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INFLUENCE OF UNBALANCE OF LOADS ON QUALITY OF ELECTRIC ENERGY IN A LOW VOLTAGE LINE

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Abstract

The paper presents results of investigations of deviations of voltage from rated value (δU) and the voltage unbalance coefficient (α_{U2}) at the rural consumers' sites supplied from the final section of a low voltage line under the load asymmetry conditions. Those parameters are one basic parameters describing quality of electric energy. A probabilistic model of the distinguished parameters, taking into account load unbalance, was built in scope of the investigations. A simulation programme enabling to determine voltage deviation and the voltage unbalance coefficient, among other things, for various variants of the cable cross-sections applied and various variants concerning the types of the consumers connected was elaborated on the basis of the model built; two essential types were distinguished here: living and production consumers characterised by different power consumption rate. The calculations were performed for a three-phase, four-cable airborne power line with flat arrangement of cables.

Keywords: *low voltage line, single-phase receivers, load unbalance, voltage deviations, voltage unbalance*

1. Introduction

Four-cable airborne power lines with flat arrangement of cables are the most frequent lines in the rural low voltage site networks. Consumers using three-phase and single-phase receivers for production and living purposes are supplied from those lines. Using those receivers is decisive for the line load rate. That load is unbalanced due to uneven division of power of the single-phase receivers into individual line phases and their random connecting to the network [5]. The unbalance is also influenced by: unequal phase mutual impedances of the electric power lines, unequal values of phase resistances and reactance of some receivers as well as unbalance of supply voltages. The effect of such unbalanced load is voltage unbalance – unequal values of voltages in the individual line phases. It deteriorates conditions of work of the receivers, particularly three-phase ones, e.g. engines. Moreover, the effect of unbalanced load are increased power and electric energy losses when compared to the losses which would occur in case of balanced load. Electric energy as goods must by characterised by appropriate values of the parameters. Keeping their admissible values is one of the conditions aimed at assurance of correct work of the receivers supplied by low voltage lines. From among various parameter describing energy quality one of the most significant is effective value and supply voltage unbalance. They are identified by deviation of voltage from rated value (δU) and the voltage unbalance coefficient: reverse sequence (α_{U2}) and zero sequence (α_{U0}). Due to the fact that the standardised regulations concerning electric power refer to the two first parameters, the investigations were focused on them.

2. Selection and identification of the investigation object

The investigation object is a low voltage electric power line, with unbalanced load, supplying rural consumers.

Model of line of 2nd type with zero values of transverse parameters of an equivalent circuit (transverse parameters: unitary line conductance G_o, unitary line susceptance B_o are taken into account in the medium and high voltage lines) [1] has been adopted for the analysis. The considered line type is characteristic for rural areas: four-cable airborne power lines with flat arrangement of cables. This type, being the most common, is also the most favourable due to the mutual impedances of the lines in the aspect of load unbalance, and thus quality of energy supplied to the consumers. Unequal values of mutual impedances make that the line is unbalanced as a transmission element of electric energy.

Moreover, it has been assumed that the nature of the receivers is resistance-and-induction one.

Operation and maintenance tests in a real investigation object were performed in scope of the identifications. The investigation purpose was to determine load unbalance and related voltage conditions present in low voltage networks. The investigation programme consisted, among other things, of:

- determination of values of voltages occurring at the sites of the consumers, particularly the ones consuming energy supplied by the final section of the low voltage line,
- analysis of the values of voltage deviations from the rated value (230 V) including the tests to check, if those deviations exceeded the ranges specified by the standard,
- determination of the voltage unbalance level in a low voltage network.

