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Research into harmonic power in the high-voltage networks

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Abstract. The paper presents the results of studies on the harmonic active and reactive power at nodes of 110 kV and 220 kV networks. The studies were based on the measurements made at the node of 110 kV network supplying power to an aluminum plant and at the node of 220 kV network supplying power to railway traction substation. The supply networks belong to the Unified Energy Systems of Russia. Many other facilities with high-power nonlinear loads receive electric energy from these networks. They make their contribution to the formation of harmonic conditions across the networks. The measurements of currents and voltages were used to calculate active and reactive power for harmonics 2-40. The calculations show that although the considered facilities are the sources of harmonics and generate harmonic power to the supply networks they also receive harmonic power from them. The harmonic active power flows change directions during the measurements. Their values vary in a wide range and can reach several tens of kilowatts. The values of harmonic reactive power also vary in a wide range. They change the direction of the flow and affect the values of voltage, as a rule, at the characteristic harmonics of the nonlinear electrical equipment.

Key words

Power quality, high-voltage network, measurement, harmonic active and reactive power.

1. Introduction

The paper presents the results of an analysis of harmonic active and reactive power of two high-power nonlinear loads connected to the high-voltage networks. One of them is a railway traction substation receiving power from the 220 kV network, and the other load is an aluminum plant powered by the 110 kV network. These networks are part of the Unified Energy Systems of Russia. Many other high-power nonlinear loads receive power from these networks, for example, several aluminum plants and pulp-and-paper mills, a great number of railway traction substations, and chemical plants. These facilities have electrical equipment with nonlinear voltage-current characteristics, which generates harmonic currents. The facilities, as a rule, have no technologies to prevent the penetration of harmonic currents in the supplying networks.

There are many studies on the harmonic conditions in the electrical networks. The results of their analysis are presented in numerous publications. Most of them consider low- and medium-voltage networks [1]-[4]. It is found out that the harmonic conditions in the electrical networks represent a random phenomenon. Amplitudes and phases of harmonic currents and voltages change according to the laws that depend on the network topology, composition and parameters of network components, phases of harmonic source currents, supply voltages, loads and many other factors. The high-voltage networks have long lines. Standing wave effects occurring along the long lines affect the values of harmonic currents and voltages. In the high-voltage networks with a large number of nonlinear loads, the harmonic currents are canceled. Therefore, the research into properties of harmonic parameters including harmonic power in high-voltage networks is very important [5], [6]. There are publications that present the research into harmonic power. The examples of using the harmonic power to identify the locations of nonlinear loads and estimate their contribution to the voltage distortion are investigated in [7], [8]. Active power of harmonic orders $h>1$ does not perform useful work in the conventional power systems except heating and lighting in special cases. In [9], [10], the authors discuss additional losses of harmonic active power in electrical networks and equipment. In [11], "harmonics were found to be responsible for 5.4% of all power quality costs". The research from [12] poses the problems of potential financial losses of electricity suppliers and consumers in the case of nonsinusoidal currents and voltages. Electricity meters that belong to them measure active energy not only at the fundamental harmonic but also at the other harmonics including those they do not generate. Therefore, the suppliers and consumers bear additional expenses when paying the bills for electricity. Harmonic reactive power also causes additional power and energy losses in the electrical networks.

The results of the studies can be used to develop new approaches to the distribution of responsibility between the supply networks and consumers with nonlinear loads, to control if the harmonic current generated by the consumers distorting voltage lies within the admissible limits, and to develop measures to reduce the values of harmonic voltages and currents in the supply networks.

2. Objects of the studies and measurement conditions

The parameters of the operating conditions were measured on the side of a 220 kV transformer that powers the railway traction substation and on the side of a 110 kV transformer that supplies power to the aluminum plant. The measurements at the traction substation were performed for two states of the circuit breaker Q in Figure 1:

T1 – circuit breaker Q is on, i.e. the traction network receives electricity from the winding of a 25 kV transformer, non-traction consumers receive electricity from the 11 kV winding;

T2 – circuit breaker Q is off, i.e. traction network does not receive electricity from the winding of a 25 kV transformer, non-traction consumers receive electricity from the 11 kV winding.

