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Article

A Method for the Evaluation of Power-Generating Sets Based on the Assessment of Power Quality Parameters

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Abstract: This article presents a new method for the classification of machine failures using an example of selected generating sets. Measurements and an analysis of the electrical parameters, such as the phase-to-phase voltages at the terminals of a synchronous generator, armature current, and voltage and excitation current of a synchronous generator, are the basis for determining the failure symptoms. The existing energy quality coefficients are adopted as symptoms for the assessment of failures in the monitored generating set. We assume in this method that the description of the input–output relationship is in the form of a black box and use the binary diagnostics matrix (*BDM*) to investigate the failure–symptom relationships between the inputs (intentional failures) and outputs (failures symptoms = fault-sensitive power quality (PQ) coefficients). The method presented in this article enables the detection and classification of both electrical damage in a synchronous generator and mechanical damage in a diesel engine. It is anticipated that further work and development of the method will focus on the implementation of the algorithm in the form of software into a miniature IoT module for the automatic classification of failures.

Keywords: power system analysis computing; power system measurements; power quality; fault classification

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1. Introduction

In recent years, the demand for high-quality electricity has increased as ship systems have become overwhelmed by electrical and electronic devices. This article mainly concerns the classification of damage to machines and devices operating in marine power systems, mainly characterized by the AC power supply system in IT mode.

Due to their susceptibility to changes in electrical parameters, these networks are included in the group of microgrids, and disturbance analyses are carried out with the use of electricity quality coefficients [1]. Power quality problems, including voltage fluctuations, frequency fluctuations, harmonics, and transient states, reduce the quality of the energy, which leads to unavoidable and undesirable phenomena occurring in the power system, which cannot be completely eliminated but can be reduced by using certain mitigation techniques based on optimization and control techniques [2] and intelligent management on the demand side [3]. In the new generation of power networks, the main task is to locate the problem regardless of its nature, and secondly to work out how to reliably and safely respond to detected areas affected by failures [4]. In [4], we also found references to analyses using methods based on the Hilbert–Huang transform, S-transform, wavelet transform, and Fourier transform. This feature extraction method is similar to that used in the described method in this article. It is worth emphasizing that the article focuses on a description of the method used for the classification of failures in electrical machines and devices, and not the classification of PQ coefficients. Hence, the method of feature extraction processing in the form of PQ coefficients is not described in this article. The classification of machine failures should not be confused with the PQ classification of coefficients, which in this method play the role of estimators of symptoms sensitive to the appearance of a fault. Another article [4] distinguishes the classification methods based on techniques of artificial intelligence, neural networks, neuro-fuzzy systems, support vector machines, genetic algorithms, fuzzy expert systems, and miscellaneous classification systems. The current status and future trends in power quality analysis are described in [5]. Trends regarding the techniques and future work related to power quality analyses from motor and drive efficiency viewpoints are provided in [6]. Researchers are constantly striving to develop new analytical techniques, instruments, measurement methods, and new indicators and standards that correspond to and meet the requirements for the current operation of an electrical network [7]. Over time, the technology has evolved as smart technology and has been adopted from time to time, such as artificial intelligence Internet networking, pattern recognition, and data mining as smart signal processing techniques. The smart meters include digital signal processors in computers, information and communications buffers, and mass storage units. For the identification and recording of all power quality disturbances and environmental process parameters data in real-time, the producers offer advanced products [8]. A smart design, manufacturing, and operation approach as the way forward in the Industry 4.0 era to design for better energy efficiency and more intelligent ships with smart operation through-life is presented in [9]. On a larger scale, a single element, i.e., a power quality analyzer made using Internet of Things (IoT) Industry 4.0 technology, is related to the entire maritime industry in [10].

The monitoring of PQ coefficients has many applications, from monitoring network parameters to assessing whether the coefficient values exceed the normative values of PQ coefficients, through to the automatic control of network elements and network configuration changes, including a novel transformation technique based on a combined AC/DC grid-based hybrid microgrid and electric vehicle operation [11] for the adjustment of devices used to lower the values of PQ coefficients (e.g., harmonic filters) for the classification of faults in network elements, including receivers, switching and transforming devices (e.g., inverters), and electricity sources, i.e., a generator set with a synchronous generator. This work presents an analysis of the defect–symptom relationship and was based on an active experiment, providing information on both mechanical and electrical damages in the electrical signals of a synchronic generator in a generator set.

An examination of the aspects and impacts of power quality onboard ships is presented in [12]. The study focuses mainly on an assessment of the entire power system, for which the sources of electricity quality disturbances are electricity sources and sets of receivers. However, these sources are treated as a whole (e.g., a generator module or block) and the study does not contain information about the internal damage that affects the quality of the electricity. Another difference is the fact that the limit levels of the electric energy quality coefficients are determined on the basis of standards and documents and not on the basis of active experiments. It should be noted that when conducting an active experiment, the limit levels of the estimators may be based on standards documents, but they may also be determined experimentally (during an active experiment) or arbitrarily in order to test the sensitivity of the adopted estimator to damage. On the other hand, the estimators of the quality of electricity are common, but they are treated differently—they do not constitute the final reference described in the standards and only constitute a creative basis for further searches of the failure–symptom relationship. The solution described in this paper is a type of decision support method that enables the classification of generator set failures.

Although this method was based on the study of marine generating sets, it seems that it can also be applied appropriately to other means of transport than ships. The presented method can be extended to other vehicles such as electric aircrafts [13], hybrid aircrafts [14], electric cars, and trains or to renewable energy sources such as wind turbine generators [15]. The possible application of such a method to other fields may be based on the cooperation of specialists and the implementation of joint projects.

In order to compare the scope of the current publications on the use of PQ coefficients and the new method described in this paper, articles on this topic were analyzed and are summarized in Table 1.

Table 1. Comparison of the scope of current publications concerning the use of PQ coefficients.

Lp.	Title of Publication	Year, Author(s) and Journal	Aim(s)	PQ Measurement System	Need for Enhanced PQMS	PQ Factors/ Disturbances	Method of Analysis	Object of Investigation	Mitigation Technique	Remarks
1.	A Method of Evaluation for Power-Generating Sets Based on the Assessment of Power Quality Parameters	Under review. Listewnik K.J., Energies, 43 references	Presentation of a novel method of failure classification based on PQ coefficients.	PQ research monitoring system.	Embedded PQ Sensor Node (IoT)—in the course of implementation.	30 different factors as PQ estimators of failures.	Different, time and frequency domain, FFT, Hilbert.	Power-generating set—in general electrical machines and devices.	YES by detecting, classifying, and removing failures in monitored objects.	A novel Fault–symptom, PQ-based method.
2.	A Comprehensive Review of Maritime Microgrids: System Architectures, Energy Efficiency, Power Quality, and Regulations [1]	2019, Kumar D. et al. IEEE Access, 94 references	Review of the existing power quality standards highlighting the need for new requirements.	Mainly 1—the main switch board.	YES	Non-characteristic harmonics in the network. The engine scheduling approach can create pulsed loads. Below 2 kHz: Resonances, voltage and frequency variation, unbalanced, voltage and current harmonic distortion and commutation notches.	Difference	maritime power systems—microgrids.	YES Harmonics—active filters.	There are very few papers addressing the power quality issues and their impacts on maritime power systems.
3.	Special Issue “Analysis for Power Quality Monitoring” [7]	2020, De la Rosa J.-J.G. et al. Energies, 11 references	Recent advances. Objectives of PQ monitoring: compliance verification, performance analysis/benchmarking, site characterization, troubleshooting, advanced application and studies, and active PQ management.	Different, e.g., Embedded PQ Sensor Node.	Smart grid (IoT), Permanently monitor the power conditions within the grid.	Need for new parameters that reflect the current situation in the smart grid.	Different, e.g., High-Order Statistics, feature extraction in PQ contexts.	Power system grid.	NO	There is still a need for new parameters that reflect the current situation in the smart grid (SG).
4.	Power Quality Disturbance Monitoring and Classification Based on Improved PCA and Convolution Neural Network for Wind-Grid Distribution Systems [16]	2019, Shen Y. et al. Energies, 71 references	A novel algorithm based on improved principal component analysis (IPCA) and one-dimensional convolutional neural network (1-D-CNN) for detection and classification of PQDs.	Modified IEEE 13-bus Simulated in MATLAB.	Lack of information.	Root Mean Square, Skewness, Range, Kurtosis, Crest Factor, Form Factor and mean, energy, standard deviation, Shannon entropy, and log-energy entropy.	Improved Principal Component Analysis (IPCA) and One-Dimensional Convolutional Neural Network (1-D-CNN) for detection and classification of PQDs.	power quality disturbances (PQDs).	NO	-

