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VOLTAGE ASYMMETRY INFLUENCE ON RESOURCE CONSUMPTION AT POWER GENERATING PLANTS

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Abstract: The objective of this paper is to provide new research on the linkages between voltage asymmetry, energy efficiency and resource efficiency to inform policymaking in this area about possibilities of electricity saving potential. Asymmetry voltage coefficients value in Ukrainian grid were experimentally identified based on assessments of 23 Ukrainian companies during 2016-2018. It was estimated, that 26 % of transformers have asymmetry voltage coefficient of reverse sequence lower than 2 % and 12 % of transformers have asymmetry voltage coefficient of zero sequence lower than 2 %. The estimated resource saving potential for Ukrainian power generating plants is up to 1'978 GWh_{el}/a, which is up to 1.5 % of total electricity produced. Equivalent reducing electricity generation at coal power plants could prevent emissions up to 292.79 t/a of ash emissions; 733 kt/a of CO2 emissions; 5.9 kt/a of SOx emissions; 2.9 kt/a of NOx emissions; 9.03 m^3/a of nuclear waste.

Keywords: Resource consumption; Electric energy savings; Voltage asymmetry coefficients; Emissions; Electric energy losses

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INTRODUCTION

Increasing energy efficiency means using a reduced quantity of resources input for the same amount of output. There are still huge opportunities to improve energy efficiency and reduce carbon emissions in production, transportation and usage of power in most regions of the world ("EBRD's Sustainable Energy Initiative: Energy Efficiency in the Energy Sector", 2019). Resource efficiency could be improved by reducing electricity losses in the network. According to (Schonek, 2013), the average values of power losses at the different steps of the network are: 1-2 % – Step-up transformer from generator to Transmission line; 2-4 % – Transmission line; 1-2 % – Step-down transformer from Transmission line to Distribution network; 4-6 % – Distribution network transformers and cables. For example, according to the statistic (Data.worldbank.org, 2018), losses in transmission and distribution as a percentage of total injected electric energy for Ukraine are 11 % (see **Fig. 1**).

Figure 1 shows, that losses in transmission and distribution in Ukraine are roughly 11 % of total injected electric energy nowadays. The peak of losses in transmission and distribution in the period 1995 – 2003 was because of low investments in maintenance and renewal in Ukrainian electricity network, which were 30 % less, comparable with 2016 (49 million EUR/a and 69 mil-lion EUR/a, approximately) (Golian, 2017). For Poland we can see the same trend, which was 3 years after Soviet Union collapse.

It was estimated that losses in distribution for Ukraine are near 8.25 % of total injected electric energy with information from (Schonek, 2013).

According to the study (Central Electricity Regulatory Commission, 2018), near to 10 % of distribution losses are caused due to the quality of electric energy. This can result in losses due to the quality of electric energy of up to 1 % of total injected electric energy. One of the parameters of the quality of electric energy is voltage asymmetry. Even a small voltage asymmetry (up to 2 %) causes significant negative sequence currents (up to 16%). The reverse sequence currents are superimposed on the direct sequence currents and cause additional heating of insulation, which leads to its accelerated aging and decreases energy efficiency. Thus, the service life of fully loaded electric equipment operating with a voltage asymmetry of 4 % can be halved ("Influence of asymmetric voltage", 2019). These distribution losses caused by voltage asymmetry are the focus of this investigation. The purpose is to provide new re-search on the linkages between voltage asymmetry, energy efficiency and resource efficiency to inform policymaking about saving potentials.

Brief Literature Review

Possible reasons for voltage asymmetry presence in electrical grid, according to (Quispe *et al*., 2009), are:

- the existence of asymmetry loads;
- asymmetrical transformer windings or trans-mission impedances;
- single-phase loads;
- incomplete transposition of transmission lines;
- open delta transformer connections;
- blown fuses on three-phase capacitor bank;
- operation of single-phase loads at different times;
- defective transformers in power systems;
- one of the three-phases of a motor is open.

