Measurement and analysis of electric power quality indicators with targeted identification of the perpetrators of non-compliances on the example of the Belarusian energy system

Mikhail Drako[1*], *Aleh* Maiseyenka[1], and *Viachaslau* Kolik[1]

[1]Scientific-Research Project Republican Unitary Enterprise Belenergosetprojekt (RUE Belenergosetprojekt), 5, 1st Tverdy lane, Minsk, 220038, Republic of Belarus

Abstract. The existing problems of ensuring the established [1] standards of electric power quality indicators (EPQI) in electric networks of different nominal voltage are considered. The authors' practical experience in identifying the perpetrators of non-compliances in terms of non-sinusoidal voltage with the determination of their actual contributions (AC) based on the results of measurements made by their own accredited electrotechnical laboratory is summarized.

Introduction

The specificity of electric energy (EE) as a commodity lies in the fact that the quality of electricity (QE) in the electrical grid is generally influenced by all subjects of the electric power industry: power plants, electric networks, and consumers. At the same time, claims for improper QE in most cases are addressed to the energy supply organization (ESO) from consumers, who often themselves are the perpetrators of the deterioration of EPQI.

1 Regulatory and technical support

The fundamental regulatory and technical document in the field of QE is [1]. For long-term changes in the voltage characteristics [1] defines the EPQI and sets their norms; for random events, it provides reference values.

The scope of application [1] covers the transmission points of EE to users of electric networks.

In [2], the main provisions on the organization and conduct of EPQI control are established in order to determine their compliance with the standards established in [1].

The methods of measuring EPQI are defined in [3, 4]. In [3], the requirements for measuring EPQI are also given.

Methods for analyzing EPQI, determining the perpetrators of non-compliances and their AC are regulated in [5] - in the Republic of Belarus, [6] - in the Russian Federation.

[7] and [8], contain ESO recommendations for determining the requirements for connecting distorting installations.

2 Reasons for non-compliances with the EPQI. Targeted identification of perpetrators. Corrective (normalizing) measures

2.1 Frequency deviation

The non-compliance is practically not observed in the unified energy system and is not considered in this article.

2.2 Slow voltage changes

The perpetrators of non-compliances in terms of positive and negative voltage deviations are generally ESOs. For example, unacceptable negative voltage deviations occur when the electrical network has insufficient capacity. The most effective corrective measures are: strengthening the electrical network and improving dispatching control.

2.3 Non-sinusoidal voltage

Higher voltage harmonics in electrical networks are caused by the emission of higher current harmonics by distorting electrical receivers and converter devices with a nonlinear volt-ampere characteristic (VAC). The methodology of targeted identification of the perpetrators of non-compliances related to higher harmonics and calculating their AC, as mentioned above, is outlined in [5, 6]. The AC are compared to permissible contributions (PC). By default, the PC is equal to the limit norm [1]. The excess of the AC over the PC indicates that this source is the perpetrator.

* Corresponding author: m.drako@besp.by

Chokes, passive and active filters, and filter-compensating devices are used to combat higher harmonics. Separation transformers with one of the winding connections in a "triangle" configuration can be used for harmonics with orders that are multiples of the number three.

Passive filters are tuned to filter a certain higher harmonic, while active filters operate across the entire spectrum of higher harmonics. The filter-compensating device (FCD) combines the functions of filtering higher harmonics and compensating for reactive power.

2.4 Voltage asymmetry in three-phase systems

In low voltage electrical networks, voltage asymmetry most often occurs when single-phase consumers are incorrectly distributed in phases, when the operation mode is not full-phase during the single phase-to-ground fault (SGF), and due to improper network conditions, primarily contacts. In networks of 10(6) kV and above, different phase parameters can also cause unbalance (for example, different capacities due to non-transmission lines, PTL).

