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SIMULATION MODEL TO EVALUATE VOLTAGE ASYMMETRY IN A RURAL LOW VOLTAGE POWER LINE

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Key words: loads asymmetry, simulation model, voltage asymmetry.

Abstract

This paper presents a simulation model to evaluate phase voltage unbalance in rural local low voltage power lines. The voltage asymmetry has been evaluated by the voltage asymmetry coefficient value α_{U2}, being one of the essential parameters characterizing quality of electric energy supplied from a low voltage power line to the consumers.

SYMULACYJNY MODEL OCENY NIESYMETRII NAPIĘĆ W WIEJSKIEJ LINII NISKIEGO NAPIĘCIA

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Słowa kluczowe: asymetria obciążeń, model symulacyjny, niesymetria napięć.

Abstrakt

W artykule przedstawiono symulacyjny model oceny niezrównoważenia napięć fazowych w terenowych wiejskich liniach niskiego napięcia. Niesymetria napięć była oceniana przez wartość współczynnika asymetrii napięciowej α_{U2}, który jest jednym z podstawowych parametrów charakteryzujących jakość energii elektrycznej dostarczanej do odbiorców z linii niskiego napięcia.

Introduction

The current and voltage asymmetry in three-phase power networks is mostly caused by asymmetrical loads and asymmetrical transmission devices. Work of a three-phase power supply system is called asymmetrical or symmetrical, when the working conditions of a single or of all phases are not equal. Short-term and long-term asymmetrical operational types of work occur in three-phase systems. A short-term asymmetry is usually caused by breakdown processes. They are mostly asymmetrical short-circuits and switching off one of the phases within a cycle of automatic reswitching. Long-teem asymmetry in an industrial system may occur when connecting asymmetrical loads to a power network, when asymmetrical elements occur or when a transmission system works asymmetrically.

Asymmetrical states of work occur particularly in rural low voltage distribution networks. Such states result from the phase loads asymmetry, caused by unequal distribution of power on individual phases of single-phase receivers and random nature of connecting receivers to a power line.

The loads asymmetry in rural low voltage networks is an important problem, what was proven by the results obtained from investigating the current asymmetry and unbalance coefficients, the values of which reached significant figures (KOWALSKI et al. 1983, NIEBRZYDOWSKI 1992). If the loads asymmetry investigations are performed, they are being carried out in transformer stations, that means at the power line start, thus simplifying their realization and reducing the costs. Because of the fact that measuring currents and voltages (particularly at the end of a LV power line) is ineffective, the analysis of the loads asymmetry and its consequences based on simulation methods is of special importance.

Investigation object

The investigation object is a low voltage power line (LV) supplying energy to rural consumers. The model of the LV power line under analysis is shown in Figure 1. A model of II type power line characterized by zero values of the transverse parameters of a substitutive diagram (power line unitary conductance $G_o = 0$, power line unitary susceptance $B_o = 0$) has been adopted for the analysis purposes. The considered type of four-cable airborne power line, with flat arrangement of cables is characteristic for rural areas. It is also the most popular and the most disadvantageous due to power lines reciprocal impedance in terms of the loads asymmetry, and thus quality of the energy supplied to its consumers.

In order to determine the loads asymmetry and the voltage conditions occurring in low voltage power lines related to it, operational investigations have been performed in a real object. Both temporary and 24-hour registering measurements of voltages and loads (currents and powers) at the start of the power line (in a transformer station 15/0,4 kV with LV rails) were performed within the framework of the investigations.

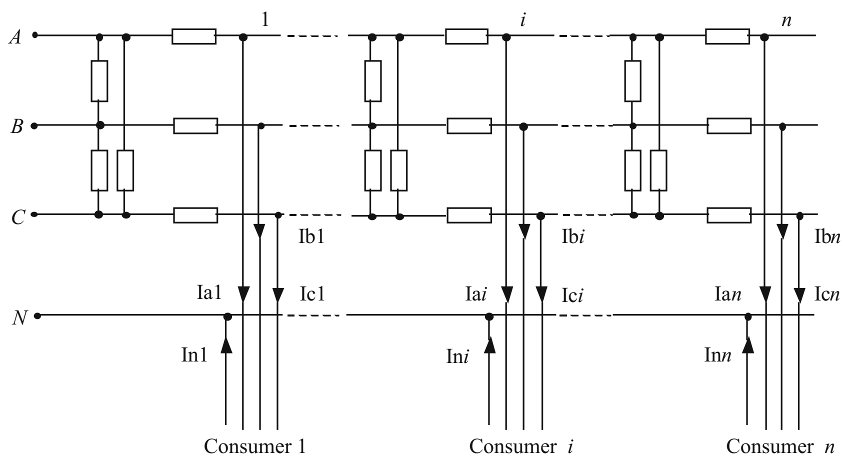

Fig. 1. Low voltage power line model

Probabilistic model to determine chosen parameters characterizing electric energy quality

The purpose to evaluate asymmetry in a low voltage power line is realization of more expensive, time consuming investigations in a real power line at each consumers' place at the same time. For that reason a simulation model was built to facilitate determination of the voltage drop and deviation values and voltage asymmetry with, among other things, various variants of distribution of consumers along the power line, various values of power consumed by the consumers and various levels of phase loads asymmetry.