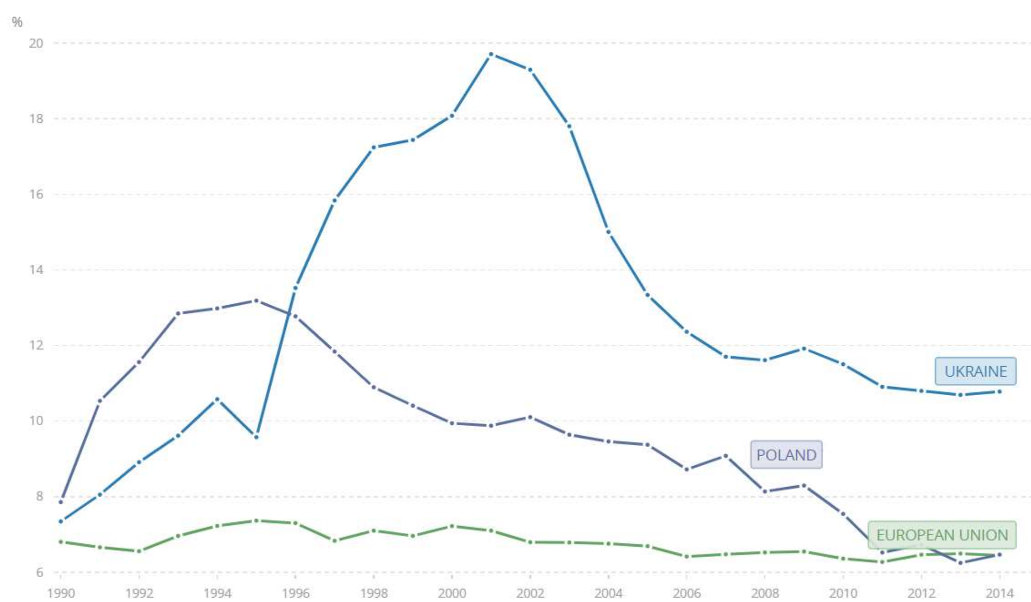

Fig. 1. Losses in transmission and distribution in Ukraine.

The analysis of the effects of voltage asymmetries in the operation of electrical equipment showed that the losses in copper wires, caused by the positive sequence voltage, behaves differently to the copper losses of negative sequence (Chen *et al*., 2018). Voltage asymmetry also negatively affects the temperature regime of wires' insulation (Kostic & Nikolic, 2010). The authors pointed out, that increasing of voltage asymmetry level up to 5 % increases temperature of wires' insulation up to 30 0C for class A insulation and up to 40 0C for class B insulation from the work (Eliminate Unbalanced Voltages - Take Action, 2011). Since every 10 °C increase in temperature cuts the insulation life in half, 3 % voltage asymmetry could reduce the life of the winding to about one-fourth of expected lifespan. It is estimated (Edan, 2013), that voltage asymmetry causes decrease transformer efficiency and increase losses in transformers from total non-load state and short circuit state up to 20 % (data from authors' provided assessments). These losses from power quality have become a matter of concern for the power sector (Silva *et al*., 2017). High-capacity operational equipment with automatic transformer control is used to achieve sufficient voltage quality according to international standards. However, it does not make sense to build up a public supply system that fulfils the high requirements of a small amount of very sensitive devices (Ratering-Schnitzler *et al*., 1997).

Ukrainian power generation sector

In Ukraine up to 6 % of power generation stem from hydropower, 40 % from coal power plants, and up to 50 % from nuclear power plants (UKRENERGO, 2018). The remaining 4 % stem from different renewables generation plants. They are not taken into account because of lack of information in this study. **Table 1** summarizes the national statistics of electricity generation for the main production sources for two characteristic days of the year.

Using data about power generation in summer and in winter period from **Table 1**, the yearly generated electric energy by different power generating plants was estimated in **Table 2**.

