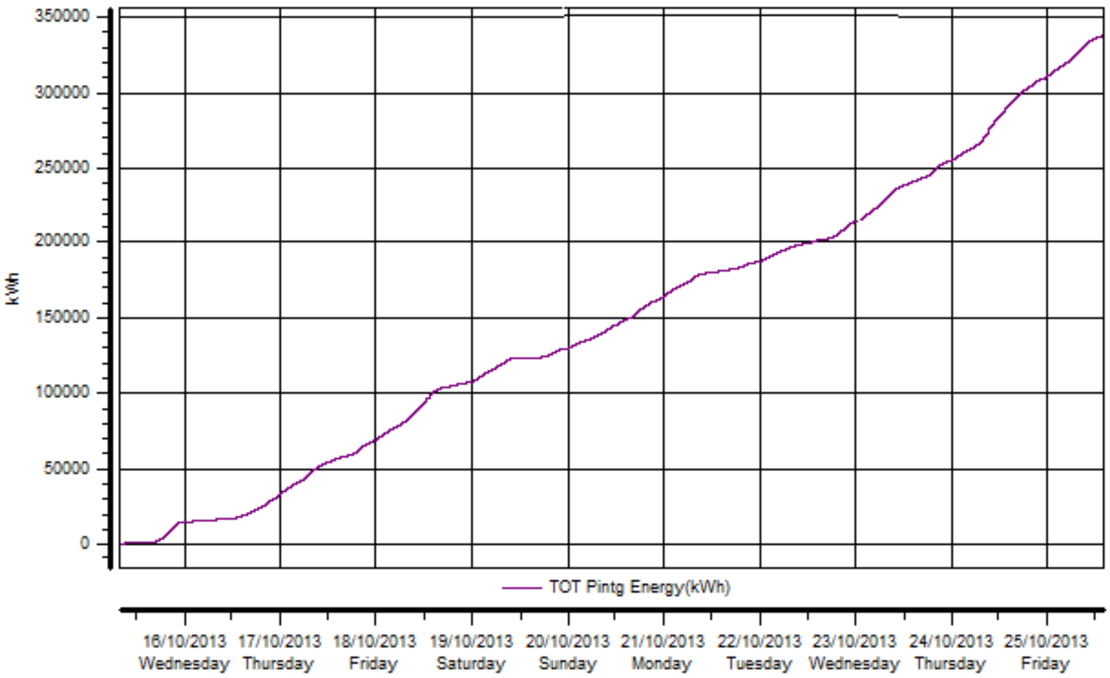


(c)

Fig. 11. Time plots for (a) frequency, (b) active power output and (c) the energy offered in point 1 during the period 15/10/2013 to 25/10/2013.

In Figure 12 is shown the case of an event at the moment 08.09.40 at 15/10/2013, where the waveform of the line to line voltage U_{BC} was disturbed. In this case, high frequency and low amplitude oscillations are superimposed around the negative maximal value of the $U_{B\text{-}C\ line}$ to line voltage. The deviation in the voltage and current rms values is considered too small.