If non-compliances in asymmetry are detected, an audit of the nearest sections of the electrical network should be carried out and, for 0.4 kV PTL, a redistribution of single–phase consumers by phases should be carried out. If the asymmetry non-compliances persist after this, the perpetrators should be identified with the determination of their AC (using the same method as for higher harmonics, in accordance with [5, 6]).

Special balancing devices are used to eliminate asymmetry. For example, 6-20/0.4 kV transformers with Y/Z_H winding connection schemes, as well *as* Z/Z_H with a balancing device are effectively used in 0.4 kV networks.

2.5 Voltage fluctuations and flicker

The cause of flicker as a rule the sharply variable load of consumers with insufficient "network strength" to external influences and interference. The network strength is characterized by the short-circuit power (SC). The characteristic of a distorting source by the degree of its distorting effect at this particular point in the network is characterized by the SC ratio, calculated expressions are given, for example, in p. 3.10 [9].

Targeted identification of the sources and perpetrators of the flicker should generally be performed in the same way as for rapid voltage changes. It is recommended to rely on p. 4.6.3 [5]. At the same time, the more complex but effective methods proposed in [10] are of significant interest due to the wide spread of non-compliances related to flicker in electrical networks of all rated voltages. These methods are similar to the methods of identifying sources of higher harmonics and asymmetry in accordance with [5, 6]: the perpetrators and their AC should be determined by current interharmonics or current derivatives. In our opinion, the methods proposed in [10] require practical testing before widespread application.

2.6 Dips and overvoltages

The causes of dips and overvoltages can be, on the one hand, SGF and SC, disconnections of PTL and regulating devices in electric power grids of the ESO, on the other hand, abrupt load changes in consumer networks.

It is not possible to present a single formalized algorithm for identification of perpetrators. In our opinion, it is necessary to establish an empirical correlation between rapid voltage changes and events in the electric networks of ESO and consumers.

To prevent these non-compliances, it is necessary to strengthen the network scheme, increase its reliability of operation, and develop its active-adaptive characteristics.

If consumers are the perpetrators, work should be carried out with them to limit their electromagnetic effects that affect the occurrence of these non-compliances (with the possible application of standards [9, 11]).

2.7 Pulsed overvoltages

The causes of pulse overvoltages are lightning strikes and switching in electrical networks. In the specialized literature, electrostatic discharges and the consequences of a nuclear explosion are also called. The equipment is protected from pulsed overvoltages using special protective or limiting devices.

3 Measuring instruments

In [3] and [4], the measuring instrument (MI) refers to EPQI analyzers. At the same time, when connecting the EPQI analyzer to secondary circuits, not only the EPQI analyzer, but also the measuring current transformers (CT) and voltage transformers (VT) are MI and elements of the measuring channels. In this case, the requirements for CT and VT are not lower than for telemetry systems.

The characteristics of MI used for measuring higher harmonics and interharmonics are defined in [3].

When measuring short-term and long-term doses of flicker in accordance with [13], EPQI analyzers using a class F1 flickermeter should be used. Class F3 flickermeters can be used for monitoring EPQI. It is important to note that if the EPQI analyzer includes a flickermeter function, then the use of a separate flickermeter is not required.

The EPQI analyzer should provide measurement of the operating parameters of the electrical network: voltages and currents of higher harmonics (or corresponding non-sinusoidal coefficients), phase shift angles (primarily between currents and voltages) or (and) powers of higher harmonics.

For portable EPQI analyzers, a set of current clamps of various ratings must be provided to ensure proper measurement accuracy. Current clamps must be connected without breaking current circuits (according to the principle of a Rogovsky coil or similar). It is also preferably that it is possible to download primary measurements (instantaneous values of phase currents and voltages) in a displayed format, for example, in EXCEL.

4 Measurement

As indicated above, the measurement of normalized EPQI is performed in accordance with the requirements of [1]. In addition, the measurements of non-normalized EPQI and operating parameters of the electric network required for the analysis of EPQI are regulated in [5] and [6].

