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INCREASED POWER AND ENERGY LOSSES IN LOW VOLTAGE POWER LINE CAUSED BY LOAD ASYMMETRY

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Abstract

The paper presents a simulation model enabling determination of load resultant active power and energy losses, with regard to load in rural distribution low voltage power networks supplying the so called scattered consumers. The subject of examinations was a three-phase, four-wire, airborne low-voltage power line. The studied type of line is characteristic to, and most commonly used in, rural areas. The considerations included twenty-four-hour load measurement at representative consumers and at the beginning of the line – in a MV/LV transformer station. On the basis of the developed model, a simulation program enabling calculation of power and energy losses has been elaborated. Also, selected results of examinations concerning increase in active power and energy caused by load asymmetry for power line supplying two types of consumers: residential and production ones, have been presented.

Keywords: *low-voltage line, rural consumers, single-phase receivers, load asymmetry, power and energy losses*

1. Introduction

Load asymmetry in a low-voltage line results in current asymmetry in the line, limitation of power consumption, power asymmetry and increase in active and passive power losses in an inductive line.

However, in reality, in the line fixed operation states, there should be distinguished two kinds of asymmetry [4]:

a) internal asymmetry of the power line elements (lines and transformers) caused by different self- and inter-impedances and of particular phases,
b) external asymmetry:
   - supply point, when three-phase voltage in the line power point (MV/LV station) is unsymmetrical,
   - receiving point asymmetry when receptions connected in particular points of the power line are of different power in each phase,
   - receiving spatial when single-phase receptions of the same or different power are connected to the line at different points.

Receiving external asymmetry, including both the point ad the spatial asymmetry, and especially asymmetry occurring in four-wire low voltage power network 3×400/230V is of the biggest practical importance.

The considerations were limited to load power losses in the line as one of the most negative effects for rural distribution low voltage power lines. Due to the fact that active power losses [1] are most common, the considerations have been focused on them. Asymmetry of the power line is caused by the consumers themselves who use single-phase receivers. It results in non-uniform power distribution in the line. With the line asymmetrical load, active power losses are the sum of losses in particular wires, i.e. phase and neutral ones. The increase in power losses and related energy losses in lines, in case of load asymmetry, in relation to power losses with asymmetrical loads, is caused by transmitting the so called asymmetry power [4, 5]. Load asymmetry occurs mainly in rural low-voltage power networks where lines are relatively long and to which a relatively smaller numbers of consumers using receivers of higher powers and take energy of higher values than in urban power networks are connected. All the consumers receiving energy connected to the line have an influence over the loss values, and therefore, a simulation model enabling determination of active power and energy losses with regard to load asymmetry has been developed.

2. Simulation model for power and energy loss determination in low-voltage power line

Considering a low-voltage power line in terms of power and energy loss determination, it was necessary to define division of the power into phases, at particular consumers. This power division is defined by a load unbalance coefficient:

a) indirect load coefficient

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

b) minimal load coefficient

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

c) maximal load coefficient

$$w_i = \frac{P_{\max i}}{P_i} \tag{3}$$

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 current of the phase, respectively: the most, medium and the least loaded, in its particular receiving points

Mutual relation between coefficient values is defined by the dependence:

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

For symmetrical load, these coefficients reach values: $k_{1i} = 1$, $k_{2i} = 1$, $w_i = 1/3$, whereas, in case of extreme asymmetry, when the total power is taken by one phase, their values are as follows: $k_{1i} = 0$, $k_{2i} = 0$, $w_i = 1$.

Permitted value ranges of particular coefficients are defined by dependencies:

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

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

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>

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

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

Permitted ranges of their values are also presented in Table 1.

Table 1. Permitted value ranges of load asymmetry coefficients

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**

On the basis of the performed research, concerning phase loads at representative consumers in rural areas, values of load unbalance coefficients have been demonstrated in Table 2.

Table 2. Values of load unbalance coefficients at rural consumers

Load unbalance coefficients	w_i	k_{1i}	k_{2i}
Arithmetical mean	0,541	0,650	0,287
Standard deviation	0,134	0,233	0,239
Minimum	0,368	0,075	0,002
Maximum	0,928	0,967	0,783

Phase currents, in LV line, in sections between (i-1), and the i-th receiving point for the j-th time moment are determined from dependencies:

$$\underline{I}_{L1ij} = \sum_{i=1}^{n}\sum_{k=i}^{n}\underline{I}_{Akj} \qquad \underline{I}_{L2ij} = \sum_{i=1}^{n}\sum_{k=i}^{n}\underline{I}_{Bkj} \qquad \underline{I}_{L3ij} = \sum_{i=1}^{n}\sum_{k=i}^{n}\underline{I}_{Ckj} \tag{12}$$

where:

$\underline{I}_{Akj}$, $\underline{I}_{Bkj}$, $\underline{I}_{Ckj}$ – combined values of phase powers received at the *k*-th receiving point for the *j*-th time moment

$$\underline{I}_{Akj} = I_{Akj}(\cos\varphi_{Akj} + j\sin\varphi_{Akj}) \tag{13a}$$

$$\underline{I}_{Bkj} = I_{Bkj}(\cos\varphi_{Bkj} + j\sin\varphi_{Bkj}) \tag{13b}$$

$$\underline{I}_{Ckj} = I_{Ckj}(\cos\varphi_{Ckj} + j\sin\varphi_{Ckj}) \tag{13c}$$

$$I_{Akj} = \frac{P_{Akj}}{U_{Akj}\cos\varphi_{Akj}} \qquad I_{Bkj} = \frac{P_{Bkj}}{U_{Bkj}\cos\varphi_{Bkj}} \qquad I_{Ckj} = \frac{P_{Ckj}}{U_{Ckj}\cos\varphi_{Ckj}} \tag{14}$$

where:

P_{Akj}, P_{Bkj}, P_{Ckj} – values of phase powers taken in the *k*-th receiving points for the *j*-th time moment,
$\cos\varphi_{Akj}$, $\cos\varphi_{Bkj}$, $\cos\varphi_{Ckj}$ – values of power phase coefficients taken in the *k*-th receiving points for the *j*-th time moment,
U_{Akj}, U_{Bkj}, U_{Ckj} – values of phase voltages in the *k*-th receiving points for the *j*-th time moment.