The results of the performed investigations of the voltage conditions in a low voltage site network, referred to the voltage value and its unbalance are presented in the Tables 1 and 2

Tab. 1. Values of the voltage deviations at the sites of the consumers supplied by the final section of the low voltage line

Measurement method	Voltage deviation		
	Average value [%]	Value rage [%]	Admissible value range [%]
Momentary measurements at 74 consumers' sites in the autumn-and-winter season, in the evenings:			
- with the receivers switched on	-2.48	-10.6 ÷ +5.13	-10 ÷ +10
- after switching on an additional 1 kW single-phase receiver	-2.47	-10.9 ÷ +4.83	
- after switching on an additional 2 kW single-phase receiver	-3.17	-12.2 ÷ +5.43	

Calculations of the value of the load deviations show that the average values are within the admissible range –10 ÷+10%, however exceeding the lower admissible limit was observed in 10% of cases. Growing the lower limit of the values going beyond the admissible range occurred together with an increase in power of the additional receiver being switched on.

At the investigation stage it was attempted to answer the question how the voltage conditions are changed when a rural consumer buys a new single-phase receiver, facilitating the work on the farm, and connects it to a single-phase network.
In many farms (19.8% of the consumers) the admissible value of the voltage unbalance coefficient (2%) was already exceeded with the current load (Table 2). After connecting a 1 kW receiver to a randomly selected phase, the number of the consumers with exceeded admissible value of the unbalance coefficient increased to 21,6%, and after connecting a 2 kW receiver to the same phase – as much as by 31%. It should be taken into account that connection of additional single-phase receivers improved voltage unbalance at some consumers' sites, however this state was worsened in a considerable part of cases.

Tab. 2.Voltage unbalance at the consumers' sites supplied by the final section of the low voltage line

Measurement method	Sample (consumers) number	α_{U2} [%]	α_{Uadm} [%]	Percentage of admissible value exceeded
- with the receivers switched on	69	1.29	2	19.8
- after switching on an additional 1 kW single-phase receiver	69	1.40	2	21.6
- after switching on an additional 2 kW single-phase receiver	69	1.79	2	31.0

Thus it was concluded that after introduction of new single-phase receivers improving technological processes in farms and used at households, taking into account the current state of the rural low voltage networks, exceeding the admissible values of the voltage unbalance coefficient should be expected.

Measurements of voltages at the medium voltage/low voltage stations were used to determine the voltage unbalance coefficient. It turned out that the phase voltages were practically balanced there, and the average value of the coefficient was around 0.02%.

The standard PN-EN 50160 specifies the limitations not only as to the admissible value for the parameters being the voltage deviation and supply voltage unbalance, but also admissible percentage number of exceeding those limiting values during a week time. Five-percent number of exceeding limiting values out of all weekly performances is admissible [7].

3. Probabilistic model to determine deviations and voltage unbalance coefficients in a low voltage line

The values of the voltage drops and consequently levels and unbalance voltage in a low voltage line are influenced by the parameters of the line as a transmission element, being its length, arrangement of cables, cross-sections of the cables, distribution of the receiving points as well the consumers through the value of the consumed power and unbalance of phase loads. Due to the quantity of those factors that are decisive for the level and voltage unbalance in the line and due to the difficulties related to performance of the complex investigations concerning loads of consumers as well as their cost, a model of simulation determination of the selected quality parameters of electric energy was elaborated. It facilitates to determine values of the voltage drops and deviations and voltage unbalance with various methods of distributing the consumers along the line, different values of the power consumed by the consumers and various levels of phase load unbalance. The input data refer to:

- length of the line l;
- number of consumers n,
- distance of the receiving points from the line beginning l_i;
- cross-sections of the cables: phase s, neutral s_n;
- distance between the cables b_{AN}, b_{BN}, b_{CN}, b_{AB}, b_{BC}, b_{CA};
- value of the power consumed by the consumers P_i.