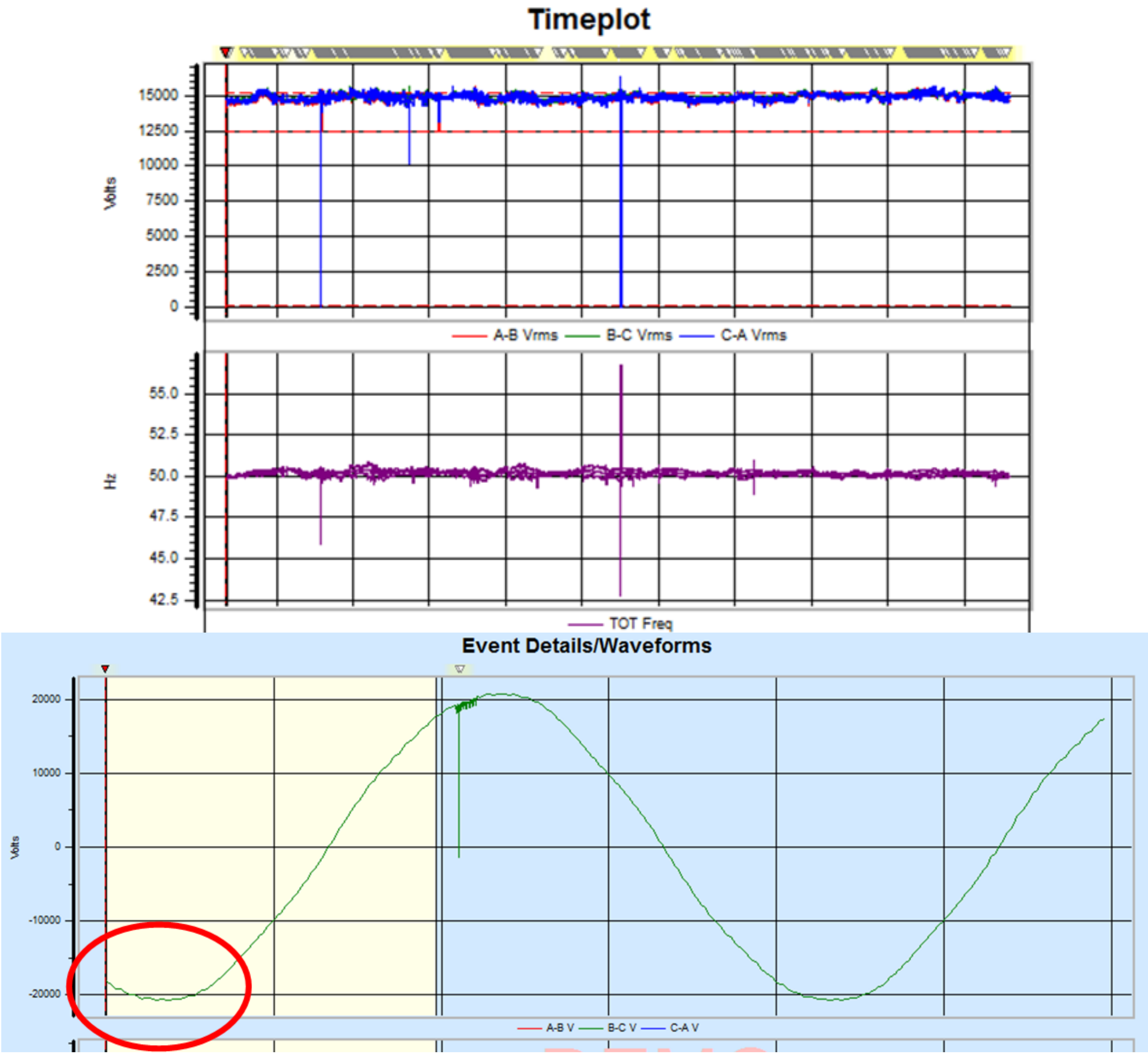


Fig.12. Illustration through the DRANVIEW program of a line to line voltage waveform deformation.

Figure 13 illustrates the exceeding of the S_{pt} index limit (which has been defined by the International Standards) due to the flicker effect. This is indicated by the horizontal line (1.00). This exceeding had reached about 5.5 times its value Limit. The direction of the arrow indicates an overrun or a drop.

It should be noted that the frequency of the samples in each figure of all cases and the calculation of each indicator is done every 10 minutes, except for events where exceeding occur within the limits of the system variable. In the case of exceeding the limits, calculations are performed more often, even several times in one second (transient phenomena, etc.). In point 2 measurements were made with another DRANETZ instrument in a similar way, from which corresponding time plots emerged.

9. Evaluation of the Power Quality of the Electricity Grid under Study According to the European Standard EN 50160

The evaluation of the power quality is achieved by the systematic monitoring of defined electrical variables of the system and the calculation of specific indicators, defined by the international standards. The phenomena related to the power quality are as follows: a) frequency changes; b) active value voltage, c) flicker phenomena (index P_{st}andP_{lt}), d) voltage dips, e) voltage increases - overloads, f) voltage interruption, g) harmonics of voltage and current (index V_THDRes and I_THDRes respectively), h) intermediate harmonics voltage (index V_TIDRes and I_TIDRes respectively), j) harmonics telecommunications signals.