Table 1. Typical electric energy generation capacities from power generating plants national statistics for two characteristic days (UKRENERGO, 2018)

Hour of the day	Power of generation at Ukrainian power generating plants [MW_{el}]							
	24.07.2018 (summer average day)				10.01.2018 (winter average day)			
	Hydro	Coal	Nuclear	Total	Hydro	Coal	Nuclear	Total
0	630	6 727	9 221	16 578	890	8 375	9 609	18 874
1	847	5 363	9 221	15 431	1 047	7 383	9 640	18 070
2	409	5 753	9 220	15 382	1 259	7 428	9 623	18 310
3	470	5 836	9 237	15 543	981	7 435	9 643	18 059
4	60	5 949	9 259	15 268	925	7 428	9 647	18 000
5	264	5 714	9 248	15 226	930	7 540	9 623	18 093
6	62	5 249	9 260	14 571	522	7 750	9 621	17 893
7	217	5 691	9 244	15 152	1 426	7 918	9 623	18 967
8	279	6 069	9 236	15 584	1 377	8 676	9 618	19 671
9	1 223	6 141	9 254	16 618	2 273	9 072	9 577	20 922
10	1 444	6 313	9 243	17 000	2 400	9 369	9 587	21 356
11	1 323	6 427	9 217	16 967	2 750	9 225	9 567	21 542
12	2 051	5 981	9 234	17 266	2 541	9 176	9 601	21 318
13	2 017	6 178	9 126	17 321	2 550	8 958	9 597	21 105
14	2 131	6 370	9 126	17 627	2 695	8 954	9 602	21 251
15	1 777	6 777	9 125	17 679	2 746	8 938	9 610	21 294
16	1 520	6 872	9 127	17 519	2 875	8 942	9 596	21 413
17	1 463	6 950	9 113	17 526	3 397	8 933	9 606	21 936
18	1 342	6 987	9 125	17 454	3 660	8 737	9 606	22 003
19	1 364	6 766	9 122	17 252	3 700	8 342	9 611	21 653
20	1 168	6 878	9 134	17 180	3 106	8 149	9 605	20 860
21	1 280	6 956	9 165	17 401	3 057	8 186	9 610	20 853
22	1 420	7 045	9 146	17 611	2 370	8 503	9 610	20 483
23	515	6 617	9 141	16 273	1 226	8 468	9 610	19 304
Maximum generated power in hour, MW_{el}				17 679	Maximum generated power in hour, MW_{el}			22 003
Calculated figure of transformers TM-1000, which are needed for distribution				18 000	Calculated figure of transformers TM-1000, which are needed for distribution			23 000

Table 2. Estimation of annual electric energy generation in Ukraine at hydro/coal/nuclear power generating plants

Annual generation of electric energy at Ukrainian power generating plants [GWh_{el}/a]		
Hydro	Coal	Nuclear
13 676.22	63 628.92	81 213.48

In Ukraine the most common type of transformer (information based on assessments of 23 different Ukrainian companies that were provided by authors of this article during 2016-2018) is a TM-1 000 with a capacity of 1 000 kVA. Based on this typical transformer a figure of 23 000 transformers in Ukraine for winter season and 18 000 transformers in Ukraine for summer season were estimated at enterprises for the consumption of electric energy. It is possible to calculate losses in transformers from asymmetry voltages with these estimated figures in Table 1 and **Table 2**. For this investigation assessments at Ukrainian enterprises during 2016–2018 were analysed. Methodology of these assessments is provided in the following section.

METHODOLOGY

Method of voltage asymmetry analysis

Measurements of voltages values have been collected from 23 Ukrainian companies during 2016 – 2018 years. The 3-phase power analyser AKTAKOM ACM-3192 was connected to the 0.4 kV of transformer output (in 90 % of situations transformer was TM-1 000) (see **Fig. 2**).