When connecting EPQI analyzers to secondary current and voltage circuits, secondary circuits of CT and VT must be turned on for measuring or accounting for EE (without breaking the current circuits).

Currents, voltages and angles between them should be measured by the same MI. Based on this, it is advisable and convenient to connect the analyzer in the EE metering cabinet or telemetry cabinet, where there are current and voltage circuits.

During measurements, it is necessary to assess the reliability of measurement results. Unreliable measurement results may be obtained due to a number of reasons: incorrect operation of the MI, errors in the connection scheme, improper measurement conditions, errors in the analyzer configuration. In our practical activities, we use two main approaches to assessing the reliability of measurement results:

1) comparison of measured values with the same values obtained from the EM (electricity meter), telemetry equipment, and protection terminals;

2) assessment of the reliability of measurement results from the point of view of known physical laws and accumulated observation results.

According to the standards [5, 6], in order to identify sources of higher harmonics and voltage asymmetry at a certain point in the electrical network, simultaneous measurements should be carried out at all outgoing electrical connections with averaging for every 3 seconds. But, first, only a small part of the EPQI analyzers measures the current and power vectors of higher harmonics and averages them over a time interval of 3 s. Second, the number of electrical connections extending, for example, from a 10 kV power rail section can be about 12-20 or more. This means that the same number of EPQI analyzers will be required for measurements. Considering the high cost of these devices, as well as their simultaneous demand at different problem points of the electrical network, this requirement can be considered practically impossible.

In our practice, we are forced to apply the following approach. One EPQI analyzer is installed to monitor the EPQI for the entire measurement period, and its current circuits are installed for input into this power rail section or for electrical connection related to the alleged perpetrator. Cyclic monitoring of the EPQI is performed on the remaining electrical connections using 1–2 analyzers with the analyzer set for 5–10 minutes. Measurements made on all electrical connections within one cycle are taken as one-time. The calculations of AC for each connection case include the measurement results averaged over their own actual measurement intervals.

5 Analysis of measurement results. Emerging problems and possible solutions

In terms of the actual analysis of the EPQI and the presentation of its results, complex application issues also arise [5, 6]. For example, for a three-phase system, it is unclear whether to average the results of measurements and calculations by phases or to present them separately for each phase. In our opinion, we should do the latter, since the picture for different phases may generally be different.

For the analysis of EPQI, there is an urgent need for application software that can work both in delayed time mode and in the pace of the process.

6 Illustrative examples of completed work on EPQI measurement and analysis

6.1 The distorting source is a 330 kV shunting reactor controlled by magnetization (SRCM)

Such reactors have thyristor circuits with non-linear VAC in the control system and are therefore known to be distorting sources. Therefore, the technical requirements for the purchase included the following points:

1. Standards [1] should not be violated at all points of connection of the SRCM to the substation network (at the same time, the standards for 220 kV were applied to 330 kV);

2. The emission of higher harmonic currents in the 330 kV power winding with respect to the first harmonic should not exceed 3 % (taking into account the requirements of p. 2.1.17 [16]).

The measurements of EPQI revealed that the emission of higher harmonic currents in the power winding, as a rule, exceeded 3% and sometimes reached 12-14%. For a voltage of 330 kV, non-compliances were revealed in the non-sinusoidal coefficients of the 5th and 7th harmonics, as well as in the total non-sinusoidal coefficient. An analysis of the measurement results according to [5] showed that the distorting sources for the 5th and 7th harmonics are this SRCM and a similar SRCM installed at another substation. At the same time, for the 5th harmonic, the AC of the SRCM at this SS exceeded the PC, which means that, regardless of the other SRCM, this SRCM is the perpetrator. For the 7th harmonic, the AC of each of the two SRCM did not exceed the PC.