Table 1. *Cont.*

Lp.	Title of Publication	Year, Author(s) and Journal	Aim(s)	PQ Measurement System	Need for Enhanced PQMS	PQ Factors/ Disturbances	Method of Analysis	Object of Investigation	Mitigation Technique	Remarks
5.	A Review of Distributed Control Techniques for Power Quality Improvement in Micro-grids [17]	2017, Zeeshan H.M.A. et al. IOP Conf. Series: Materials Science and Engineering, 22 references	Major aspects for the development in this field are to avoid large power breakdowns in micro-grid.	Information and communication technologies (ICT) at supervisory layer provide monitoring. Lack of details.	Cyber–Physical Systems (CPS) involve a combination of cyber and physical resources to provide sensing, processing, and computational platforms.	Imbalance of voltage profile, frequency mismatch, current distortions, and inaccurate management of active and reactive power.	Advanced Control Techniques: Harmonic mitigation, Voltage compensation, Power imbalance compensation, Droop control technique.	Microgrids	YES The decentralized subsystems for harmonic compensation and active–reactive power-sharing.	-
6.	Review of Ship Microgrids System Architectures, Storage Technologies and Power Quality Aspects [18]	2017, Jayasinghe S.G. et al. Inventions, 70 references	Investigate recent developments in these areas and provide readers with a critical review on power quality issues, energy storage technologies, and strategies that could be used to improve the power quality in ship microgrids.	Lack of information.	Lack of information.	Voltage variations, frequency variations, and waveform distortions, which are commonly referred to as harmonic distortions.	Experts analysis based on publication review.	Ship microgrids.	Energy storage is considered as a technology for mitigating voltage and/or frequency deviations. Passive filtering used for reducing harmonic distortions.	It is important to select the appropriate energy storage technology considering the type of power quality issue(s) being addressed.
7.	Three Decades of Marvelous: A Significant Review of Power Quality Events Regarding Detection and Classification [4]	2018, Mian Khuram Ahsan M.K. et al. Journal of Power and Energy Engineering, 234 references	Study of power quality events, such as automatic classification and signal processing via creative techniques and the noises' effect on the detection and classification of power quality disturbances.	Lack of information.	Lack of information.	Frequency: slight deviation, sever deviation. Voltage: average voltage. Flicker, Sag: short, long, long-time disturbances. Under-Voltage: short, long. Swell: temporary short, temporary long. Over-Voltage Harmonics and Miscellaneous Signals.	Detection: Hilbert–Huang Transform, S-Transform, Wavelet Transform, and Fourier Transform. Classification: techniques of artificial intelligence, neural network, neuro-fuzzy system, Support Vector Machine, Genetic Algorithm, Fuzzy Expert System, Miscellaneous.	Electrical power system.	NO	Detection and classification PQ disturbances are two of the key aspects of the electrical power system.

Table 1. *Cont.*

Lp.	Title of Publication	Year, Author(s) and Journal	Aim(s)	PQ Measurement System	Need for Enhanced PQMS	PQ Factors/ Disturbances	Method of Analysis	Object of Investigation	Mitigation Technique	Remarks
8.	Advances in Power Quality Analysis Techniques for Electrical Machines and Drives—A Review [6]	2022, Osornio-Rios R.A. et al. Energies, 160 references	Study about the relationship existing between the motors and drives that induce electric disturbances into the grid, affecting its power quality, and also how these power disturbances present in the electrical network adversely affect, in turn, the motors and drives.	Lack of information.	Real-time monitoring for energy saving.	Transients, Short-duration voltage variation, Long-duration voltage variation, Power imbalance, Waveform distortion, Voltage fluctuations, Power frequency variation.	Fast Fourier transform (FFT), the short-time Fourier transform (STFT), discrete Fourier transform (DFT), discrete wavelet transform (DWT), Hilbert–Huang transform, S-transform.	Electrical machines and drives	Different active or passive wave-shaping techniques are used to mitigate the harmonic content effects.	The monitoring systems of the power grid have areas for improvement. PQ monitoring is often avoided as a measure for enhancing energy efficiency.
9.	Optimal Power Systems Restoration Based on Energy Quality and Stability Criteria [19]	2022, Quinteros F. et al. Energies, 42 references	Study considers contingencies for which the disconnection of transmission lines and generation units is carried out randomly.	Different solutions: sensors to monitor the electrical parameters on both sides of a switching device, monitor the variables in real time.	Lack of information.	Variables such as voltage, angular deviation, and power.	Optimal AC power flows (OPF-AC), optimal DC power flows (OPF-DC).	Electric power systems (EPS).	Optimal route is generated to restore the elements that went out of operation.	-

Table 1. *Cont.*

Lp.	Title of Publication	Year, Author(s) and Journal	Aim(s)	PQ Measurement System	Need for Enhanced PQMS	PQ Factors/ Disturbances	Method of Analysis	Object of Investigation	Mitigation Technique	Remarks
10.	Current Status and Future Trends of Power Quality Analysis [5]	2022, De la Rosa J.-J.G. et al. 153 references	Overview on PQ trends in several fields related to instrumental techniques that are being used in the smart grid to visualize the quality of the energy, establishing a solid literature base from which to start future research.	Commercial instrumentation, instrumentation designed by researcher.	Increasing trend towards monitoring research and instrumentation for PQ. Lack of details.	Sag, swell, flicker, harmonic, interruption, transient, notch, sag + harmonic, sag + transient, sag + flicker, sag + notch, sag + spike, sag + interruption, swell + harmonic, swell + transient, swell + flicker, swell + notch, swell + spike, swell + interruption, flicker + harmonic, spike + interruption, spike + harmonic, spike + transient, notch + interruption, notch + harmonic, notch + transient, harmonic + interruption, harmonic + transient, more than 2 events.	Discrete Fourier Transform (DFT)/Fast Fourier Transform (FFT), Wavelet Transform (WT), S-Transform (ST), Short-Time Fourier Transform (STFT), Kalman Filter (KF), Hilbert–Huang Transform (HHT), Singular Spectrum Analysis (SSA), Higher-Order Statistics (HOS), Artificial Intelligence (AI), Total Harmonic Distortion (THD), Root Mean Square (RMS).	Photovoltaic (PV) and wind renewable systems.	Depends on disturbance type, e.g., for Harmonics: Filters, low-voltage line reactors, constant voltage transformers, motor generators, high-speed flywheel, standby UPS, online UPS, UPS and engine generator, unified power quality conditioner UPQC, D-STATCOM, spinning reserve, adjustable speed drive.	Current networks contain numerous coupled load effects; thus, new disturbances are not simple; they are usually complex events, the sum of several types of disturbances. Likewise, depending on the type of installation, the objective of the PQ analysis changes, either by detecting certain events or simply focusing on seeing the state of the network.
11.	Power Quality Mitigation via Smart Demand-Side Management Based on a Genetic Algorithm [3]	2022, Eisenmann A. et al. Energies, 58 references	Investigation the possibility and potential of an active mitigation technique to handle the PQ degradation caused by nonlinear loads in future industrial electrical grids, without the need for conventional measures such as passive or active filtering	Demand-side management (Smart DSM)	Implementing DSM in the Industry 4.0 application	THD of the voltage. The total demand distortion (TDD) of the load current or specific harmonics	NSGA-II algorithm	Industrial electrical grids	The mitigation method is based on genetic-algorithm-guided optimization for smart operational planning of the grid elements	-

Based on the analysis of the articles presented in Table 1, it can be said that the summary of the article shown in item 2 reflects the situation well—there are very few papers addressing the power quality issues and their impacts on maritime power systems. With the exception of [6], item 8 in Table 1, which deals with machines and electrical devices (i.e., the monitoring systems of the power grid have areas for improvement), the other studies focus on PQ monitoring and the detection of disturbances in power networks. There are few studies dealing with indications of which device element is responsible for PQ disturbances, as is the case with the method described in this article. The presented method fits well in the contemporary research area, while at the same time developing in a unique direction, indicating which damaged elements of the electrical source (in this case the generating set) cause PQ disturbances. In the future, this should not only result in the detection and classification of PQ disturbances in power networks, but should also affect the production of network elements, including sources, switching elements, and loads receivers, in such a way that it is possible to provide the energy industry with products resistant to disturbances and that do not cause PQ disturbances.

This article describes the new contributions of the research, consisting of:

1. A description of the new method of classification for faults in generating sets, based on the use of the existing power quality coefficients;
2. An assumption in this method that the description of the input–output relationship takes the form of a black box and using the binary diagnostics matrix (*BDM*) to investigate the fault–symptom relationship between inputs (deliberately caused faults) and outputs (faults symptoms = susceptible to faults in PQ coefficients);
3. A presentation of the set of symptoms obtained as a result of the active experiment and the new method, enabling the detection of specific failures in the tested generating set, and as a result the classification of these failures;
4. A presentation of the possibilities for the further development of the method and the classification of electrical machines failures based on the analysis of the electricity produced and consumed by them.