According to the international standard (International standard. E02. GOST 13109-97, 2002), data was taken during at least 10 minutes when the transformer load was maximal, which was possible for every investigated enterprise. Using effective values of linear (UAB, UCA, UBC) and phase voltages (UA, UB, UC) (they were fixed every 2 seconds), there were calculated asymmetry voltage coefficients of reserve and zero sequence, according to international standard "GOST 13109-97. Electric energy. Electromagnetic compatibility of technical equipment. Power quality limits in public electrical systems" (International standard. E02. GOST 13109-97, 2002), which is valid for Ukraine (Leonorm.com.ua, 2018). According to mentioned standard, the following equations were used (1) – (6). Effective values of voltages of the reverse and zero sequences of the main frequency were calculated:

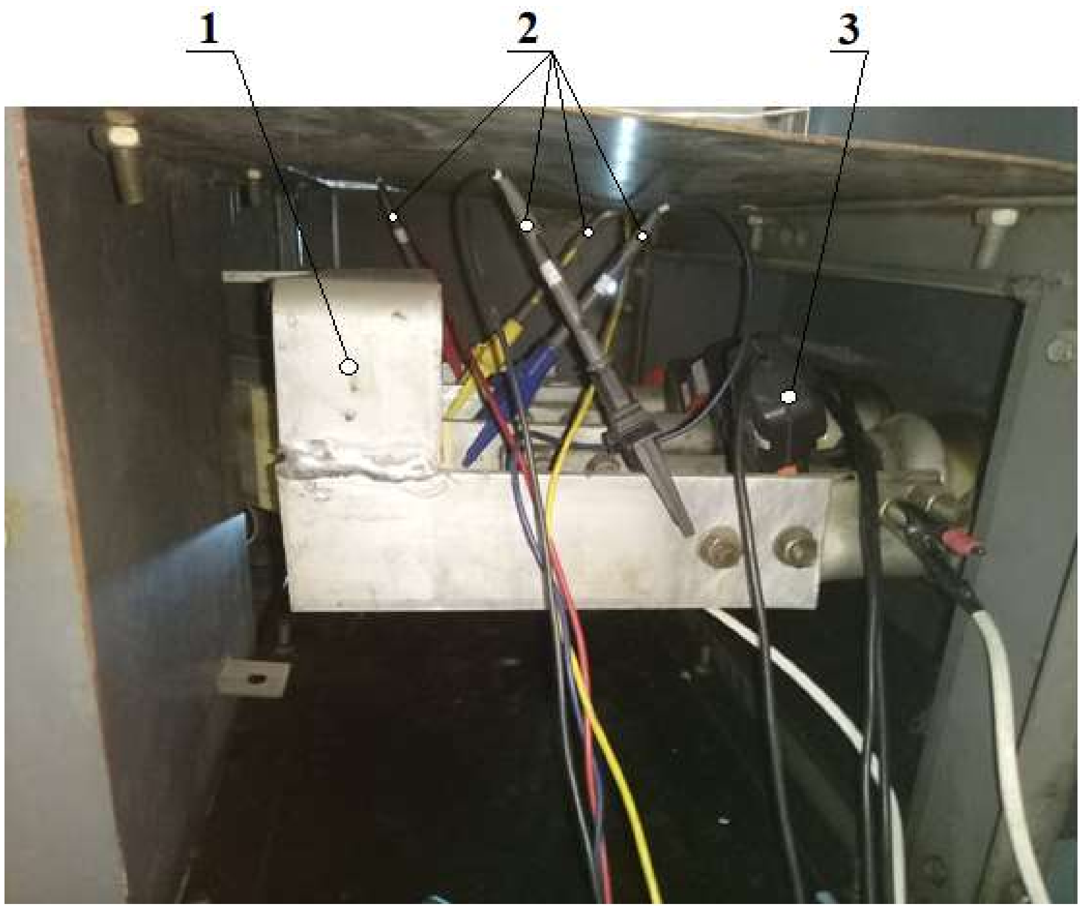

Fig. 2. Connection of power analyser with 0.4 TM-1 000 transformer output, where 1 – electrical cables from transformer, 2 – probes for measuring voltage, 3 – probes for measuring current.