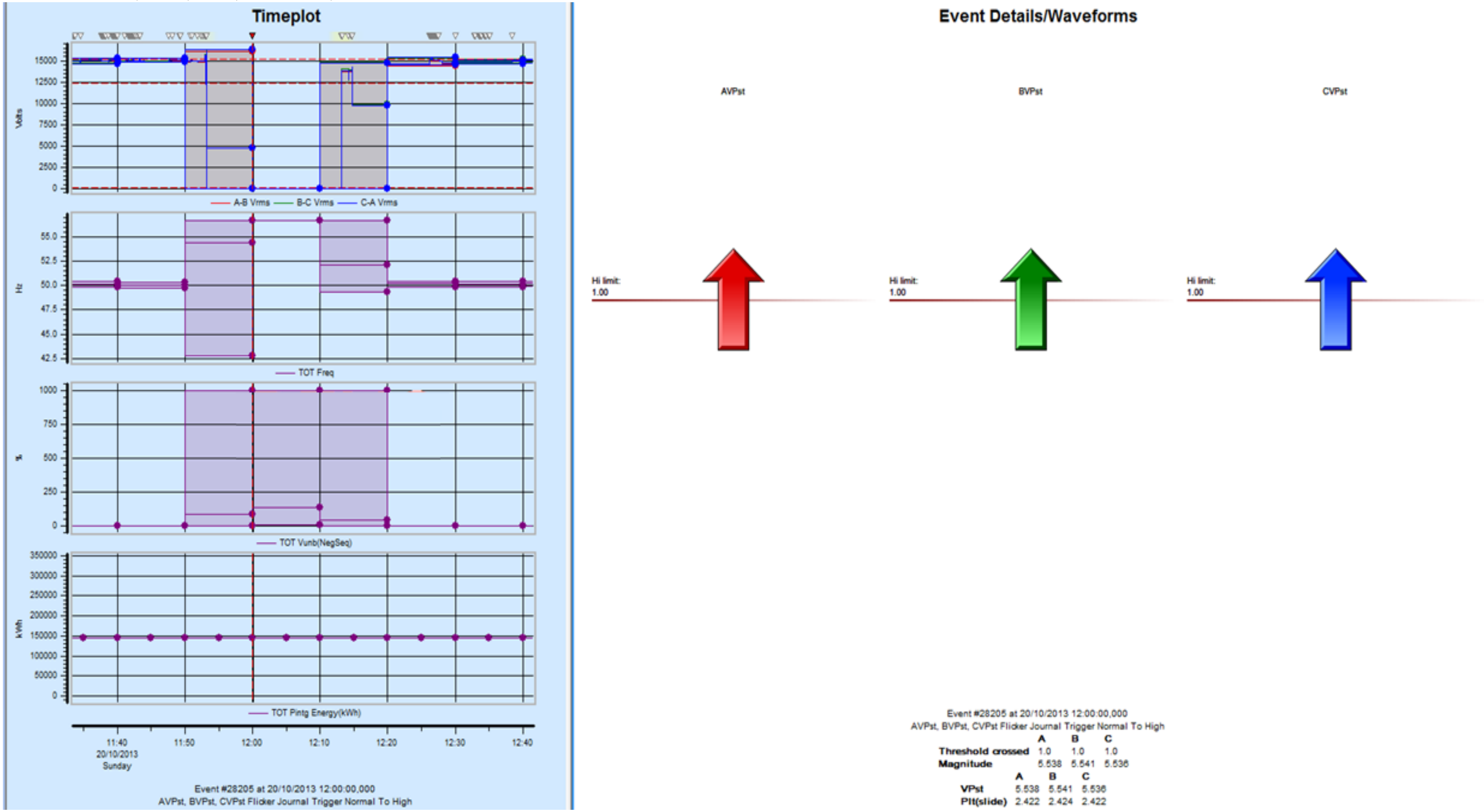


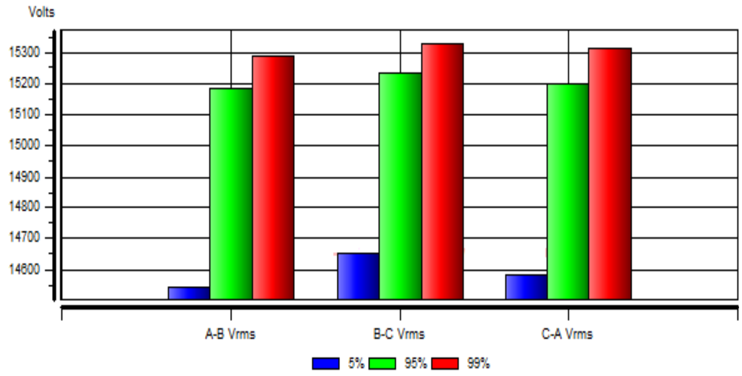
Fig. 13. Illustration of Pst overrun for the three phases through the DRANVIEW program on an event on 20/10/2013.