The rest of the paper is structured as follows. Section 2 describes the test object, along with the sequence of work, the generating sets used for testing, and the measuring equipment used for the tests. In addition, it includes a classification of the test signals and a selection of the electrical parameters that are measured. Section 3 provides a brief description of the phenomena causing deviations. Then, Section 3.1. includes a description of the development process for a set of power quality factors and Section 3.2. describes the theoretical model for fault assessment. Section 4 presents our research results and discussion. This section provides examples of selected susceptible and non-susceptible symptoms and includes a binary diagnostic matrix (*BDM*) based on the research described in this article. Section 5 summarizes this research, which aimed to develop a method for assessing the technical condition of a generating set on the basis of the failure–symptom ratio. The references are given at the end of this article.

2. Methodology

In the development of a method for assessing the suitability of a generating set for generating electricity of a required quality level, the following steps were taken (also presented in Figure 1):

- The identification of the generating sets used for this research;
- The analysis of phenomena occurring in power-generating sets that affect the quality of the electricity generated by the synchronous ship generators (taking into account expert knowledge);
- The elaboration of data registration and processing methods, as well as the selection of the measurement quantities used for the registration and analysis;
- The development of electricity quality coefficients independently for each electrical diagnostic parameter;

- The completion of a passive experiment to determine the current technical condition of the generating sets and to determine their suitability for generating electricity of the required quality;
- The identification of the most common forms of failure in generating sets, as well as the planning and completion of an active experiment to determine the fault–symptom correlation;
- A critical analysis of the research results and determination of the limit state symptoms.

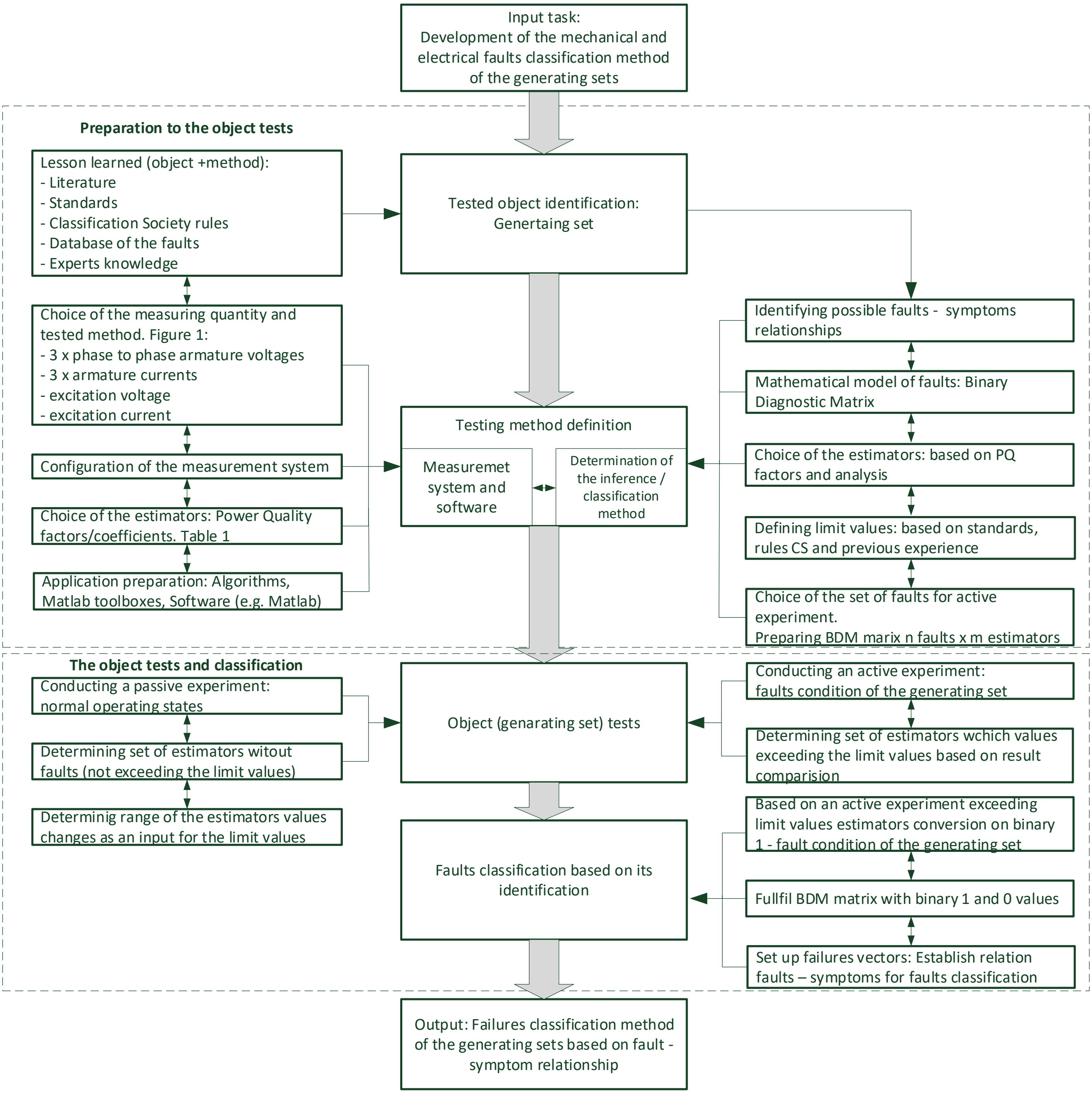

Figure 1. The flowchart of the proposed method.

2.1. *Description of the Generating Sets Used for the Research*

A ZE-400 generating set was used for this research. It consisted of an SW-400 diesel engine as the propulsion drive and a GCPf-94c/1 synchronous generator. The generating sets used for this study came from the laboratory at the Polish Naval Academy (Figure 2) and were destined for major renovation work. This situation enabled diagnostic measurements to be made before and after renovation and allowed the selected types of failures to be simulated. Ultimately, all failures were repaired within the framework of the main renovation work. The selected generating sets constituted the basis for the experimental research on the diagnostics systems of synchronous ship generators and the development of a system for assessing the ability of generating sets to generate electricity of the required quality.

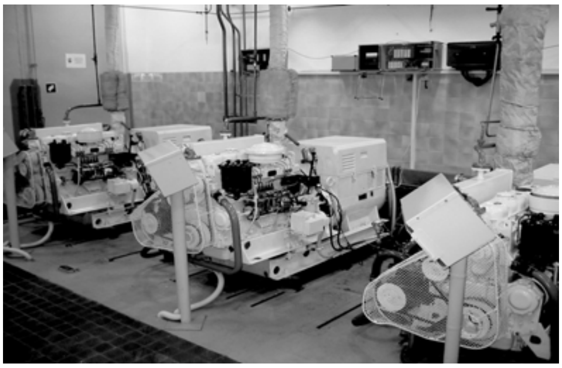

Figure 2. General view of the laboratory with ZE-400 generating sets.

The 60 kVA power GCPf-94c/1 synchronous generator has a WS 60 N-type automatic voltage regulation system and was designed to generate electricity in alternating currents (f = 50 Hz, 3 × 400 V) on sea vessels with an unlimited sailing range. This generator can also be used for land purposes, e.g., in public transport and construction.

The generator is driven by a diesel internal combustion engine with a 0–5% droop speed. The generator body is connected to the engine body by means of a flange. The assembly is based on a shared foundation frame. The propeller motor and generator shafts are connected by flexible coupling. The piston fuel pump supplies fuel through the injectors to the combustion chambers of the diesel engine. This engine is equipped with a Woodward-type centrifugal speed controller.

2.2. The Method Used for Registering and Processing Data

Operating parameters are usually measured by the monitoring system for the operating parameters located at the research station or in the ship environment in the appropriate fields of the main switchboard (e.g., the RMS values are measured for electrical parameters) and are used to determine the external conditions for measuring instantaneous diagnostic parameters. Here, the measurement of instantaneous parameters was enabled by a diagnostic subsystem designed based on the research requirements. In these studies, a sampling frequency of 25 kHz per measuring channel was assumed, arising from the establishment of data recording that enabled the analysis of the first fifty current and voltage harmonics and provided the possibility of performing tests in accordance with certain standards, e.g., IEC 61000-4-7:2002 + AMD1:2008 CSV [20]. The instantaneous diagnostic parameters were understood to be physical quantities, e.g., phase-to-phase voltages and armature currents measured with the parameters of an analogue–digital converter that ensured the recording and analysis of instantaneous currents and voltages. When carrying out further work, one might consider increasing the sampling frequency to extend the useful measurement bandwidth to facilitate the observation of EMC disturbances in the signal and to increase the frequency resolution at low frequencies.