$$U_{2(1)i} = \sqrt{\frac{1}{12}\left[\left(\sqrt{3}U_{AB(1)i} - \sqrt{4U^2_{BC(1)i} - \left(\frac{U^2_{BC(1)i} - U^2_{CA(1)i}}{U^2_{AB(1)i}} + U_{AB(1)i}\right)^2}\right)^2 + \left(\frac{U^2_{BC(1)i} - U^2_{CA(1)i}}{U^2_{AB(1)i}}\right)\right]}, \quad (1)$$

$$U_{0(1)i} = \frac{1}{6}\sqrt{\begin{gathered}\left[\frac{U^2_{BC(1)i} - U^2_{CA(1)i}}{U_{AB(1)i}} - 3\,\frac{U^2_{B(1)i} - U^2_{A(1)i}}{U_{AB(1)i}}\right]^2 + \\ + \left[\sqrt{4U^2_{BC(1)i} - \left(U_{AB(1)i} - \frac{U^2_{BC(1)i} - U^2_{CA(1)i}}{U_{AB(1)i}}\right)^2} - 3\sqrt{4U^2_{B(1)i} - \left(U_{AB(1)i} - \frac{U^2_{B(1)i} - U^2_{A(1)i}}{U_{AB(1)i}}\right)^2}\right]^2\end{gathered}} \quad (2)$$

where $U_{2(1)i}$ is the effective value of the voltage of the reverse sequence of the main frequency in three-phase voltage system in the i-th observation, V; $U_{0(1)i}$ is the effective value of the voltage of the zero sequence of the main frequency in three-phase voltage system in the i-th observation, V; $_{(1)}$ means the main frequency of the electric parameter.

Afterwards asymmetry voltage coefficients of reserve and zero sequence were calculated for every period (9 periods with an interval of 20 seconds, accordingly to the mentioned standard):

$$K_{2Ui} = \frac{U_{2(1)i}}{U_{1(1)i}} \cdot 100, \quad (3)$$

$$K_{0Ui} = \frac{\sqrt{3}U_{0(1)i}}{U_{1(1)i}} \cdot 100, \quad (4)$$

where $U_{1(1)i}$ is the effective value of the voltage of the direct sequence of the main frequency in the i-th observation, V.

In the end average square of asymmetry voltage coefficients of reserve and zero sequence were calculated

$$K_{2U} = \sqrt{\frac{\sum_{i=1}^{N} K^2_{2U}}{N}}, \quad (5)$$

$$K_{0U} = \sqrt{\frac{\sum_{i=1}^{N} K^2_{0Ui}}{N}}, \quad (6)$$

where N is the number of observations.

Asymmetry voltage coefficients in Ukrainian electric grid

Using the method from the international standard mentioned before (International standard. E02. GOST 13109-97, 2002), **Fig. 3** depicts the estimated asymmetry voltage coefficients of reserve and zero sequences at Ukrainian enterprises.