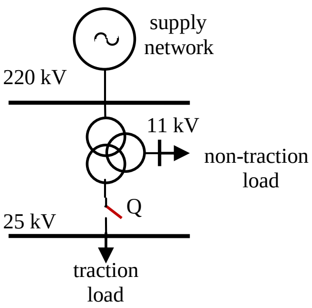

Fig. 1. A scheme of transformer and circuit breaker.

The device "Omsk" was used to measure currents and voltages in three phases with an interval of 1 minute during 24 hours. The device was connected through voltage transformers to the high-voltage buses and to current transformers installed at the inputs of high-voltage transformers. Measurements of currents and voltage are carried out with accuracy established in the Russian Standard [13].

3. Theoretical principles of the analysis

The equivalent circuit in Figure 2 represents the electrical network and nonlinear load with respect to the connection node.

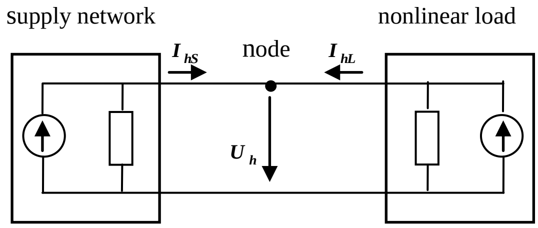

Fig. 2. An equivalent circuit of the supply network and nonlinear load for the *h*-th harmonic.

The notations used in the scheme are:

$\boldsymbol{I}_{hS}$ - the *h*-th harmonic current phasor of the supply network,

$\boldsymbol{I}_{hL}$ - the *h*-th harmonic current phasor of nonlinear load.

Current $\boldsymbol{I}_{hS}$ is a resultant *h*-th harmonic current phasor of all nonlinear loads available in the supply network except for current $\boldsymbol{I}_{hL}$. The value and phase of current $\boldsymbol{I}_{hS}$ depend on a large number of factors [14]. The harmonic current phasor $\boldsymbol{I}_h$ at the node in Figure 2 is determined by the sum of currents $\boldsymbol{I}_{hS}$ and $\boldsymbol{I}_{hL}$, i.e.

$$\boldsymbol{I}_h = \boldsymbol{I}_{hS} + \boldsymbol{I}_{hL} . \quad (1)$$

The measurements at the node provided the root mean square voltages U_h and currents I_h, as well as their phase angles φ_{Uh}, φ_{Ih}. These were used to calculate the values of harmonic active and reactive power according to [15]

$$P_h = U_h I_h \cos \varphi_h , \quad (2)$$

$$Q_h = U_h I_h \sin \varphi_h , \quad (3)$$

where, φ_h - phase angle between voltage and current of the *h*-th harmonic.

The value of phase angle φ_h is calculated as

$$\varphi_h = \varphi_{Uh} - \varphi_{Ih} . \quad (4)$$

The angle φ_h makes it possible to determine the direction of active and reactive power flows with respect to the nodes at which the measurements were made [15]-[17]. If φ_h lies on the interval from 0 to π/2 both active and reactive power is directed from the supply network to the load. If φ_h lies on the interval from 3π/2 to 2π, the active power is directed from the supply network to the load, and reactive power is directed from the load to the supply network. In these cases, the node is a load node for the *h*-th harmonic [15]. If φ_h lies on the interval from π/2 to π, active and reactive power is directed from the load towards the supply network. If the angle φ_h lies on the interval from π to 3π/2, the active power is directed from the load to the supply network and reactive power flows have a reverse direction. In these cases, the node is a generating node for the *h*-th harmonic [15].

4. Results of power analysis

A. *Active power of the fundamental harmonic*

The measurements show that the studied facilities have different curves of the active power of the fundamental harmonic. The value of active power of the traction substation changes dramatically over time (curve T1 in Figure 3). With disconnection of the traction network, it declines and changes insignificantly (curve T2 in Figure 3). The value of active power of the aluminum plant remains virtually the same throughout the day (Figure 4). The curves of power presented in the Figures are for one phase.

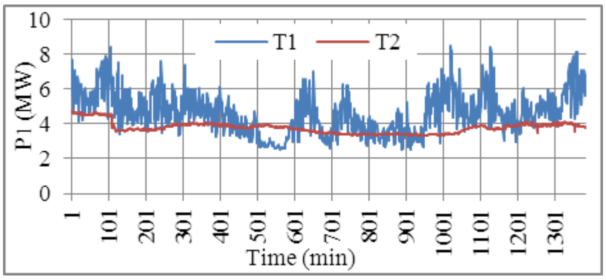

Fig. 3. Active power curves of the traction substation.