The flow of information from measuring the currents and voltages of a synchronous generator and the mechanical vibrations is shown in Figure 2 as the testing method definition. The subsequent levels are presented from the top to bottom as stages of the presented method for assessing the failures of a generating set.

The analysis of this research subject enabled the number of instantaneous diagnostic parameters to be limited to:

- Phase-to-phase (armature) voltages at the synchronous generator terminals: Figure 3, point 1 shows the screws to which the wires used for measuring the armature voltage were screwed;
- Armature current (wire current): Figure 3, point 2 shows one of the wires on which the armature current was measured with the current clamps;
- Excitation voltages: Figure 3, point 3 shows the terminal block to which the excitation voltage measurement leads were connected;
- Excitation current: Figure 3, point 4 shows the wire on which the excitation current was measured with the current clamp;
- Mechanical vibrations (velocity and displacement) of a ship's generating set, Figure 4.

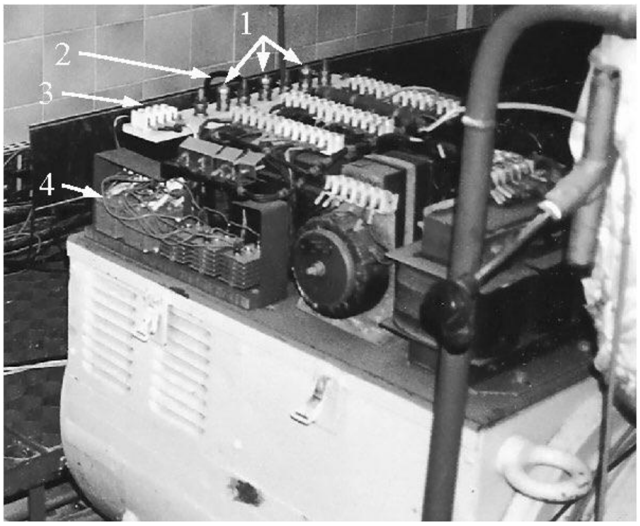

Figure 3. The WS 60 N voltage regulator with the current and voltage measuring points marked.

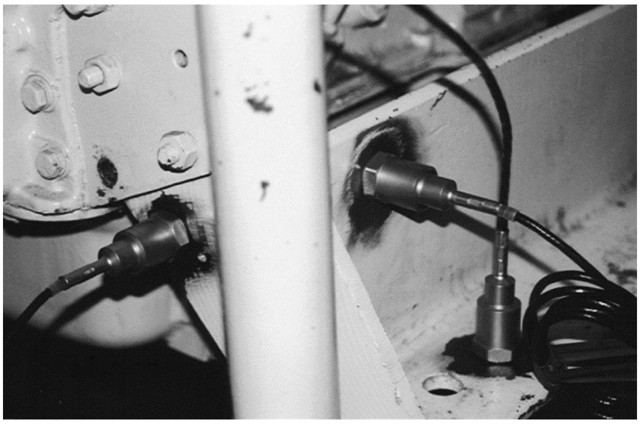

Figure 4. A view of the mounting point of the accelerometers on the foundation frame used for measuring vibrations in three directions.

The measurement subsystem used for diagnosing instantaneous diagnostic parameters (Figure 5) was based on an 8-channel A/C converter integrated with a NI CompactDAQ measuring system. The subsystem was supported by an application for analyzing the electric power quality (Figure 6), which was developed in the MATLAB programming language for the needs of the diagnostic experiment. The application enables:

- The presentation of signal time series;
- Input signal filtering;
- The determination of the signal envelope (using a Hilbert transform);
- A spectral (Fourier) FFT-based signal analysis;

- Calculations of electricity quality factors;
- Downloading signal vectors from one or more files;
- Archiving input data and performing analyses.

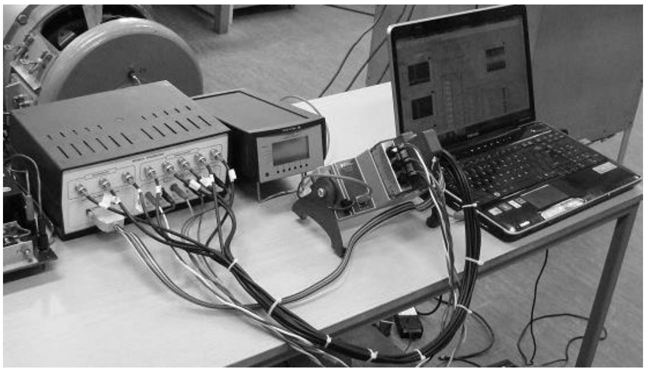

Figure 5. Modular computer subsystem used for measuring diagnostic parameters.

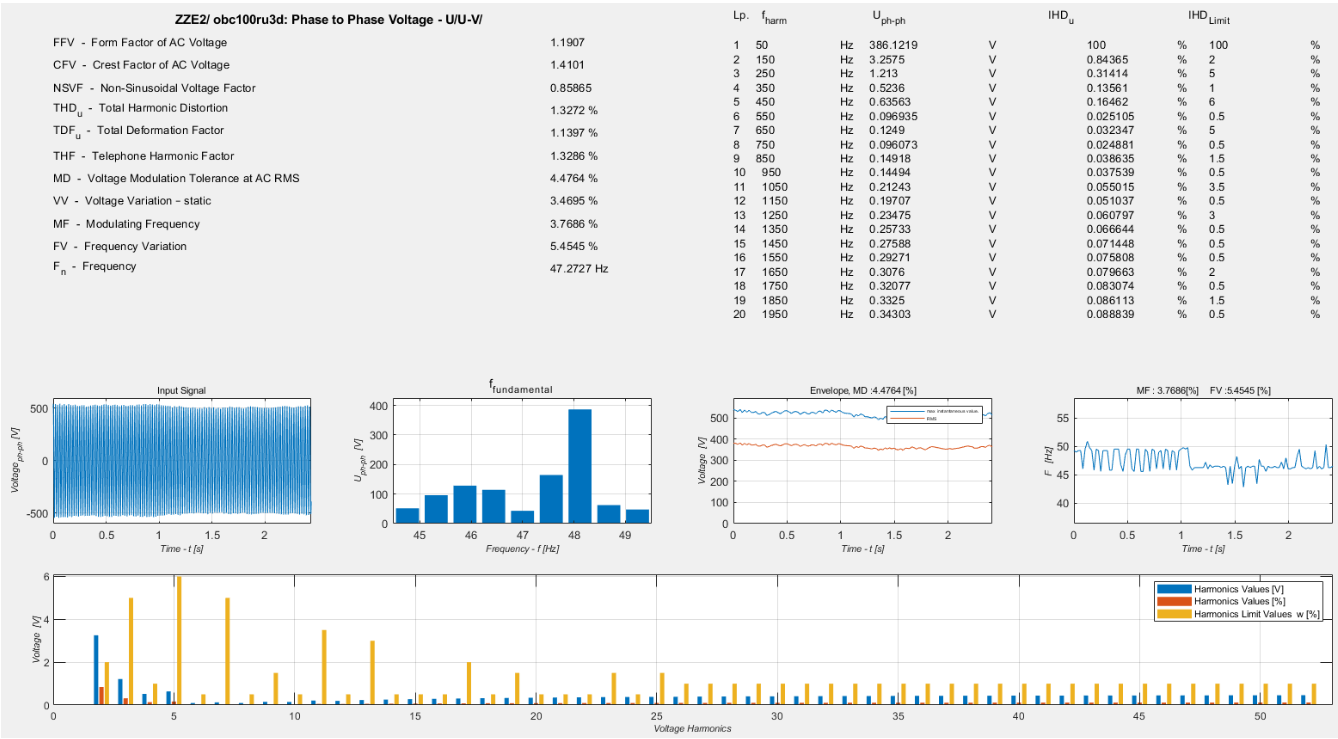

Figure 6. The MATLAB user interface of the ELPAR application: a set of analyses for synchronous generator armature voltages.

3. Description of the Research Methods

In the diesel engines that drive the synchronous generators, special attention should be devoted to phenomena causing deviations from the set speed and decreases in power in the drive shaft. In terms of the engine design, the values of these deviations are primarily determined by:

- The air supply system;
- The construction of sets and elements that determine the course of pressure in the cylinder (fuel supply system, combustion chamber);
- The system and number of cylinders, as well as their firing order;
- The moment of inertia of rotating masses (engine, flywheel, and generator).