The EN50160 Standard defines the maximum and minimum value limits and maximum frequency deviation from predetermined values as well as the maximum number of occurrences (deviations from the limits) in the total of measurements taken at a specific time. For example, the voltage frequency of the investigated deviation in a non-interconnected network can be 50 Hz ±2 %, (this is 49 - 51 Hz), for 95% of the values obtained from one week's measurements. The sampling of this variable should be done every 10 seconds. Thus, for the reliable evaluation of the power quality, it is necessary to statistically process the data for each electric variable or for each index that determines the corresponding physical phenomenon.

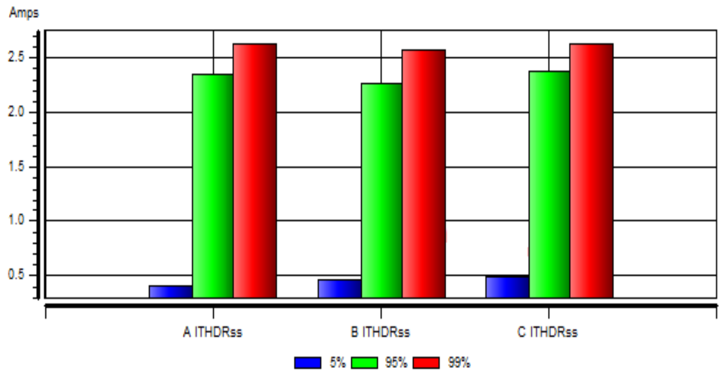
In the present study, we analyze the following variables for each observation point at the measurement intervals: a) the active value of the line to line or phase voltage, b) the index THD for each current of the line, c) the voltage of the negative and zero sequence as a percentage of the positive voltage sequence, d) voltage frequency. For these variables, measurements were made at both observation points during the periods 25/10/2013 to 15/11/2013, 7/10/2013 to 28/10/2013 and 7/11/2013 to 21/11/2013.

Figures 14 (a), (b), (c), (d) show the distributions of certain system variables values, which has come of measurements in point 1 and after statistical processing of them. The representation of values distributions was done through bar graphs, using a three-color code. The blue bar refers to the line to line voltage UA-B and means that 5% of the measured active values do not exceed 14. 550 V. Consequently, 15% of the total measurements do not exceed the value of 15.150 V. On the other hand, the line rms value reaches values up to 15.290 V in the interval of the 99% of all measurements. It is noted that the nominal voltage of the interconnection bus of the region's wind farm at point 1 is 13,800 V. The permissible range for the values of line voltages values as defined by EN 50160 refers to 95% of the total measurements taken within one week. Therefore, the information resulting from the analysis of green bars for each of Fig. 14 (a),(b), (c), (d) is critical for the evaluation of the power quality. However, these figures were derived from data recorded between 15/10/2013 to 25/10/2013, over a week. For this reason, the data had to be sorted at appropriate intervals to compare with those defined by EN 50160. This process was carried out by using the DRANVIEW program.

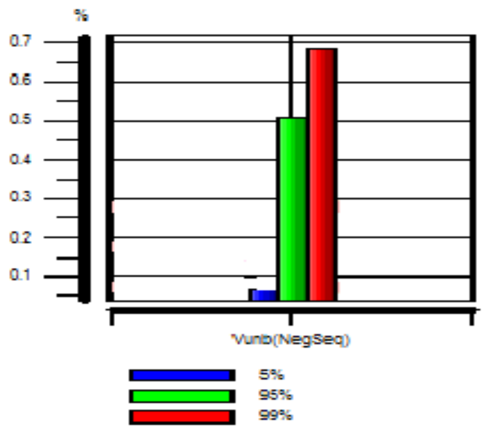
Figure 14 (b) shows that 95% of the total calculated I_THDRes values do not exceed 2.4 A. Considering that the nominal current of the bus, determined by the relevant staff for the DRANETZ instrument, was 34.6 A, the I_THDRes index does not exceed 7% for 95% of the measurements. This percentage is within the limits set by the standards. Corresponding results are deduced for the calculated percentage values of the negative and the null sequence. The frequency of the electrical network over the measurement period does not exceed 50.36 Hz in 95% of the measurements, while 99% of this does not exceed 50.41 Hz (Figure 14.d). The fluctuation of these values does meet the limits set by the DSO (Days Sales Outstanding) for the non-interconnected islands grid.