The model input data are related to:
– length of the power line l;
– number of consumers n,
– distance from the receiving points to the power line start l_i;
– cross-sections of: phase s, neutral s_n cables;

– distance between the cables: b_{AN}, b_{BN}, b_{CN}, b_{AB}, b_{BC}, b_{CA};
– value of power consumed by the consumers P_i.

A topology was specified for the power line, it means that on the basis of single-time generated: length of the power line l out of the Weibull distribution with the parameters $p = 2$, $\lambda = 0.8$, corresponding to the circuits data collected from the territory of Poland (GAWLAK 1992), given number of receiving points n their distribution along the power line l_i was generated on the basis of triangle distribution with the density function $f = 2(b\text{-}y)/(b\text{-}a)^2$ (a = 80 m, $b = l$) (HELLWIG 1993). Adopting triangle distribution was caused by the fact that greater number of consumers is usually situated close to a MV/LV transformer station and their number gets lower as the distance gets longer.

The temporary loads for 24-hour work were generated out of an empiric distribution. In each generation point (time moment) an average value and standard load deviation were taken out of the normal distribution based on 14 full days of 24-hour work at a consumer's place. An exemplary average 24-hour graph of loads in an agricultural holding is presented in the Figure 2.

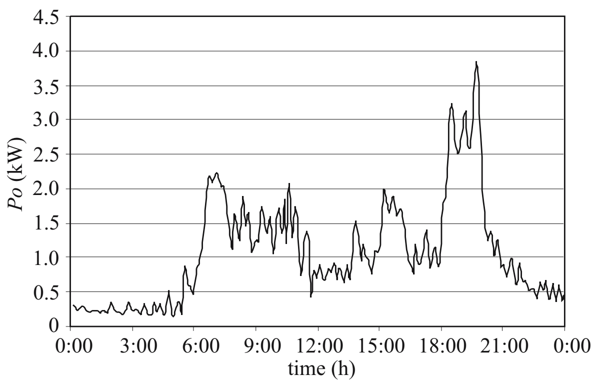

Fig. 2. Average 24-hour graph of the loads in an agricultural holding (14 days)

The value of power consumed by a consumer at the given time moment is a sum of the power value in particular phases. In each group of values of three phase powers the following may be distinguished: $P_{\max i}$ – power of the most loaded phase, P_{pi} – power of the intermediately loaded phase, $P_{\min i}$ – power of the least loaded phase. Subsequently, power in the i-th receiving point of the power line may be presented with the following relationship:

$$P_i = P_{\max i} + P_{pi} + P_{\min i} \tag{1}$$

On the basis of the said powers it is possible to determine coefficients being a measure of the consumer's phase loads unbalance (KUJSZCZYK 1991):

– intermediate load coefficient

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

– minimal load coefficient

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

where:

$I_{\max i}$, $I_{\min i}$, I_{pi} – load of the maximally, minimally and intermediately loaded phase in the i-th terminal.

In order to provide more comprehensive evaluation of the phase loads unbalance, a maximal load coefficient, described with the following relationship (KOLBER, PIECHOCKI 2005), was introduced apart from the aforementioned coefficients:

$$w_i = \frac{P_{\max i}}{P_i} \tag{4}$$

It describes the share of power consumed by the most loaded phase in relation to total power consumed at a receiving point. It may be stated that this coefficient describes to what extent the most loaded phase is a dominant phase when compared to the remaining ones in terms of the consumed power.

Between the above coefficients there is the following relationship:

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

Division of power into the phases was realized by generating load asymmetry coefficients values w_i, k_{1i}, the distributions of which are presented by histograms (Fig. 3 and Fig. 4).

In case of symmetrical load, these coefficients take the following values: $k_{1i} = 1$, k_{2i}, $w_i = 1/3$, however in case of an extreme asymmetry, when the total power is consumed by one of the phases, their values are as follows: $k_{1i} = 0$, $k_{2i} = 0$, $w_i = 1$.