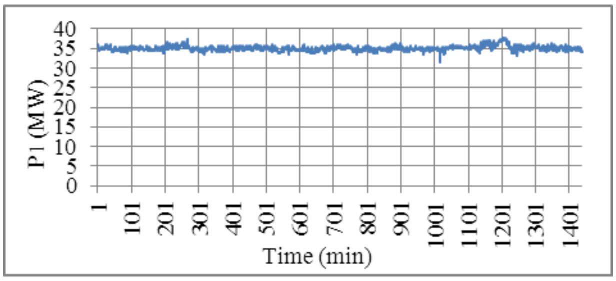

Fig. 4. Active power curve of the aluminum plant.

Table I presents the maximum values (max), minimum values (min), average values (aver) and standard deviations (st) for active power of the fundamental harmonic (P_1). Notations of the Table I are: T1, T2 – traction substation, AL – aluminum plant, A, B, C - phases. Statistical estimates in Table I demonstrate that in condition T1 there is inequality P_1 in phases, i.e. the condition is unsymmetrical. In condition T2 the values of P_1 in phases are virtually equal. At the aluminum plant there is also inequality P_1 in phases.

Table I. - Statistical estimates of P_1 (MW)

Object	Phase	$P_{1\,max}$	$P_{1\,min}$	$P_{1\,aver}$	$P_{1\,st}$
T1	A	8.5	2.5	4.7	1.2
	B	9.8	2.6	4.8	1.1
	C	8.7	3.4	5.0	0.9
T2	A	4.7	3.3	3.8	0.3
	B	4.6	3.2	3.6	0.3
	C	4.8	3.3	3.8	0.3
AL	A	37.7	31.4	35.0	0.7
	B	38.6	32.7	36.1	0.7
	C	38.8	32.5	36.2	0.7

B. Active power of harmonic orders h>1

Active power of loads for harmonics 2-40 was calculated using expression (2). The analysis of the calculated power shows that the direction of active power flows for all harmonics varies during the measurement period. However, for some harmonics the predominant direction, i.e. observed for more than 50% of the time of measurement, is the direction from the load to the supply network and for the others from the supply network to the load. Figures 5-7 show the diagrams, which indicate the directions of harmonic active power flows for one phase at the connection nodes of the traction substation and aluminum plant in terms of the time it takes for the active power to flow from the loads to the supply networks. The diagram in Figure 5 corresponds to the condition T1. It shows that for more than 50% of the time of measurement, the active power of nine harmonics (3, 7, 11, 13, 15, 21, 25, 29 and 35) was directed from loads, connected to the windings of 11 kV and 25 kV transformers, to the supply network. The active power flows of the remaining thirty harmonics were directed from the supply network to the loads for more than 50% of the time of measurement. The diagram in Figure 6 corresponds to the condition T2. In this condition for more than 50% of the time of measurement, the flows of active power of fourteen harmonics (2, 3, 5, 7, 17, 19, 23, 29, 32, 34-38) of the loads connected to the 11 kV winding went in the direction of the supply network. The active power flows of the other twenty five harmonics most of the time had a reverse direction. The diagram in Figure 7 shows that for more than 50% of the time of measurement active power flows of eight harmonics (2-7, 23 and 25) were directed from the load to the supply network. The direction of active power flows for the remaining thirty one harmonics was reverse.

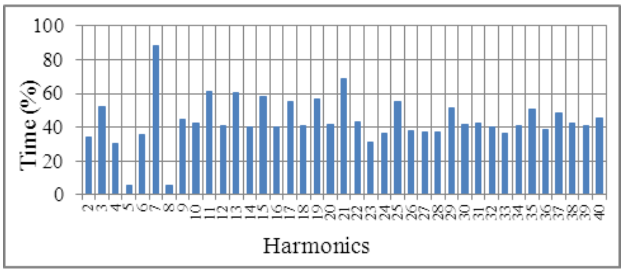

Fig. 5. Diagram of directions for harmonic active power from the load to the supply network for traction substation in the condition T1.