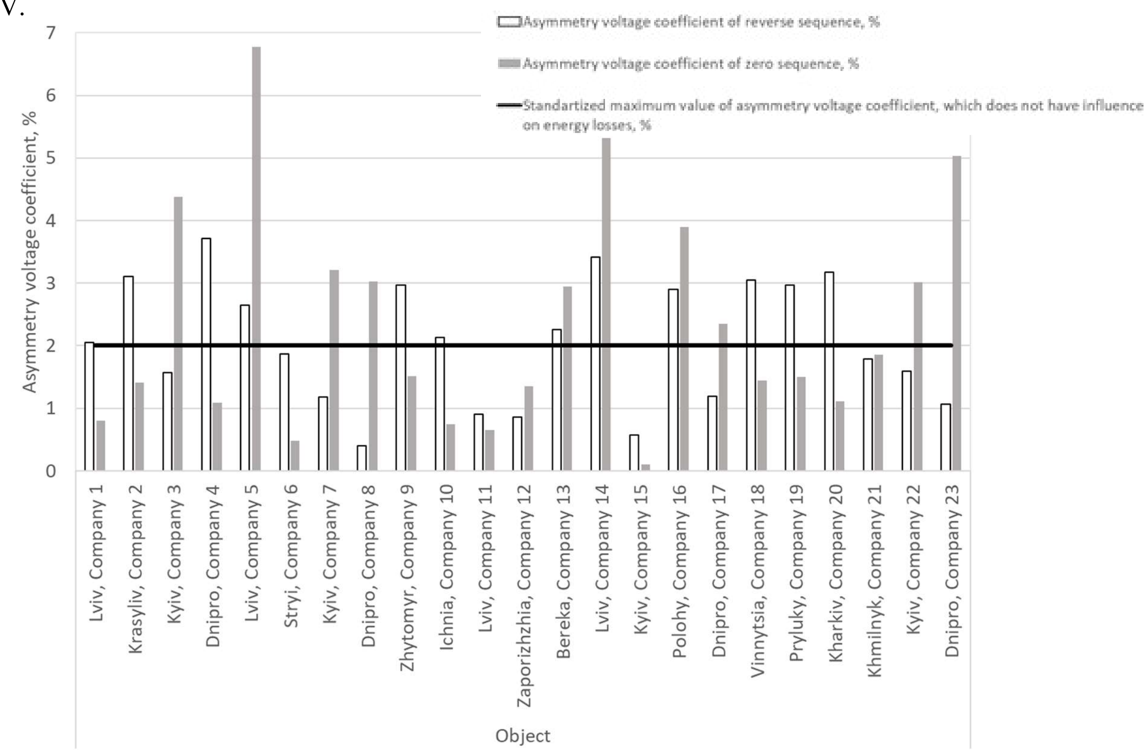

Fig. 3. Comparison of asymmetry voltage coefficients of reserve and zero sequence at Ukrainian enterprises with its standardized maximum value, which not influences on electric energy losses.

Figure 3 reveals that not all companies have unacceptable values of more than 2 %. This analysis of asymmetry voltage coefficients higher 2 % was used to estimate figures for the country (see **Fig. 4** and **Fig. 5**). After this extrapolation, according to the methodology from (Ded and Parshukova, 2014), the level of electric energy losses for Ukrainian due to asymmetries were calculated.

Figures 4 and **5** show that 26 % of transformers have asymmetry voltage coefficient of reverse sequence lower than 2 % and 12 % of transformers have asymmetry voltage coefficient of zero sequence lower than 2 %. These transformers will not be included in electric energy losses calculation. All the other transformers have losses due to asymmetry voltage coefficient higher than 2 %. Their losses will need to be compensated by increasing of electric energy generation and resource consumption at power generating plants.

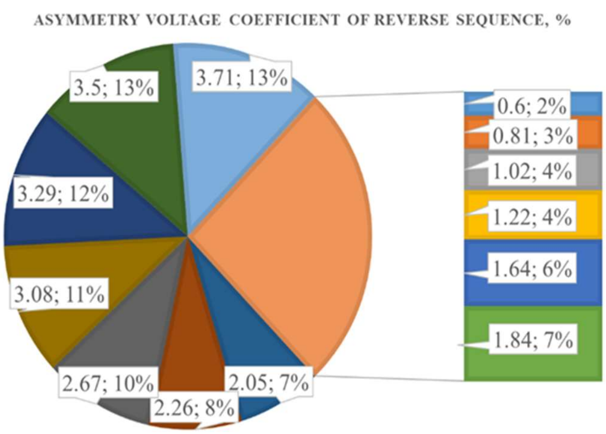

Fig. 4. Asymmetry voltage coefficient of reverse sequence extrapolation.