Topology was determined for the line, it means on the basis of once generated: length of the line l from Weibull distribution with the parameters p=2, λ=0,8, which corresponded to the data on the circuits gathered from the territory of Poland [2], determined number of receiving points n their distribution along the line l_i on the basis of the triangular distribution [3] was generated. Next, the phase line was specified randomly: the most, intermediately and the least loaded by a consumer at each i-th receiving point. The momentary loads for daily changes were generated from empiric distribution. In each generation point (time moment) the average value and standard deviation of load was taken from normal distribution on the basis of 14 days of daily changes at the consumer's site. Division of loads into phases was performed by generation of the value of the load unbalance coefficients in the particular receiving points on the basis of empiric distributions obtained from the load measurements performed at the consumers' sites. Those coefficients were defined as relations of respective phase loads [6]:

a) maximum load coefficient [4]

$$w_i = \frac{P_{\max i}}{P_i} \tag{1}$$

b) intermediate load coefficient

$$k_{1i} = \frac{P_{pi}}{P_{\max i}} \approx \frac{I_{pi}}{I_{\max i}}, \tag{2}$$

c) minimum load coefficient

$$k_{2i} = \frac{P_{\min i}}{P_{\max i}} \approx \frac{I_{\min i}}{I_{\max i}} \tag{3}$$

where:

$$P_i = P_{\max i} + P_{pi} + P_{\min i} \tag{4}$$

P_{maxi}, I_{maxi}, P_{pi}, I_{pi}, P_{mini}, I_{mini} – power and phase current respectively for being the most, intermediately and the least loaded in particular receiving points

Mutual relation between the values of the coefficients is determined by the relation:

$$k_{1i} + k_{2i} = \frac{1}{w_i} + 1 \tag{5}$$

The value of the coefficient k_{2i} was determined on the basis of the relation (5) after prior generation of the values of the coefficients w_i and k_{1i} .
The admissible ranges of their values are presented in the Table 3.

Tab. 3. Admissible values of the coefficients of load unbalance

w_i	**0.33**	0.36	0.4	0.44	**0.5**	0.57	0.67	0.8	**1**
k_{1i}	**1**	0.875÷1	0.750÷1	0.625÷1	**0.5÷1**	0.375÷0.75	0.25÷0.5	0.125÷0.25	**0**
k_{2i}	**1**	0.875÷0.75	0.750÷0.5	0.625÷0.25	**0.5÷0**	0.375÷0	0.25÷0	0.125÷0	**0**

For balanced load those coefficients take the values: $k_{1i} = 1$, $k_{2i} = 1$, $w_i = 1/3$, however in case of an extreme unbalance, where the total power is taken by one phase, their values are as follows: $k_{1i} = 0$, $k_{2i} = 0$, $w_i = 1$. The momentary values of the coefficients of power - $\cos\varphi_{fi}$ for the receiving points were generated on the basis of the empiric distributions obtained from measurements performed at a medium voltage/low voltage station. The values of the phase loads and the phase coefficients of power made it possible to determine currents in the line (in the phase and neutral cables) between the receiving points. Those currents were the basis to determine drops of voltages, and thus values of phase voltages, deviation of phase voltages and coefficients of voltage unbalance in receiving points. The voltage deviation and coefficient of voltage unbalance are respectively defined by the following relations [5]:

$$\delta U_{fi} = \frac{U_{fi} - U_n}{U_n} \cdot 100\% \qquad (6)$$

where:

U_n – rated voltage (U_n=230V),
U_{fi} – phase voltage.

$$\alpha_{U2i} = \frac{U_{2i}}{U_{1i}} \cdot 100\% \qquad (7)$$

where:

U_{2i} , U_{1i} – symmetrical components of phase voltages, respectively: of reverse and concurrent sequence in the i –th terminal