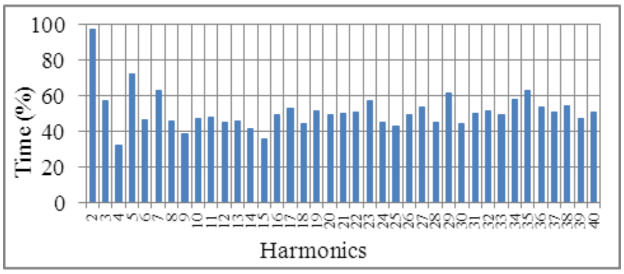

Fig. 6. Diagram of directions for harmonic active power from the load to the supply network for traction substation in the condition T2.

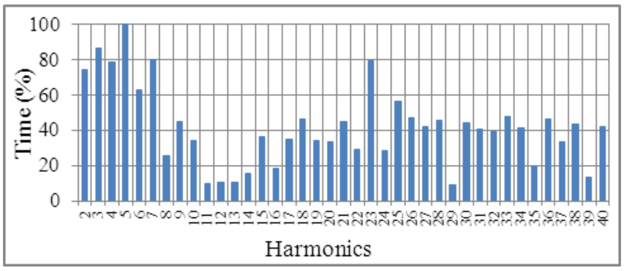

Fig. 7. Diagram of directions for harmonic active power from the load to the supply network for aluminum plant.

A distinctive feature of active power of different harmonics is the fact that the active power flow can have different directions at the same time, which is confirmed by Figure 8. The scatter plot demonstrates the directions of active power flows at the 3-rd and 7-th harmonics during a 20-minute interval. Harmonic active power with the “minus” sign is directed to the supply network and with the “plus” sign to the load. At some time instants, their directions coincide both in the direction of the network and in the direction of the load, at the other time instants the power flows have opposite directions.

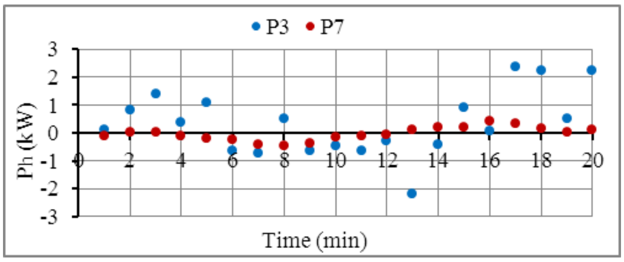

Fig. 8. Directions for 3-rd and 7-th harmonic active power.

In the condition T1, the values of active power at harmonics 2-40 lie in the range from several watts to several kilowatts in both directions. Further, it will be necessary to conduct thorough studies to establish a threshold value of harmonic power below which the measured power should be considered as high-frequency noise. As the order of harmonic increases, the active power values decline. The active power values of odd harmonics exceed the active power values of even harmonics. The active power of even harmonics does not exceed several tens of watts. Table II demonstrates the statistical estimates of the most significant values of the harmonic active power for one phase.

Table II. – Statistical estimates of harmonic active power (kW)

Object	h	$P_{h(-)}$			$P_{h(+)}$		
		max	aver	st	max	aver	st
T1	3	14.0	1.2	2.0	7.6	1.1	1.2
	5	2.1	0.5	0.5	5.6	1.2	0.8
	7	2.4	0.4	0.3	1.3	0.1	0.2
	9	1.2	0.1	0.2	0.9	0.1	0.1
	11	0.8	0.1	0.1	0.8	0.1	0.1
	13	0.4	0.1	0.1	0.9	0.0	0.1
	23	0.1	0.0	0.0	1.3	0.0	0.1
	25	0.1	0.0	0.0	1.3	0.0	0.0
T2	3	0.7	0.1	0.1	1.3	0.2	0.2
	5	0.6	0.1	0.1	0.8	0.2	0.1
	7	0.1	0.0	0.0	0.2	0.0	0.0
	9	0.2	0.0	0.0	0.3	0.0	0.0
	11	0.1	0.0	0.0	0.3	0.0	0.0
	13	0.1	0.0	0.0	0.2	0.0	0.0
	23	0.0	0.0	0.0	0.3	0.0	0.0
	25	0.0	0.0	0.0	0.4	0.0	0.0
A	3	1.2	1.2	0.2	4.4	0.7	0.5
	5	0.3	0.3	0.1	5.1	2.4	0.8
	7	1.3	0.4	0.3	2.2	0.7	0.4
	9	0.6	0.1	0.1	0.3	0.1	0.1
	11	32.5	13.0	7.2	8.0	2.8	1.9
	13	30.2	8.9	6.0	6.3	1.5	1.4
	23	0.8	0.2	0.1	0.6	0.2	0.1
	25	0.6	0.1	0.1	0.6	0.2	0.1