As a result of the claims made by the customer to the supplier based on the results of measurements and calculations, the SRCM supplier installed a higher harmonic filter in the compensation winding of the 330 kV SRCM as part of the fulfillment of warranty obligations. The control measurements made after the installation of the filter did not reveal any violations of the points of technical requirements.

6.2 Group of problematic 110 kV substations

The three studied substations (SS) are adjacent, two of them have intersystem overhead lines (OHL) with a voltage of 110 kV.

As a result of measurements on the 110 kV power rails of all three SS, non-compliances were established in the 5th and 9th harmonics. It was revealed that these non-compliances are caused by the combined effect of current emissions of these harmonics along the 110 kV intersystem lines and along individual 10 kV feeders (via transformers). Also, 110 kV SS connected to the branch line from an intersystem line was also revealed to be a source of the 5th harmonic.

Also, non-compliances in the 10th, 12th, 14th and 16th even harmonics were detected in the 1st 110 kV section of one of the SS. It is considered that the appearance of even harmonics is unlikely and is due to the use of rather specific electrical receivers. In this case, the presence of such electric receivers is not confirmed. There was a hypothesis that during non-working hours, along with a decrease in the load and an increase in voltage levels, the old transformer installed on the SS switches to a nonlinear magnetization mode (overexcitation), which, in turn, is accompanied by the emission of even harmonics. This hypothesis is supported by the monograph [14], which provides a mathematical description of the conditions for the emission of even harmonics in transformers.

6.3 There are no inconsistencies, but there is a harmful effect

In one of the areas of the electrical networks, the staff detected background acoustic noise in the transformers at the 10/0.4 kV TSS (transformer substation) feeding the pumps of the Water Utility. It was immediately assumed that this noise arises from higher harmonics emitted by the frequency-controlled drives of the pumps.

Measurements were conducted at two such TSS. As a result, non-compliances with the standards [1] were not identified. However, at the same time, very high levels of the components of the higher harmonic were established: (up to 100–110% relative to the 1st harmonic).

When using the current emission standards established in [9], the standards for 5, 7, 11, and 13 harmonics, as well as the permissible harmonic parameters, are exceeded several times.

In this case, a paradoxical situation has developed: there are no violations [1], but the harmful effect of higher harmonics is present. At the same time, there are violations of the requirements of the standard [9]. However, the action of [9] applies only to single devices, so the requirements of [9] are not legally applicable directly in this situation. In such cases, the requirements for limiting the emission of higher current harmonics can be stipulated in the Technical Specifications for power supply.

7 Own developments and research

For certain EPQI analyzers, we have identified errors in the measurement of phase shift angles. This is most likely related to the incorrect application of the method for determining the phase shift, given, for example, in [15]. This method involves determining the phase shift as the root of the equation $tg\varphi=A$. However, nowhere is the criterion for selecting one of the two roots specified. Therefore, we use the method of signal transition through zero. As a result, we have developed a specialized program for the calculation and analysis of EPQI. The source data consists of primary measurements, i.e., instantaneous values of phase currents and voltages (≥1024 points per period of the fundamental frequency), obtained from the archives of EPQI analyzers. The program calculates normalized and non-normalized EPQI for any time interval, without averaging, which is important for the analysis of short-term phenomena and fast processes.

We plan to test the methods for address detection of flicker sources proposed in [10]. Since EPQI analyzers do not measure the required values, our program will be updated for this purpose.

In the future, experiments are planned to identify the sources of even harmonics in electrical networks. The experiments will be performed for the 110/10 kV transformer mentioned above and the 220/110/10 kV autotransformer.

Conclusion

To ensure proper QE in electrical networks at all levels, it is necessary to organize systematic approach to the control and monitoring of EPQI, analysis of measurement results, and conducting organizational and technical corrective (normalizing) measures.

It is required to revise the existing regulatory and technical documentation, taking into account the accumulated practical experience, and in certain cases, it is advisable to expand its scope of application. For example, the norms [1] can be applied not only to the points of transmission of EE from the ESO to the consumer.

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