In terms of the engine operation, the values of these deviations are determined by:

- The variable speed drive;
- The quality of the fuel supply;
- The condition of the crank system (rings, cylinders);
- The weather conditions (pressure, temperature at which the engine works);
- Other phenomena.

Due to the flexible coupling fitted between the engine drive shaft and the generator shaft, micro-phenomena such as torque pulsation resulting from the cyclicality of fuel ignition moments in the cylinders are barely visible on the synchronous generator shaft.

In synchronous generators on ships, the quality of the electricity has an impact on:

- The size and type of load;
- The method of switching the receivers operating in the ship's power system on and off;
- The governor speed controller;
- The proper fuel supply;
- The voltage regulation system.

The above failures may cause distortions in the sinusoidal signals of supply voltages delivered by the synchronous generator manifested as exceeding the permissible values of selected estimators (Table 2).

Table 2. Table of the failures, symptoms, estimators, and their limit values.

Possible Symptoms	Type of Electrical Parameter	Estimators *E*	Units	Limit Values *L*	Description
S1	An armature voltage	*VT*	[V]	400 V ± 10%	Steady-State Voltage Tolerance
S2		*VV*	[%]	10	Voltage Variation—Static
S3		*MD*	[%]	2	Voltage Modulation Tolerance at AC RMS
S4		*TRV*	[%]	15	Transient Recovery Voltage
S5		*LVUR*	[%]	7	Line Voltage Unbalance Rate
S6		*TTRV*	[s]	2	Time of Transient Recovery Voltage
S7		*FFV*	-	>1.3	Form Factor of AC Voltage
S8		*CFV*	-	>1.43	Crest Factor of AC Voltage
S9		*NSVF*	-	<0.98	Non-Sinusoidal Voltage Factor
S10		THD_u	[%]	5	Total Harmonic Distortion
S11		TDF_u	[%]	5	Total Deformation Factor
S12		*THF*	[%]	5	Telephone Harmonic Factor
S13		IHD_u	[%]	3	Individual Harmonic Distortion [21]
S14		*S-SFV*	[%]	5	Steady-State Frequency Variation
S15		*MF*	[%]	2	Modulating Frequency
S16		*FV*	[%]	10	Frequency Variation
S17		*TFV*	[s]	2	Time of Frequency Variation
S18	An armature current	*IT*	[A]	I_n ± 10%	Nominal Current Tolerance
S19		*FFI*	-	>1.3	Form Factor of AC Current
S20		*CFI*	-	>1.43	Crest Factor of AC Current
S21		h_{Di}	[%]	1	Non-Sinusoidal Current Factor
S22		THD_i	[%]	5	Total Harmonic Distortion
S23		TDF_i	[%]	5	Total Deformation Factor
S24		IHD_i	[%]	3 (≤2.3 A)	Individual Harmonic Distortion
S25	An excitation voltage	*EVT*	[V]	U_{fn} ± 10%	Nominal Excitation Voltage Tolerance
S26		*RV*	[V]	≤100	Ripple Voltage (peak-to-peak value)
S27		IHD_{ue}	[%]	3	Individual Harmonic Distortion
S28	An excitation current	*EIT*	[A]	I_{fn} ± 10%	Nominal Excitation Current Tolerance
S29		*RC*	[A]	1.2	Ripple Current (peak-to-peak value)
S30		IHD_{ie}	[%]	3	Individual Harmonic Distortion

3.1. Development of a Set of Power Quality Factors

The first step aimed at determining the set of electricity quality factors was an analysis of the following classification society rules and studies from the literature: Lloyds Register of Shipping [22]; Det Norske Veritas [23]; Polish Register of Shipping, Part VIII: Electrical Equipment and Automation [24]; Polish Register of Shipping, Part VIII: Electrical Installations and Control Systems [25]; American Bureau of Shipping [26]; Testing and Measurement Techniques—Power Quality Measurement Methods [27]; Electrical Installations in Ships—Definitions and General Requirements [28]; Potential Hazards of Excessive Harmonic Distortion of Currents and Voltages of Onboard Electrical Systems [29]; Characteristics of Shipboard Electrical Power Systems in Warships of the North Atlantic Treaty Navies [30]; Measuring Relays and Protection Equipment [31]; A Review of Ship Microgrids: System Architectures, Storage Technologies, and Power Quality Aspects [18]; A Review of Legal Aspects of Electrical Power Quality in Ship Systems in the Wake of the Novelization and Implementation of IACS Rules and Requirements [32]; Power Quality Analysis for Greener Shipping by Implementing an On-Board Electric Power Quality Monitoring System [33]; Shipboard Power Quality Problem: What It Is, What Causes It, Effects of It, and Technologies to Correct It [34]; Impact of Harmonic Currents of Nonlinear Loads on Power Quality of a Low-Voltage Network–Review and Case Study [35]. On this basis, the sensitivity potential of the selected coefficients for causing potential failures in the generating set elements was determined. On the basis of the measurements of the instantaneous values of the diagnostic parameters, the symptoms (power quality coefficients and malfunctions of individual elements of the device) were determined. The quality of the electricity is determined by:

- Deviations in voltage and current;
- Fluctuations in voltage and current;
- Changes in frequency;
- The proportion of higher harmonics in the voltage and current waveforms;
- The symmetry of the multiphase systems.

It was assumed that good energy quality occurs when these parameters are close to the nominal values, and we can consider the energy quality as sufficient when these parameters do not exceed the limits permitted by the regulations, standards, and our own tests. The generating set can then be rated as capable of generating energy with the specified parameters.

The deviation of the quality parameters beyond the limit values leads to an electricity supply of insufficient quality, while exceeding the specified limit states for individual coefficients qualifies the generating sets as unfit for purpose. Significant deviations in quality parameters are equated with failure, because the recipient will not be able to make use of the electricity due to its insufficient quality. The set of symptoms based on the power quality coefficients selected for assessing the technical condition of the generating set is presented in Table 2.

3.2. Theoretical Model of Fault Assessment

The preparation of the mathematical framework of the diagnostic inference process is the basic stage in developing a diagnostic model. Let us assume a model of a diagnostic system based on a black box, where we have input n in the form of disturbances (failures) of the parameters pertaining to the correct operation of the monitored machine:

$$F = \{f_i : i = 1 \dots n\} \quad (1)$$

as well as output m with the following symptoms:

$$S = \{f_j : j = 1 \dots m\} \quad (2)$$

which we assume (e.g., on the basis of a functional analysis of the machine or expert knowledge) to be diagnostically sensitive, i.e., to react to emerging or given (in the case of an active experiment) failures. The symptoms were selected based on an analysis of the literature—including standardization documents, our own experience, and previous research—or arbitrarily in order to check the sensitivity of the symptoms that were adopted. Symptoms (S) are features of diagnostic signals with specific values. While conducting an active experiment, one (1) can determine what the failures will be. During the experiment, certain failures (F) were assumed from the amount of n; these are listed in Section 4.2. Table 1 presents a list of the estimators that were adopted, which assume numerical values resulting from calculations according to specific rules concerning the measurement values. These estimators can be called diagnostic signals, which will, by comparison with the permissible or limit values, eventually assume a binary value (0 or 1). Depending on whether the limit values have been exceeded (reached), they either assume a binary value of 1, or in the case where the determined values of the estimators are within the adopted limits, they assume a binary value of 0.

In this way, for [36] we obtain a Cartesian two-dimensional plane with n rows and m columns pertaining to $RFS \subseteq F \times S$. Ultimately, a V matrix [37,38] is created with dimensions $n \times m$ and the individual elements of this matrix assume the values $v_{i,j}$. In [39], it is assumed that this may be called a binary diagnostic matrix or *BDM*.

This matrix can be presented as a set of failures determined on the basis of symptoms, where the lines of J (for a specific fault, you can specify a unique sequence of symptoms that occur only for that fault) look like this:

$$F(s_j) = \{f_i \in F : v(f_i, s_j) = 1\} \forall i \in \{i \ldots n\}; \\ \forall j \in \{j \ldots m\} \tag{3}$$

The I columns (specific symptoms may exist for different failures) appear as follows:

$$S(f_i) = \{s_i \in s : v(f_i, s_j) = 1\} \forall i \in \{i \ldots n\}; \\ \forall j \in \{j \ldots m\} \tag{4}$$

Thus, the *BDM* matrix consists of rows that represent symptoms (in the case of this work, 30 symptoms were determined, n = 30; Table 1) and columns that represent failures (which were specified later in this work, m = 7; Section 4.2). The generally adopted form of a matrix is given below:

$$V = \begin{bmatrix} S_{11} & \cdots & S_{1m} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nm} \end{bmatrix} \tag{5}$$

Examples of diagnostic matrices developed within the ongoing work are presented in Section 4.2. For the purposes of this research, a matrix of $n \times m$ = 30 × 7 = 210 elements is prepared in this work.