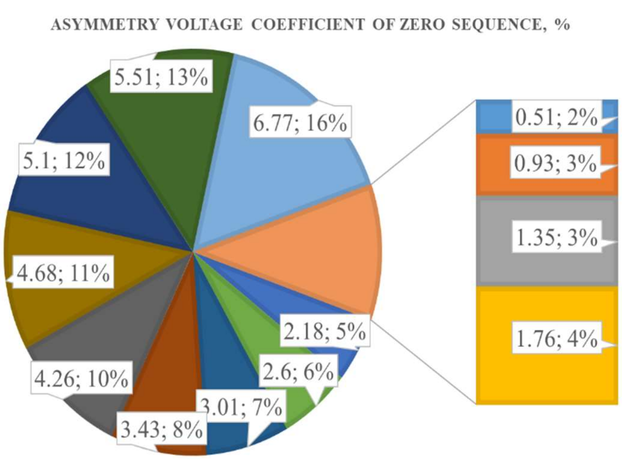

Fig. 5. Asymmetry voltage coefficient of zero sequence extrapolation.

RESULTS AND DISCUSSION

Extra Consumption of Resources and Extra Emissions of Coal power generating plants due to Asymmetry voltage coefficients losses. It was assumed that average power of transformers at companies is 1 000 kW, according to the experience of author`s assessment. For this case calculations of electric energy losses in transformers for summer and winter periods for different values of asymmetry voltage coefficients higher 2 % were provided in **Fig. 4** and **Fig. 5**. The losses of electric energy in transformers due to asymmetry voltage coefficients of reserve and zero sequence need to be compensated by additional production as estimated in **Table 3**. This production requires extra resources and produces extra emissions (see **Table 5**).

Specific environmental resource consumptions and emissions for the main types of power generating plants are presented in **Table 4**.

Based on these characteristic values relevant for the environment of coal power generating plants, presented in **Table 3**, the reduction potential due to asymmetry for resource consumption and emission generation at power generating plants were estimated for Ukraine in **Table 5. Table 5** depicts the environmental benefit potential when keeping voltage asymmetry within standardized values. Unfortunately, there is key barriers for decreasing these losses – in case of normalization of voltage asymmetry it will be unknown, which power generating plant will generate less energy and in result will consume less resources. For normalization of voltage asymmetry, there are well known and widely used technical options:

- replacing transformers Y/Y on Y/Z;
- balancing of consumers by phases;
- installation of:
- phase voltage stabilizers;
- philtres;
- reactive power capacity banks.

All mentioned options are available for implementation at places near to consumers. This means, that with the implementation of this options, electric energy and resources, could be saved. The amount of savings could be calculated for electric energy and estimated for resources or emissions.

CONCLUSIONS

In the presented project the asymmetry voltage coefficients value in Ukrainian grid was estimated based on measurements in 23 characteristic Ukrainian companies during 2016-2018. It was estimated, that 26 % of trans-formers have asymmetry voltage coefficient of reverse sequence lower than 2 % and 12 % of

Table 3. Estimated annual electric energy losses in transformers due to the voltage asymmetry calculation in Ukraine

Parameter		Value	
		Summer	Winter
Transformer type		TM-1 000	
Nominal power, kVA		1 000	
Losses of non-load regime, kW		2.1	
Losses of short circuit, kW		12.2	
Voltage of short circuit, %		5.5	
Assumed working hours of transformers per season and year, h/a		4 380	4 380
Condition – Asymmetry voltage coefficient of reverse sequence (%)	Parameter	Value	
2.05	Hours in this working modus of transformers per season	1 260	1 540
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	9 358.64	11 438.34
2.26	Amount of working transformers	1 440	1 760
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	12 999.12	15 887.82
2.67	Amount of working transformers	1 800	2 200
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	22 679.30	27 719.15
3.08	Amount of working transformers	1 980	2 420
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	33 197.19	40 574.34
3.29	Amount of working transformers	2 160	2 640
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	41 321.89	50 504.53
3.5	Amount of working transformers	2 340	2 860
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	50 662.50	61 920.83
3.71	Amount of working transformers	2 340	2 860
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	56 924.38	69 574.24
Condition – Asymmetry voltage coefficient of zero sequence, %	Parameter	Value	
2.18	Amount of working transformers	900	1 100
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	7 559.45	9 239.33
2.6	Amount of working transformers	1 080	1 320
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	12 903.43	15 770.86
3.01	Amount of working transformers	1 260	1 540
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	20 176.14	24 659.73
3.43	Amount of working transformers	1 440	1 760
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	29 942.31	36 596.16
4.26	Amount of working transformers	1 800	2 200
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	57 733.29	70 562.92
4.68	Amount of working transformers	1 980	2 420
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	76 646.36	93 678.88
5.1	Amount of working transformers	2 160	2 640
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	99 295.31	121 360.94
5.51	Amount of working transformers	2 340	2 860
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	125 560.69	153 463.07
6.77	Amount of working transformers	2 880	3 520
	Annual electric energy losses in transformers due to voltage asymmetry* per season, MWh$_{el}$/a	233 294.48	285 137.70
Total annual electric energy losses in transformers due to voltage asymmetry, GWh$_{el}$/a		1 978	