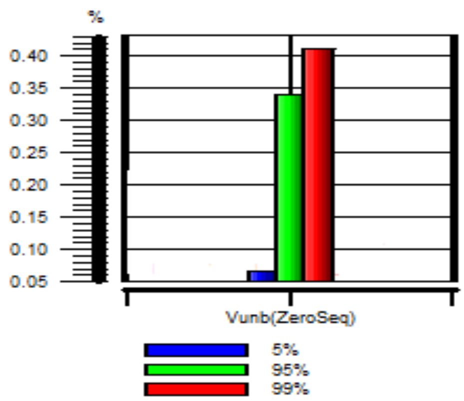


(a)

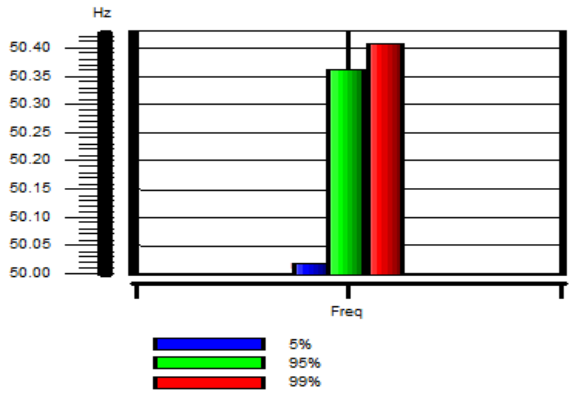


(b)





(c)



(d)

Fig. 14. Distribution of valuesfrom the statistical analysis of the measurement results as a function of the number of samples

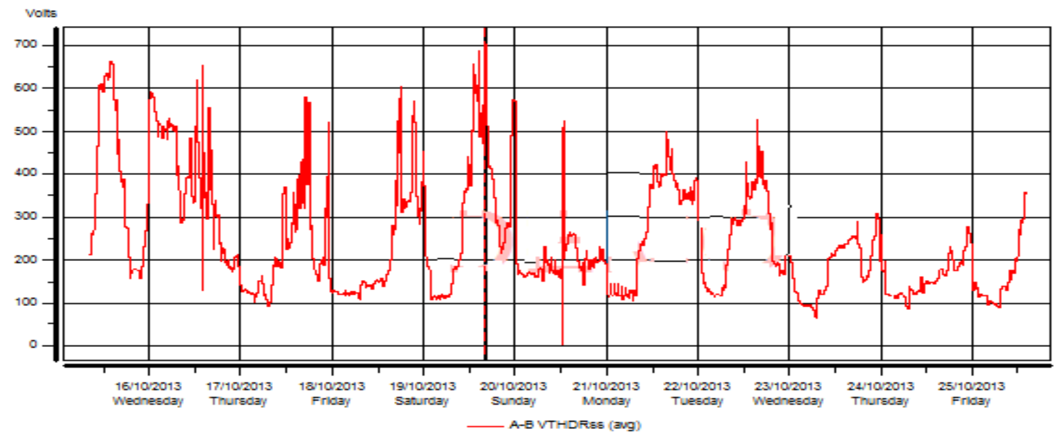
(a) Measured active values of line voltage

(b) Values of calculated harmonic indexes for line currents(c) percentages of the calculated negative (a) and zero (b) sequences as functions of the number of samples