For symptomatic diagnostics, the process of diagnostic inference is carried out, consisting of searching for unknown values of technical conditions (in particular unsuitability) on the basis of known values of diagnostic parameters (symptoms):

$$S \geq Z \tag{6}$$

where S is a symptom of the technical condition of Z, and:

$$S \geq F \tag{7}$$

where S is a symptom of a given fault F.

In the case of model-supported diagnostics, it is assumed that we have a model of a technical object. Usually, the mathematical model of the object is considered. The model can represent the correct operation of an object or the operation of this object in the event of a certain malfunction.

Diagnosing the technical condition consists of comparing selected quantities (feature values) obtained from the model of the object and the real object (Figure 7).

Based on this comparison, the so-called residua can inform us about the occurrence of faults in the diagnosed technical facility. The calculation of the residues is as follows:

$$R = |E - N| \tag{8}$$

where E is the value of the estimator for each possible symptom and N represents the nominal values for each possible symptom, e.g., 400 V for the steady-state voltage tolerance (*VT*), 1.11 for the form factor of the AC voltage (*FFV*), and 1.414 for the crest factor of the AC voltage (*CFT*).

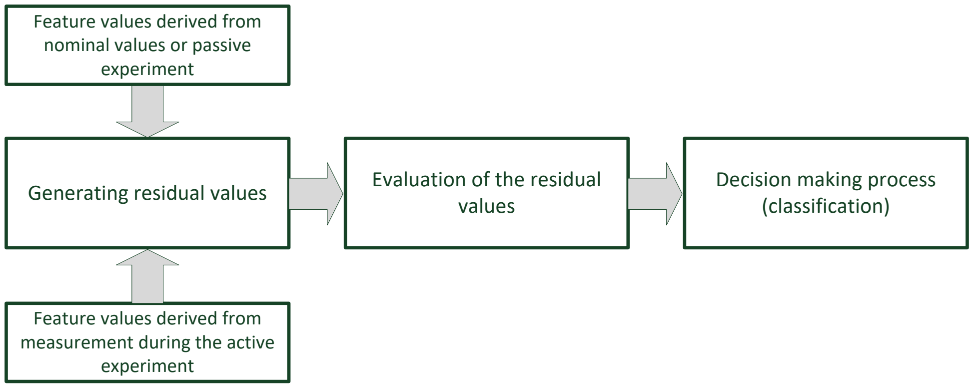

Figure 7. Diagram of the process of generating the residual values.

This work uses a two-state binary classifier to predict one or two possible outcomes. A two-class problem (binary problem) has the possibility of only two outcomes—"yes or no", "success or failure", "1 or 0". The evaluation of the residue value with the use of the mathematical condition statement takes the following form:

$$R > |E - L| \to 1 \text{ and } R < |E - L| \to 0 \tag{9}$$

where L represents the limit values for each possible symptom; 1 is used when the estimator is susceptible to failure and is qualified as a symptom of a given fault; 0 is used when the estimator is insensitive to damage and is not qualified as a symptom of a given fault, and in the equation of the fault–symptom relation it is omitted.

For example, the $\boldsymbol{F_3}$ failure (fault in the governor speed controller) identifies the following symptoms:

$$\boldsymbol{F_3}(S_1, S_2, S_3, S_9, S_{14}, S_{15}) = 1 \tag{10}$$

4. Research Results and Discussion

Determining the generating sets' capability to generate the electricity of the required quality was a necessary condition for conducting the active experiment. Based on the tests carried out, the generating sets tested were determined as fit for purpose and the power quality factors were within the assumed limits.

4.1. The Passive Experiment

A passive experiment involves a means of observing a phenomenon without outside interference. The purpose of the passive experiment was to determine the technical condition of the generating sets tested and the quality of electricity based on the factors adopted.

4.2. The Active Experiment

An active experiment includes a method for studying a phenomenon, consisting of planning the interference from the outside and then observing the changes this interference will cause. The purpose of the active experiment was to determine the symptoms (fault-oriented measurement quantities) and to obtain information not only about the condition of the electric power supply set tested, but also about what damaged element or system was determined as being in a non-functional state.

The active experiment involved a real generator set being subjected to all failures by carrying out actual damage or changes to the actual elements of the tested generating set.

Interviews were conducted on ships and in shipyards to obtain information on the typical failures incurred by ZE-400 generating sets. After analyzing these data and comparing them with information obtained from experienced operators of generating sets (ship and shipyard engineers), as well as on the basis of the previously mentioned literature and [40,41], the following failures in the generating sets were selected for the active experiment:

1. Short circuit of the rectifier element (diode) in the voltage regulator of the synchronous generator: fault no. 1, $\boldsymbol{F_1}$—the fault involved short-circuiting one rectifying diode in a real automatic voltage regulator of a synchronous generator;
2. Break in the rectifier element (diode) in the voltage regulator of the synchronous generator: fault no. 2, $\boldsymbol{F_2}$—the fault involved opening the circuit of one rectifying diode in a real automatic voltage regulator of a synchronous generator;
3. Fault in the governor speed controller (GSC) by changing the gradient of the regulator's static characteristic (slower response to effect of changes in load on the rotational speed controller in the SW-400 piston internal combustion engine): fault no. 3, $\boldsymbol{F_3}$—the fault involved deregulating the regulating elements in the actual automatic regulator of the rotational speed of the internal combustion engine driving the synchronous generator;
4. Fault to the governor speed controller (GSC) by breaking the spring of the rotational speed controller of the SW-400 piston internal combustion engine: fault no. 4, $\boldsymbol{F_4}$—the fault involved cutting the spring in the actual automatic speed regulator of the internal combustion engine driving the synchronic generator;
5. Loosening one of the generating set's anchor points to the foundation: fault no. 5, $\boldsymbol{F_5}$—the fault involved physically unscrewing one of the four bolts securing the frame of the actual generator set to the foundation;
6. Disruption (cut-off) in the fuel supply to an injector in cylinder no. 1 of the SW-400 piston diesel engine: fault no. 6, $\boldsymbol{F_6}$—the fault involved physically cutting off the fuel supply (by closing the valve previously installed on the fuel line) to the injector of the combustion engine driving the synchronous generator;
7. Disruption (cut-off) in the fuel supply to two injectors in piston numbers 1 and 6 of the SW-400 piston diesel engine: fault no. 7, $\boldsymbol{F_7}$—the fault involved physically cutting off the fuel supply (by closing the valves previously installed on the fuel lines) to the injectors on cylinders 1 and 6 of the actual internal combustion engine driving the synchronic generator.

The research conducted during the active experiment consisted of the consecutive simulation of failures and the multiple registration of diagnostic parameters (Tables 1 and 2) before and after the failures occurred. Then, the impacts of the failures on the selected electricity quality factors was analyzed. As an example of the implementation of a section of the research conducted during the active experiment, the following failures were selected.

4.2.1. The Active Experiment: Fault of the Diesel Engine Governor Speed Controller—$\boldsymbol{F_3}$

The fault consisted of changing the gradient of the regulator's static characteristics (slower response to load changes). The test was carried out at idle speed and at the rated power load P_n. Fault $\boldsymbol{F_3}$ is an example of designated symptoms being susceptible to this type of fault—the estimated values obtained during the tests exceeded the limit values (in the binary of the diagnostic matrix they then changed the value from 0 to 1).

In both cases, the following parameters were measured:

- An armature voltage (phase-to-phase voltage at the synchronous generator terminals): $U_{U\text{-}V}(t)$, $U_{V\text{-}W}(t)$, $U_{W\text{-}U}(t)$;
- An armature current: $I_1(t)$, $I_2(t)$, $I_3(t)$;
- An excitation voltage: $V_e(t)$;
- An excitation current: $I_e(t)$.