The active power of the 3-rd and 5-th harmonics has the greatest values. These two harmonics are characteristic of the one-phase traction load. After the disconnection of the traction network supply, i.e. in the condition T2, the values of harmonic active power decreased greatly (Table II). Harmonic active power $P_{h(-)}$ is directed to the supply network and $P_{h(+)}$ to the load. At the connection node of the aluminum plant to the supply network the active power at the 11-th and 13-th harmonics in both directions has the greatest values. Both harmonics are also characteristic of the rectification circuit, which is applied at the aluminum plant.

Conventional electric power systems are designed to operate with a sinusoidal voltage waveform. If the network has one nonlinear load it receives power at the fundamental frequency. Part of this power is converted in the nonlinear load to the power at the different frequencies, which represent harmonic power. This power directs to the supply network where it dissipates in the resistances of the electric power system equipment (capacitor banks, transformers, rotating machines and etc.), heat it and reduce service life. If the network contains several nonlinear loads, the voltage at their terminals can be nonsinusoidal. Loads will receive the power of both the fundamental harmonic and the different harmonics. The mechanism of harmonic power generation is well described in [12], [18].

From the perspective of the supply network and most of electricity consumers the active power of the harmonics 2-40 does not perform useful work. In [12] the author calls it detrimental power and denote by P_d. It was indicated above that the parameters were measured during 24 hours with an interval of 1 minute. The values of the detrimental total power for one measurement obtained within a 1-minute period can be determined as an arithmetic sum of active power at harmonics 2 – 40, flowing through the node in both directions, i.e.

$$P_{d\Sigma} = \sum_{h=2}^{40} (|P_{h(-)}| + P_{h(+)}) . \quad (5)$$

An array of calculated $P_{d\Sigma}$ consists of 1440 elements in 24 hours. Table III presents the statistical estimates of the arrays $P_{d\Sigma}$ for the studied facilities. Table III also gives the estimates of detrimental electric energy W_d during the time of measurement. They were obtained under the assumption that $P_{d\Sigma}$ remained constant within a 1-minute period. At the connection node of aluminum plant, power losses made up around 591kWh in 24 hours.

Table III. – Statistical estimates of P_d (kW), W_d (kWh)

Object	$P_{d\Sigma\,max}$	$P_{d\Sigma\,min}$	$P_{d\Sigma aver}$	W_d
T1	54.5	0.4	3.1	73.7
T2	28.1	0.1	0.6	13.6
A	62.1	3.4	24.7	591.2

C. Reactive power of harmonic orders $h>1$

Harmonic reactive power was calculated using expression (3). As well as the harmonic active power, it has different values, which lie within the range from several var to several kilovar. As the harmonic order rises the value of active power declines. Reactive power as well as active power is directed either to the supply network or to the load. The directions of harmonic reactive power do not coincide with the directions of harmonic active power. It often happens that the load node for harmonic active power is a generating load for harmonic reactive power. The statistical estimates for the most significant values of harmonic reactive power are presented in Table IV. Harmonic reactive power with the "minus" sign ($Q_{h(-)}$) is directed to the supply network and with the "plus" sign ($Q_{h(+)}$) – to the load.

Table IV. – Statistical estimates of harmonic reactive power (kvar)