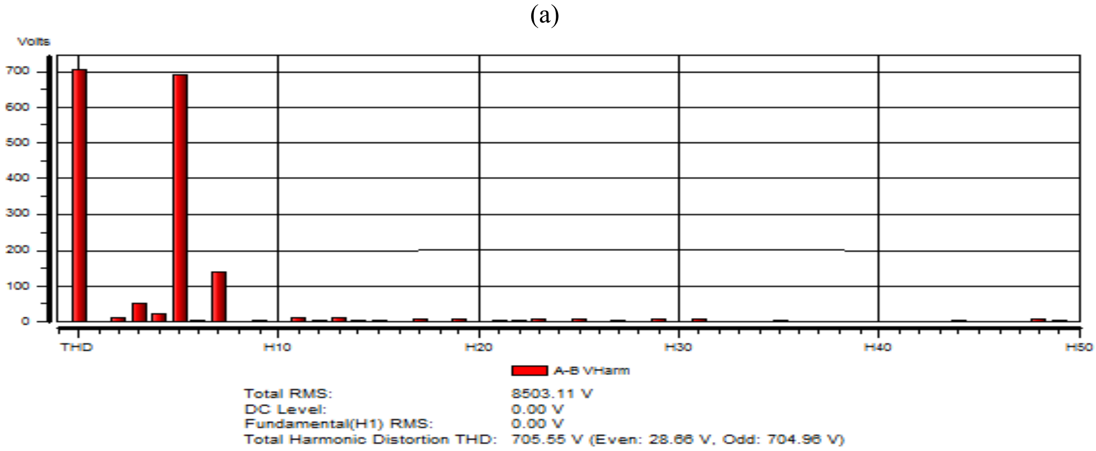
(d) Measured values of the frequency of the electrical network.

Figure 15 illustrates the time variation of the VTHDR index, which refers to the harmonic content of the line voltage U_{AB}. Additionally, the average values for the amplitude of each harmonic to 50th harmonic are calculated over the time of the measurements. The resulting widths are compared with those in the table of the corresponding standards and are found to be within the specified limits. With a red vertical line the events and their moments are marked with the maximum calculated value of the $THDR_{es}$ index for the line voltage under consideration. Similar calculations were made for the line current. It was found that no current index exceeded the value of 8%, defined by the standard.

Using data collected from the SCADA systems the RES penetration rate has been determined on the total power during the specified time intervals. This instrument provides the possibility of monitoring the production units (thermal stations and wind farms) by recording the maximum, minimum and average values as well as the THD index. These data are collected in central servers, recorded per second, and then given the possibility of further processing. Measurements have been made during the aforementioned time intervals at the two selected points of the island complex and data tables and respective time plots have been produced. From these a characteristic illustration of the energy variables has been selected, which is shown in Fig. 16.

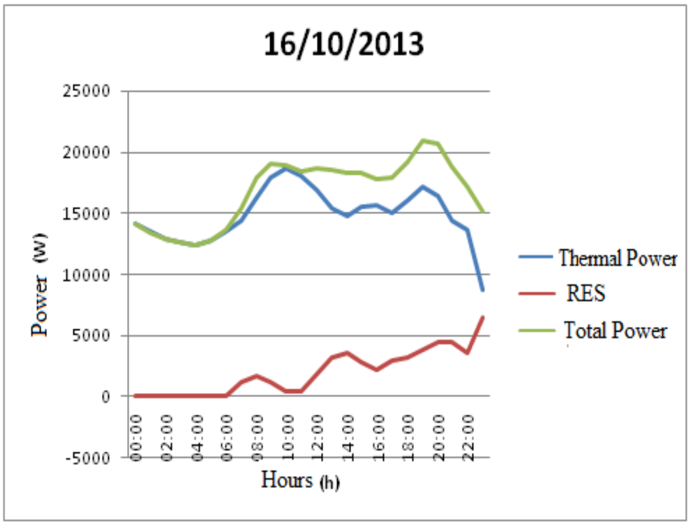


(a)

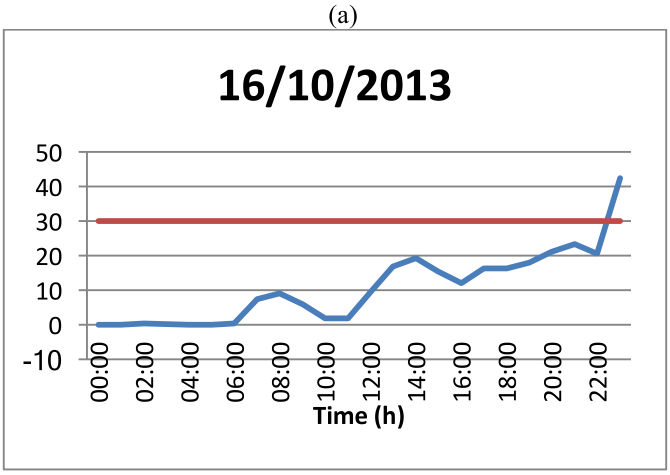


(b)

Fig. 15. Time plot: (a) the calculated harmonic content (THD) for the line voltage U_{AB}, (b) the average value for the index THD for the line voltage U_{AB} and the mean values of the 50^{th}harmonic width during the measurement interval.