For measurements carried out at idle speed, the following phase-to-phase voltage (Figure 8) coefficients were exceeded: S_1, S_2, S_3, S_9, S_{14}, and S_{15}. The armature current, voltage, and excitation current coefficients for the simulated fault selected for testing were found to be within acceptable limits. Therefore, the symptoms listed for failure $\boldsymbol{F}_3$ assume a binary value of 1 in the matrix; for the other symptoms (coefficients), no deviations from the standard waveforms were found to exceed the permissible levels. Therefore, the binary value was taken as 0. According to Equation (3), the subsets of failures $\boldsymbol{F}_3(s_j)$ indicated by the corresponding values of the diagnostic signals sj that were determined by comparing the values of the estimators with their limit values for the excitation voltage presented in Table 3 are as Equation (10) and follows:

$$\boldsymbol{F}_3(S_{4-8}, S_{10},\ S_{11-13},\ S_{16-30}) = 0 \tag{11}$$

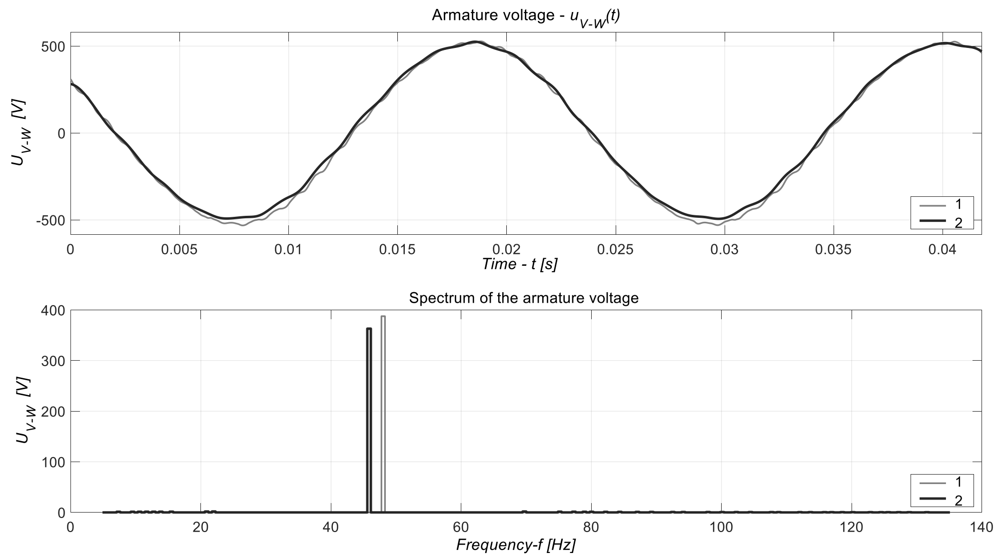

Figure 8. Phase-to-phase voltage $U_{V\text{-}W}(t)$: fault no. 3 to the governor speed controller. Load rate 100% P_n: 1, rated signal; 2, signal during the breakdown.

Table 3. The armature voltage for GSC fault no. 3, $\boldsymbol{F}_3$.

Symptoms	Factors	Units	Measurement Values	Limit Values	Binary Value	Fault No. 3
S1	*VT*	[V]	356.8	>360 and <440	1	
S2	*VV*	[%]	10.8	10	1	
S3	*MD*	[%]	2.06	2	1	$\boldsymbol{F}_3$
S9	*NSVF*	-	0.93	<0.98	1	
S14	*S-SFV*	[%]	5.7	5	1	
S15	*MF*	[%]	5.26	2	1	

This means that the symptoms indicated in Equation (6) turned out to be susceptible to breakdown, and assuming the value of 1, exceeded the adopted limit values. Analogical indications were adopted for the remaining failures.

For the measurements carried out at the rated power load of 100% P_n, the factors listed in Table 3 were exceeded.

Figure 8 shows one of the armature voltages, $U_{V\text{-}W}(t)$, with a fragment of its waveform and spectrum. In the figure, we can see the changes in the voltage and frequency amplitudes. The figure shows the reduction in the armature voltage and the reduction in its frequency (see Table 3). A detailed analysis with the use of adopted estimators and a binary diagnostic matrix allowed us to significantly increase the level of useful information and assign a set of symptoms to a specific fault like in Equation (10).

4.2.2. The Active Experiment: Loosening One of the Generator Set's Mounting Points to the Foundation—F_5

Fault F_5 is an example of designated symptoms not being susceptible to this type of fault—the estimator values obtained during the tests do not exceed the limit values. In the binary diagnostic matrix, they do not change value from 0 to 1.

The example below shows the lack of diagnostic sensitivity of the assumed symptoms to the simulated failure. The fault involved unscrewing the screw securing the set to the foundation. During the simulation of the damage to the bolt securing the set to the foundation, the following parameters were tested (at idle speed and rated load P_n):

(a). The phase-to-phase voltage at the synchronous generator terminals;
(b). The excitation voltage;
(c). The mechanical vibrations of the generating set at one point of the foundation.

Increasing the vibration level in the cases of phase-to-phase voltage and excitation voltage did not result in exceeding the permissible values for the selected coefficients.

However, for the mechanical vibrations, the simulated fault caused a change in the effective values in the vibration velocity spectrum. Figure 9 shows a decrease in the value of the vibration velocity for the longitudinal axis X and transverse axis Y. For the vertical axis Z, an increase in the value of the vibration velocity can be seen. All harmonics of the vibrations recorded during the failure occurrence were wider, which may indicate greater changes in frequency, as well as showing symptom *S14* (steady-state frequency variation). The solution may be to identify new additional symptoms from the estimators based on the vibration parameters.

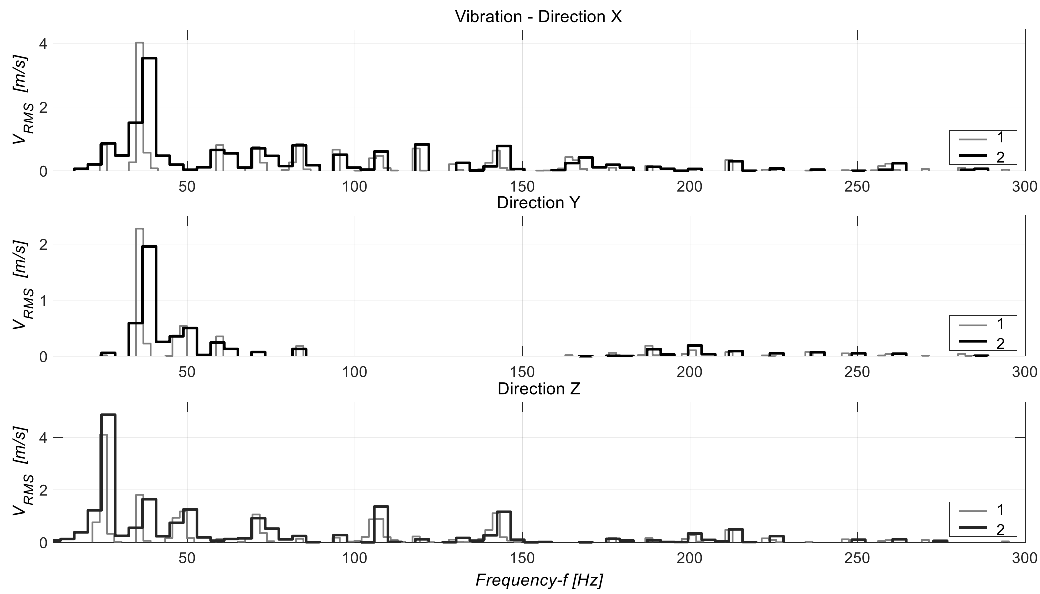

Figure 9. The fault at point 4 where the foundation frame is mounted to the ground—spectrum of the effective vibration velocity value: 1—rated signal; 2—signal during the breakdown.

The non-susceptible estimator (not responding to the given machine fault) does not exceed their limit values, despite the failure. Not a single symptom has a binary value of one in the *BDM*. The corresponding symptoms in the *BDM* (Table 4) are as follows:

$$F_3(S_1, \ldots, S_{30}) = 0 \quad (12)$$

Table 4. The binary elements of the binary diagnostic matrix (*BDM*) determined as a result of the experimental studies.

Possible Symptoms	FAILURES F_1	F_2	F_3	F_4	F_5	F_6	F_7
S_1	1	0	1	1	0	1	1
S_2	1	0	1	1	0	1	1
S_3	1	0	1	0	0	0	1
S_4	1	0	0	0	0	0	0
S_5	0	0	0	0	0	0	0
S_6	1	0	0	0	0	0	0
S_7	1	0	0	0	0	0	1
S_8	1	0	0	0	0	0	0
S_9	1	0	0	0	0	0	1
S_{10}	0	0	0	0	0	0	1
S_{11}	0	0	0	0	0	0	0
S_{12}	0	0	0	0	0	0	0
S_{13}	0	0	0	1	0	0	0
S_{14}	0	0	0	0	0	0	0
S_{15}	1	1	1	1	0	0	1
S_{16}	0	0	1	1	0	0	1
S_{17}	0	0	0	0	0	0	0
S_{18}	1	0	0	0	0	0	0
S_{19}	1	0	0	1	0	0	0
S_{20}	1	0	0	0	0	0	0
S_{21}	1	0	1	0	0	0	0
S_{22}	0	0	0	0	0	0	0
S_{23}	0	0	0	0	0	0	0
S_{24}	0	0	0	0	0	0	1
S_{25}	1	1	0	0	0	0	0
S_{26}	1	1	0	0	0	0	0
S_{27}	1	1	0	0	0	0	0
S_{28}	1	0	0	0	0	0	0
S_{29}	1	1	0	0	0	0	0
S_{30}	1	1	0	0	0	0	0

Figure 9 illustrates that the differences are slight between characteristic 1 (no fault) and characteristic 2 (fault involving the physical disassembly of one bolt securing the generator set to the foundation frame) and that none of the symptoms exceed the limit values and have a value of 0. This is an example of a fault to which symptoms are not susceptible, as reflected in Equation (12). Whenever the symptom is susceptible to a fault, it assumes a logical value of 1 in the *BDM* (when a given failure causes the symptom limit values to be exceeded), and when the symptom is not susceptible (i.e., when the failure does not exceed the symptom limit values) it has a value of 0 (zero) in the *BDM*. This is clearly observable in Table 4—all $\boldsymbol{F_5}$ failure symptoms have a value 0. Using the set of symptoms presented in Table 1, based on the parameterization of the armature voltage and current, as well as the excitation voltage and current, it is not possible to recognize this fault. What is the answer? During further research, the set of "electrical" symptoms may be extended to include "mechanical" symptoms, e.g., based on vibration estimation.