Object	h	$Q_{h(-)}$			$Q_{h(+)}$		
		max	aver	st	max	aver	st
T1	3	14.2	1.5	1.8	2.5	0.3	0.3
	5	1.4	0.3	0.3	8.2	1.4	1.2
	7	2.8	0.4	0.4	1.4	0.1	0.1
	9	0.6	0.1	0.1	1.2	0.1	0.1
	11	0.5	0.1	0.1	0.6	0.1	0.1
	13	0.7	0.1	0.1	0.3	0.0	0.0
	23	0.3	0.0	0.0	0.1	0.0	0.1
	25	0.7	0.0	0.0	0.5	0.0	0.0
T2	3	0.1	0.0	0.0	1.2	0.2	0.2
	5	0.0	0.0	0.0	0.7	0.1	0.1
	7	0.1	0.0	0.0	0.1	0.0	0.0
	9	0.0	0.0	0.0	0.1	0.0	0.0
	11	0.1	0.0	0.0	0.1	0.0	0.0
	13	0.1	0.0	0.0	0.1	0.0	0.0
	23	0.2	0.0	0.0	0.0	0.0	0.0
	25	0.2	0.0	0.0	0.0	0.0	0.0
A	3	2.2	0.3	0.3	1.4	0.3	0.3
	5	3.8	1.2	0.9	1.8	0.3	0.3
	7	2.4	0.7	0.4	1.2	0.3	0.3
	9	0.3	0.1	0.1	0.5	0.1	0.1
	11	27.7	7.8	5.3	2.5	0.7	0.6
	13	17.2	2.9	2.8	9.0	2.9	1.7
	23	1.3	0.5	0.3	0.2	0.1	0.1
	25	0.9	0.3	0.2	0.7	0.1	0.1

The reactive power is known to affect the value of voltage at the nodes of the network. It is interesting to assess how the values of harmonic reactive power and its directions affect the values of respective harmonic voltages. We calculated the correlation ratios between the values of harmonic reactive power directed to the supply network and to the load and the respective harmonic voltages. The results are presented in Table V. The qualitative assessment of the correlation ratio between the values of reactive power and harmonic voltage was made using the Chaddock scale. In the case the values of the correlation ratio lie in the ranges 0.7-0.9 or 0.9-0.99 the correlation between the parameters is strong and very strong. In Table V the correlation ratios with the mentioned values are highlighted in bold. The greatest value, equal to 0.9, is observed in the correlation ratios at connection node of the aluminum plant when the reactive power is directed to the supply network at the 11-th, 23-rd and 24-th harmonics, as well as at the traction substation in the condition T2 with the reactive power flows directed toward the load at the 23-rd harmonic. The overwhelming majority of correlation ratios lie within the range from 0.3 to 0.7, which is indicative of a moderate or noticeable degree of correlation between the harmonic reactive power and respective harmonic voltage values.

Table V. – Correlation coefficients

h	$r_{Qh(-),Uh}$			$r_{Qh(+),Uh}$		
	T1	T2	A	T1	T2	A
3	0.5	0.0	0.4	0.4	**0.8**	0.5
5	0.0	0.2	0.5	0.5	**0.8**	0.3
7	0.6	0.2	**0.7**	0.3	0.5	0.3
9	0.4	0.0	0.4	0.5	**0.7**	0.6
11	0.5	0.5	**0.9**	0.4	0.6	0.1
13	0.6	0.5	0.6	0.4	**0.7**	0.1
23	0.5	**0.7**	**0.9**	**0.9**	0.6	0.3
25	0.2	**0.8**	**0.9**	**0.7**	0.4	0.4

The results of the studies on harmonic active power at the nodes connecting aluminum plant and traction substation to the 100 kV and 220 kV supply networks, which are presented in this paper are an extension to the analogous studies whose results are presented in [19]. In the previous paper the harmonic active power was analyzed at the nodes connecting large nonlinear loads (pulp-and-paper plant and one shop of an aluminum plant) to the 220 kV supply network. Comparison of the results concerning the directions of flows and values of harmonic active power make it possible to conclude on their similar character. However, the uniqueness of the harmonic active power conditions of each node in the high voltage network also takes place.

4. Conclusion

1) The values of harmonic active and reactive power at the nodes of high-voltage networks with a great amount of distributed nonlinear loads lie within the range from several watts to several tens of kilowatts. High values of power normally take place at characteristic harmonics of the nonlinear electrical equipment.

2) Directions of power flows at different harmonics are different. At the same time, they can be directed both to the supply network and to the load. The direction of power flow for one harmonic also changes with time. Harmonic energy losses can reach several hundred kilowatt-hours a day.

3) Harmonic active and reactive power can be used in the systems of automated monitoring of the high-voltage network condition to assess the power quality, evaluate the contributions made by the distorting consumers to the voltage distortion, and to assess power losses.

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