(a)



(b)

Fig. 16. Output on 16/10/2013.
(a) From the thermal power plant, from RES, total production
(b) Quantitative RES penetration, the marginal rate 30% (red line).

The limit of the penetration rate of 30% RES was determined by the distribution system operator according to the prevailing perception of the European grids. Taking into account the network frequency measurements on 16/10/2013, at 13.50pm, the value f = 45.85 Hz has been found, while the penetration rate from RES was 19.35%. At that time, the P_{st} index was exceeded in the three phases associated with the flicker phenomenon. All three phases were stopped at point 1. The re-connection of the wind farm was done 9 minutes later; the incident was visualized through DRANVIEW. It has been found that on 20/10/2013 at 12.00 the frequency was 42.55 Hz, while the penetration rate from RES was 27.63%. However, the values of energy from RES during the period from 8.00 to 17.00 ranged between 30% and 43%. At 12.00, there were two voltage interruptions on line P23, where the complex's largest wind farm is interconnected. From the analysis of the event, there was no direct correlation between the exceedance of the maximum permissible RES penetration rate and the occurrence of events other than the case of the interruption of line P 23, which occurred on 20/10/2013 at 12.00, then for a long time RES penetration rate was over 30%.

10. Findings on Power Quality of Paros Islands Complex

In order to decide on the quality of power in the island complex of Paros, we relied on the international standard EN 50160 and the findings resulting from the recording of the events with the DRANETZ system. The time intervals recorded events specified by this standard, at the two measuring points, were the following: 15/10/2013 to 25/10/2013, 25/10/2013 to 15/11/2013, 7/10/2013 to 28/10/2013 and 7/11/2013 to 21/11/2013.0.

The analysis of the events resulted in the following conclusions:

1. Frequency:

1.1 In accordance with standard EN50160, for time interval equal to one week, the frequency ranges must be between 50±2% for 15% of the measurements. The results from events analysis have demonstrated this.

1.2 For a period equal to one week, the frequency must be ranged between 50 ± 15% Hz for the total (100%) of the measurements. It was found that network frequency was within limits during the mentioned time intervals.

2. Changes in the rms value of the grid voltage:

For a time period equal to one week, the voltage rms value must be ranged from $U_{nominal}$ to $U_{nominal}$ ± 10% for 95% of the measurements.

3. Flicker phenomenon:

International standards EN 50160 and IEC 61000-3-7 define that the P_{lt} index (long term severity) must be less than unit (P_t<1) for 95% of the measurements for one week. It has been shown by the measured data that for 95% of the samples for each week P_t was less than unit (standards fulfilled).

4. Network voltage asymmetry:

International Standard EN 50160 states that the mean value of the negative sequence active value measurements for periods of ten minutes and for one week should be between 0% and 2% of the corresponding value for the positive sequence for 95% of the total of the measurements. By the analysis of the measurements at both selected points during the aforementioned periods it was found that the network voltage was within the limits set by the standards.

5. Harmonic content of the voltage:

In accordance with EN 50160 and in combination with IEC 61000 -4-30 the THD index should be less than 8% (THD 8%) for a time of one week. Moreover the maximum rate of the width of each harmonic from 2nd to the 25th must not exceed a set limit. After conducted analysis of the measurements that have taken place at both selected measurement points, it has been indicated that the standards had been fulfilled.

11. Conclusions

The analysis of the results, which have obtained by the measurements at the two selected points of the island complex of Paros, has shown that the variables of the electrical system have been within the limits of the standards and therefore the quality of the power was satisfactory. According to strict international standards, measurements should be performed on all critical nodes in the electric grid over a one-year period to reach safe, highest-fidelity conclusions. However, indicative measurements at the two selected points for selected time intervals have provided valuable information for assessing power quality. So, it can be concluded that the power quality in the island complex of Paros was fully satisfactory. It must be noted that the Paros island complex has been interconnected on 9/3/2018 on the continental Greece grid, so, a future work could be to conduct a survey and the measurements again in order to compare them with the present ones.

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