The admissible ranges of the respective coefficient values are described with the relationships:

$$\frac{1}{3} \leq w_i \leq 1 \tag{6}$$

$$k_{1i} \geq k_{2i} \tag{7}$$

for $w_i \in <1/3;\ 1/2)$

$$\frac{\frac{1}{w_i} - 1}{2} \leq k_{1i} \leq 1 \tag{8}$$

$$\frac{1}{w_i} - 2 \leq k_{2i} \leq \frac{\frac{1}{w_i} - 1}{2} \tag{9}$$

for $w_i \in <1/2;\ 1>$

$$\frac{\frac{1}{w_i} - 1}{2} \leq k_{1i} \leq \frac{1}{w_i} - 1 \tag{10}$$

$$0 \leq k_{2i} \leq \frac{\frac{1}{w_i} - 1}{2} \tag{11}$$

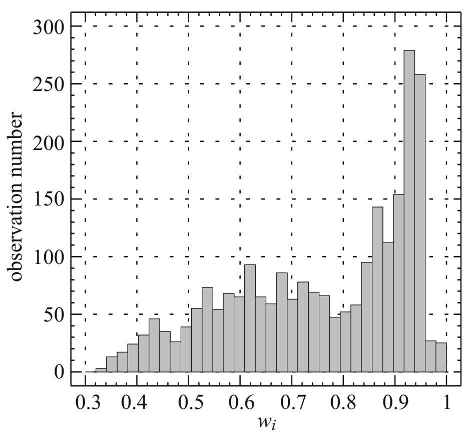

Fig. 3. Histogram of the maximal load coefficient value w_i

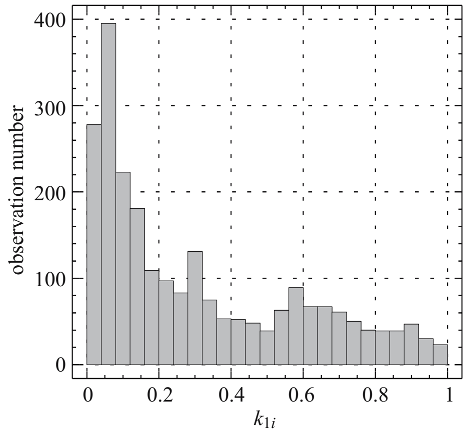

Fig. 4. Histogram of the intermediate load coefficient value k_{1i}

The value of the coefficient k_{2i} was determined on the basis of the relationship (5) after transforming it.

Some measurements were carried out in a MV/LV station for the power coefficient cosφ. On this basis beta distribution was adopted for this parameter and conformity was verified by means of a test of empirical data conformity with theoretical distribution.

Randomisation of assigning the consumer's phase loads to the power line phases was carried out by means of a pseudorandom number generator with a uniform distribution.

The phase powers and power phase coefficients cos were basis to determine the phase currents in individual receiving points, and thus the values of the phase voltages and voltage asymmetry coefficient.

$$\alpha_{U2i} = \frac{U_{2i}}{U_{1i}} \cdot 100\% \tag{12}$$

where:

U_{2i}, U_{1i} – symmetrical components of phase voltages with opposite and and consistent sequence in the i-th terminal

$$U_1 = \frac{1}{3}\sqrt{U_A^2+U_B^2+U_C^2-2U_AU_B\cos(\alpha+\frac{\pi}{3})-2U_BU_C\cos(\beta+\frac{\pi}{3})-2U_CU_A\cos(\alpha+\beta-\frac{\pi}{3})}$$

$$U_2 = \frac{1}{3}\sqrt{U_A^2+U_B^2+U_C^2-2U_AU_B\cos(\alpha-\frac{\pi}{3})-2U_BU_C\cos(\beta-\frac{\pi}{3})-2U_CU_A\cos(\alpha+\beta+\frac{\pi}{3})}$$

(13)

$$\alpha = \arccos \frac{U_A^2 + U_B^2 + U_{AB}^2}{2U_A U_B} \qquad \beta = \arccos \frac{U_B^2 + U_C^2 + U_{BC}^2}{2U_B U_C} \tag{14}$$

U_A, U_B, U_C, U_{AB}, U_{BC}, U_{CA} – values of phase and cable voltages.

According to PN-EN 50160 1998 the values of the above electric energy parameter should not exceed the admissible value:

$$\alpha_{U2i} \leq 2\% \tag{15}$$

The standardised requirements regarding the voltage asymmetry coefficient value do not describe only its admissible level but also the admissible percentage of the value excesses $\alpha_{U2} = 2\%$ within a week time. Therefore, the temporary values of the coefficient for the generated values of the phase loads in respective receiving points were determined several times per each 10 minutes of all entire days of a week in the simulation model.