4. Selected results of simulation investigations

Due to performance of the simulation, a low voltage line with the length l = 1048 m, to which 15 consumers are connected, who are distributed in the following distances from the beginning of the line was, among other things, generated:
l_1 = 82 m, l_2 = 92 m, l_3 = 105 m, l_4 = 284 m, l_5 = 296 m, l_6 = 301 m, l_7 = 312 m, l_8 = 368 m, l_9 = 495 m, l_{10} = 589 m, l_{11} = 663 m, l_{12} = 750 m, l_{13} = 795 m, l_{14} = 841 m, l_{15} = 1048 m.
Calculations of the unbalance coefficient α_{U2} were performed for different variants concerning the applied cross-section of cables and various variants concerning types of the connected consumers. Two types of consumers were considered: living and production ones. The obtained values of the coefficient for the performed simulations are presented in the Table 4 and as an example in the Fig.1.
The Fig.1 shows a histogram of values of voltage unbalance coefficients for the performed simulation in case of a supply line for the prevailing number of production consumers. Distinct fraction of values of the coefficient exceeding the admissible value of 2% may be noticed.

Tab 4. Selected results of simulation investigations of the voltage unbalance coefficient

Cross-sections of the cables		Percentage value of the exceeded admissible value of the coefficient α_{U2}		
phase	neutral			
70	70	2.09	0.49	0.00
50	70	**9.72**	2.97	0.00
50	50	**10.32**	3.97	0.20
35	50	**11.71**	**9.82**	0.99
35	35	**12.10**	**10.02**	1.09
Number of living consumers		0	5	10

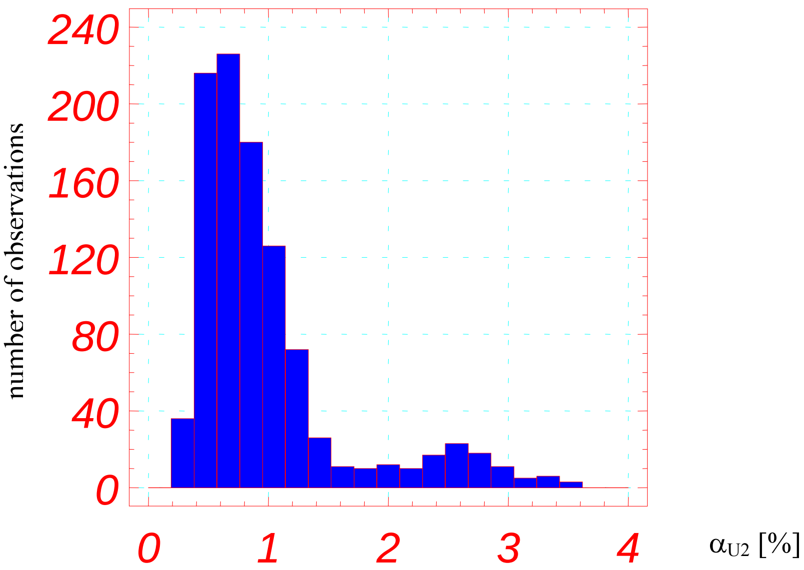

Fig.1. Histogram of values of the voltage unbalance coefficient, obtained as a result of the simulation, for the following parameters: c-section of phase cables - 35 mm^2, cross-section of the neutral cable - 35 mm^2, number of the living consumers – 5.

5. Summary

Performance of the simulation experiments with a probabilistic model allows to determine values of the selected parameters describing the low voltage line and consumers, for which there is a risk of exceeding admissible values of the selected items describing quality of the electric energy transferred. Risk of exceeding admissible values of the parameters of electric energy caused by the load unbalance is the larger the larger consumption of power in the line is. The length of the low voltage line with unbalanced consumption of power affects quality of electric energy, however significant deterioration of the parameters (δU, α_{U2}) appear at the clients' sites located within the final section of the line (e.g. more than 800 m for a line with about 1000 m length). Improvement of the values of the parameters δU, α_{U2} is obtained by increasing cross-sections of the phase and neutral cables, but it is related with bearing specific costs in order to assure adequate quality of electric energy supplied to the consumers – improvement from 25 to 40% of the values of the parameters for the simulation performed.

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