4.3. The Binary Diagnostic Matrix and Discussion of the Results

The results of the active experiment obtained by examining the fault–symptom correlation are presented in tabulated form separately for each diagnostic parameter (Tables 1 and 2). The coefficients that manifested diagnostic sensitivity to specific failures were classified as symptoms and marked with 1. As previously mentioned in Section 4.2.2, whenever the symptom is susceptible to fault, the *BDM* cell assumes a logical value of 1 (when a given fault causes the symptom limits specified in column 4 of Table 1 to be exceeded), and when the symptom is not susceptible (i.e., when a given fault does not cause the symptom limit values specified in column 4 of Table 1 to be exceeded), the *BDM* cell has a value of 0 (zero). The analysis shows that each fault has a different set of coefficients (symptoms), which makes it possible to clearly identify the specific fault.

This research managed to determine the structure of the set of symptoms susceptible to the fault simulated during the active experiment. The results are shown in Equation(13). For better orientation in the context of the matrix consisting of 210 elements, these results are presented in tabular form (Table 4). Based on the experimental studies and the summary of the symptoms presented in Table 4, the binary elements of the binary diagnostic matrix *BDM* were determined.

According to Equation (5), the binary diagnostic matrix named V takes the below binary values determined in an active experiment.

$$V = \begin{bmatrix} \mathbf{1} & \mathbf{0} & \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{1} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} & \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{1} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{1} & \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{1} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{1} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} \\ \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \quad (13)$$

The following columns contain the binary responses of the examined symptoms to the damage inflicted (1—the symptom is sensitive; 0 the symptom is insensitive). The main purpose of running diagnostic tests on the synchronous ship generator was to assess the ability of the electric power supply set to produce electricity of the required power quality based on the fault–symptom correlation.

The research consisted of developing a method for classifying generating set failures based on the relationship between the faults and symptoms. The symptoms were assumed to be the power quality coefficients for which limit values were defined. A set of 30 symptoms were determined, calculated from the waveforms of the armature voltage and current, as well as the excitation voltage and current. The failures were selected from the experiences of employees who repair power sets in a shipyard. The active experiment was carried out in such a way that generating set elements were physically subjected to selected failures one at a time during operation or before start-up, and the limit values were monitored to see if they had been exceeded. If, during the operation of the damaged generating set, the symptom limit value is exceeded, this means that the symptom is susceptible to faults and has a logical value of 1. If, during the operation of the damaged generator set, the symptom limit value is not exceeded, this indicates that the symptom is not susceptible to fault and has a value of logical 0. The results of the experiment were placed in a binary diagnostic matrix (*BDM*) where the lines are possible symptoms and the columns are failures. The result is a synoptical table showing the zero–one (binary) fault–symptom relationship, which enables the fault to be classified based on the observation of symptom limit values, which are a set of electricity quality coefficients.

The ability of the electric power supply set to produce electricity of the required quality was the basis for conducting an active experiment, the purpose of which was to select the quality factors of electricity that are susceptible to specific failures in the set.

After a detailed analysis of the test results, it was found that the values of the electrical energy quality coefficients carry information about failures not only of the ship's synchronous generator, but also about the SW-400 piston engine that propels it.

The coefficients related to the harmonics of the voltage and current waveforms S_{11} (*TDFu*), S_{12} (*THF*), S_{17} (TFV), S_{22} (*THDi*), and S_{23} (*TDFi*) did not exceed the assumed limit values, but indicated diagnostic sensitivity (while observing the signal, clear deviations from the simulated damage were noted). Therefore, in further tests the amounts by which the accepted values were exceeded in the tests should be determined. These symptoms were left in the table due to their diagnostic potential for the next stage of the study.

5. Conclusions

It is commonly assumed that power disturbances are a natural phenomenon related to the power network environment in which they occur, consisting of various elements such as energy sources, receivers, energy converters, control elements, and transmission cables. The main approach focuses on their elimination through the widespread use of harmonic filters, or in the case of [11] by changing the grid system to an AC/DC hybrid. The approach presented in the article focuses on the detection of failures in the elements of the electromagnetic network with the use of PQ coefficients as estimators. The method was presented based on an example of the classification of failures in generating sets, but it can also be used for breakers, DC/AC and AC/DC converters, and AC electric motors to show faults across the entire machine. Secondly, it will allow the power quality of the energy to be maintained (a passive experiment conducted before the active experiment allows one to state whether the PQ coefficients are within the permissible values).

Regarding the application, we can imagine a producer of generating sets (let us assume that they produced them in a large series) who receives information that some of them are not maintaining their operating parameters (e.g., the frequency, due to the incorrect slope of the static characteristic of the speed controller) and may cause faults in other network components. The article presents a complete, successfully tested method that can be automated and implemented in miniature measurement systems directly mounted on the generator set (or other network elements) for the online and real-time monitoring of failures identified as frequent, and at the same time for monitoring the power quality of the electricity. Thus, the generator set (or another network element to which the procedure contained in the described method is applied) becomes diagnostically oriented with an integrated self-diagnostics system—it increases its reliability (from the point of view of the customer) and commercial value (from the point of view of the producer).

There are limitations to the method described in this article. Due to the labor consumption involved in carrying out the entire test cycle along with the passive and active experiments, the method is most suitable for implementation in miniature IoT modules of generating sets (or other electric machines and devices after the test cycle) produced in long series or for monitoring potential large and costly failures to critical machinery, such as the electric propulsion system of a ship. Changing the model of the machine assessed by the presented method may result in the need to change the set of estimators based on the PQ coefficients. Software used for monitoring critical conditions of machines was previously developed, tested, and published in [42,43].

This study was based on ships' generating sets, but can also be applied appropriately to other transport vehicles, such as electric aircrafts, hybrid aircrafts, electric cars, and electric trains.

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Glossary

AC	Alternating-current power supply system
BDM	Binary diagnostics matrix
CFV	Crest factor of AC voltage—the ratio of its peak value to the RMS value, an important parameter for monitoring the occurrence of pulses or short-term voltage spikes. Crest factor = 1.414, but based on my research I put the limit value at more than 1.43 in Table 1
EMC	Electromagnetic compatibility disturbances
EVT	Nominal excitation voltage tolerance
EVT	Nominal excitation current tolerance
DC	Direct-current power supply system
FFV	Form factor of AC voltage—the ratio of the root mean square (RMS) value to the average value, an important parameter for monitoring the quality of the waveform. Form factor = 1.11, but based on my research I put the limit value at more than 1.3 in Table 1
FV	Frequency variation—the maximum allowable value frequency deviation (the change over time) from the rated frequency (nominal) during normal operation, excluding transient and modulation signals.
IoT	Internet of Things
Industry 4.0	Technology refers to the fourth industrial revolution, which is the cyber–physical transformation of manufacturing
IT	The IT-mode AC power supply system I indicates that the power supply side has no working ground or is grounded at high impedance. The letter T indicates that the load side electrical equipment is grounded (commonly used on ships).
MF	Modulating frequency—change in the value of the instantaneous frequency of the carrier wave
NSVF	Non-sinusoidal voltage factor: the RMS of the fundamental harmonics to the RMS of the whole voltage signal. The NSVF is equal to 1 in the absence of harmonics in the voltage waveform. Based on my research I put the limit value at less than 0.8 in Table 1
PQ	Power quality coefficients
RMS	Root mean square value
RV	Ripple voltage (peak-to-peak value)
S-SFV	Steady-state frequency variation—the maximum value expected of the frequency deviation at which the system frequency is designed to be stabilized after the occurrence of load changes
TFV	Time of frequency variation—the duration of the frequency variation

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