*values are calculated according to the methodology (Ded and Parshukova, 2014), based on measurements (see **Fig.5**).

Table 4. Specific environmental resource consumptions and emissions of main Ukrainian power generating plants per MWh_{el}

Parameter	Type of power generating plant		
	Hydro	Coal	Nuclear
Water consumption	-	1.25 m^3/MWh (Davidson *et al.*, 2002)	3.88 m^3/MWh (Meldrum, Nettles-Anderson, Heath & Macknick, 2013)
Ash emission	-	0.37 kg/MWh (Davidson *et al.*, 2002)	-
Coal use	-	480 kg/MWh (Davidson *et al.*, 2002)	0.041 g/MWh (Brünglinghaus, 2018)
CO_2 output	11 kg/MWh (Turconi *et al.*, 2013)	900 kg/MWh (Davidson *et al.*, 2002)	19 kg/MWh (Turconi *et al.*, 2013)
SOx output	0.015 kg/MWh (Turconi *et al.*, 2013)	7.4 kg/MWh (Davidson *et al.*, 2002)	0.02 kg/MWh (Turconi *et al.*, 2013)
NOx output	0.032 kg/MWh (Turconi *et al.*, 2013)	3.7 kg/MWh (Davidson *et al.*, 2002)	0.025 kg/MWh (Turconi *et al.*, 2013)
Nuclear waste	-	-	8.95E-6 m^3/MWh (Frischknecht, 2017)

Table 5. Environmental benefit potential at power plants due to normalization of the voltage asymmetry

Parameter	Type of power generating plant		
	Hydro	Coal	Nuclear
Annual electric energy losses in transformers due to voltage asymmetry, MWh/a	178 050.90	791 337.33	1 008 955.09
Water losses due to voltage asymmetry, m^3/a	-	989 171.66	3 914 745.75
Ash emissions due to voltage asymmetry, t/a	-	292.79	-
Coal/Uranium losses due to voltage asymmetry, t/a	-	379 841.92	0.41
CO_2 emissions due to voltage asymmetry, t/a	1 958.56	712 203.59	19 170.15
SOx emissions due to voltage asymmetry, t/a	2.67	5 855.90	20.18
NOx emissions due to voltage asymmetry, t/a	5.70	2 927.95	25.22
Nuclear waste, m^3/a	-	-	9.03

transformers have asymmetry voltage coefficient of zero sequence lower than 2 %. These transformers will not be included in electric energy losses calculation and will not account for significant resource losses. From the derived values for the companies a rough distribution for the country of the asymmetry voltage coefficients higher 2 % was derived. Based on this distribution annual electric energy losses in transformers and associated emissions and resource consumptions were estimated for Ukraine. The estimated potential benefits for Ukrainian power generation in case of normalization asymmetry of voltages coefficient are:

- 1 978 GWh/a (which is up to 1.5 % of total injected electric energy, according to (UKRENERGO, 2018));
- 4 900 km^3/a of water;
- 292.79 t/a of ash emissions;
- 379 kt/a of coal consumption;
- 0.41 kt/a of uranium consumption;
- 733 kt/a of CO_2 emissions;
- 5.9 kt/a of SOx emissions;
- 2.9 kt/a of NOx emissions;
- 9.03 m^3/a of nuclear waste.

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