The temporary values were averaged for the period of 10 minutes. On the basis of the averaged values of the parameters, their distributions were achieved and it was possible to determine the percentage of admissible value excess, as well as this excess level within a week time.

Verifying the model adequacy

In order to study the voltage conditions in a local low voltage network, and particularly voltage asymmetry, at the energy consumption places, the phase voltage measurements were carried out at those consumers who were equipped with three-phase terminals and who consumed energy supplied by the end-point section of a LV power line. At all 74 consumers under investigation, apart from the voltage measurements with the loads resulting from the normal use of the receivers in the given time of the day, the measurements were also performed after connecting an additional single-phase 1 kW and than 2 kW receiver to a randomly selected phase.

The average value of the asymmetry coefficient was tending to grow. In case of the measurements with the existing load at the consumer's place, the average value of the asymmetry coefficient was 1.29% with the standard deviation of 1.17%, and with the additional single-phase load of 1 kW power – 1.40%. With the additional single-phase load of 2 kW power, the average value of the asymmetry coefficient was 1.79%. In 19.8% of the agricultural holdings (consumers) the asymmetry coefficient was exceeded even with the load existing at that time. After connecting a 1 kW receiver to a randomly selected phase, the number of consumers with exceeded asymmetry coefficient went up to 21.6%, and after connecting a 2 kW receiver to the same phase 2 – as much as to 31%. It should be taken into account that connecting extra single-phase receivers caused improved asymmetry at some consumers' places, however this state was deteriorated in greater number of cases.

As a result of the simulation performed for a power line with the length of l = 1048 m supplying energy to 15 consumers (the average number of receiving points for the rural power networks is 13) the percentage of excesses of admissible value of the coefficient α_{U2} = 2% was determined out of the temporary values averaged for 10 minutes taken from a week time. In case of supplying energy to 10 production consumers and 5 residential ones the percentage of excesses of the parameter admissible value was 10.02% (Fig. 5), however the excess percentage was increased to 12.1% when supplying exclusively production consumers (increase in the power consumption in the power line).

Basing on the investigations performed in a real object and on the research carried out by means of the simulation model it may be stated that the increase in the power consumption leads to increased number of excesses of the admissible value of the voltage asymmetry coefficient. Greater percentage of the parameter excesses for the operational investigations in a local power network results from the fact that these investigations were performed in a given time of a day (peak hours), when the power consumption was the greatest, whilst the simulation investigations referred to 24-hour periods out of an entire week. However it does not change the fact that the parameter value change tendency is similar.

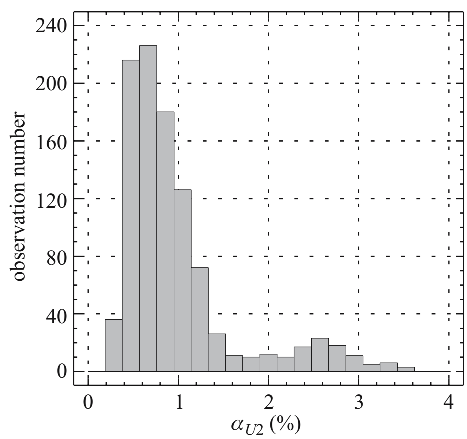

Fig. 5. Histogram of the voltage asymmetry coefficient values obtained as a simulation result for the following parameters:
– phase cables cross-section – 35 mm^2,
– neutral cable cross-section – 35 mm^2,
– number of residential consumers – 5

Summary

By analysing the investigation results in terms of the voltage asymmetry in rural low voltage networks it should be stated that the admissible value of the voltage asymmetry coefficient (α_{U2} = 2%), being one of the main parameters characterizing quality of energy supplied to the consumers, is frequently exceeded in a low voltage power line. Subsequently, it may be concluded that after putting into operation new single-phase receivers improving technological processes in agricultural holdings and used in households, it should be taken into account that the number of the excesses of the admissible value of the voltage asymmetry coefficient is going to increase with the existing condition of the rural low voltage networks. Evaluation of the load asymmetry and the related voltage asymmetry in real rural low voltage networks is difficult and expensive, as it requires to perform simultaneous measurements of the loads and voltages at all the consumers' places. The analysis of the investigation results of the voltage asymmetry at the rural consumers' places and those achieved by means of the simulation model let us state that it may be used to evaluate quality of the supply voltage substituting expensive and time consuming measurements in real premises. On the basis of the investigations performed by means of the simulation model it is possible to evaluate risk of exceeding admissible value of the parameter α_{U2} of the energy transmitted in the LV power lines.

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