Asymmetrical current in the line, in the came section, for the same time moment, is determined as the arithmetical mean of phase currents from the line:

$$I_{sij} = \frac{1}{3}(I_{L1ij} + I_{L2ij} + I_{L3ij}) \tag{15}$$

Then, power losses for asymmetrical load in the line supplying *n* customers for the *j*-th time moment, can be obtained on the basis of the dependence:

$$\Delta P_{sj} = \sum_{i=1}^{n}\frac{1}{3}(I_{L1ij} + I_{L2ij} + I_{L3ij})^2 R_i \tag{16}$$

where:

R_i – value of the line cable resistance between (*i*-l) and the *i*-th receiving point.

However, the power loss value for the *j*-th time moment in a power line, for n customers, for asymmetrical load, is determined from the dependence:

$$\Delta P_{nsj} = \sum_{i=1}^{n}(I_{L1ij}{}^2 + I_{L2ij}{}^2 + I_{L3ij}{}^2)R_i + \sum_{i=1}^{n} I_{Nij}{}^2 R_{Ni} \tag{17}$$

where:

I_{Nij} – value of current in the neutral wire of LV line between (*i*-l) and *i*-th receiving point for the *j*-th time moment,
R_{Ni} – value of the line neutral wire resistance between (*i*-l) and the *i*-th receiving point.

Power losses are determined for a given time moment, e.g. maximum load. Whereas, energy

losses can be determined in result of integration of power losses for a given period. This period can be, e.g. twenty four hours a month.
Energy loss increase coefficient caused by load asymmetry can be defined in connection with this:

$$k_E = \frac{\Delta E_{ns}}{\Delta E_s} \tag{18}$$

where:

ΔE_{ns} - energy loss with asymmetrical load,
ΔE_s - energy loss with symmetrical load.

3. Simulation program for determination of power and energy losses in low-voltage lines

The developed model served for elaboration of simulation program enabling determination of power and energy losses in LV line.

First, the line topology, i.e. for its given length, and a fixed number of receiving points n, their arrangement was generated on the basis of triangular distribution. Acceptance of triangular distribution was dictated by the fact that most of customers are usually located near the MV/LV transformer stations and their number decreases along with the distance. Next, the line phase was defined randomly: the most, medium and the least loaded by the consumers in each *i*-th receiving point.

The investigations covered day and night measurements at representative customers, and at the beginning of the line (in station 15/0,4 kV on LV rails) [2]. For carried out line simulations, values of momentary phase loads concerning the line receiving points, were generated. In each generation point, i.e. time moment, the value was generated from normal distribution with parameters obtained on the basis of measurements, during 14 days and nights, at representative customers. For simulation studies, two types of customers were accepted – individual and business ones. Load division into phases was carried out by generating empirical distributions obtained from load measurements taken at the customers. Momentary values of phase power coefficients - $\cos\varphi_{fi}$ for receiving points were generated on the basis of empirical distributions obtained from measurements at the station of 15/0,4 kV. It seems that these values do not differ much from those obtained from customers. Phase load values and values of power coefficients were the basis for determining currents in the line (in phase and neutral wire) between receiving points. It enabled the calculation of power losses in the power line, for particular time moments. Basing on values of momentary power losses, using the method of numerical integration [3], values of energy losses, for symmetrical and asymmetrical loads, were determined. It allowed the determination of coefficient value being a ratio of losses for load asymmetry to losses for load symmetry.

4. Selected results of simulation investigations

In result of simulation, there was generated, among others, a low voltage line with length of l = 1048 m, to which 10 customers are connected, located in the following distances from the line beginning:
l_1 = 82 m, l_2 = 105 m, l_3 = 284 m, l_4 = 301 m, l_5 = 368 m, l_6 = 495 m, l_7 = 589 m, l_8 = 750 m, l_9 = 841 m, l_{10} = 1048 m.
Within the conducted research, an airborne power line with flat phase and neutral wire setting whose cross-section values were:
$s = s_n$ = 35 mm^2

For the analyzed line, two types of customers were analyzed, i.e. 5 residential and 5 production consumers. Both types of customers are characterized by the following values of installed power:

a) P_z = 9 kW – residential consumers
b) P_z = 32 kW – production consumers

The value of the installed power is understood here as the sum of power of all the receivers owned by a given customer.
It is estimated on the basis of literature, that the level of this power utilization for the top loaded hours is 20-30%.
Table 3 presents simulation results of power losses for day-and-night operation, during top load, in the time of autumn and winter, as well as energy losses during one month (30) days, and 133 days of the same period, for load asymmetry and symmetry. Customer load measurements which served for phase load generation were taken in the autumn-winter time. It is assumed that 365 days of the year are divided into 232 days of spring-summer time and 133 days of the autumn-winter period [5]. The value of power losses for peak load, during 24 hour's time, obtained in result of simulations was consistent with load asymmetry obtained at the beginning of the line which was: $\alpha_{i2} = 0{,}18$ $<\alpha_{i2} = I_N \ / \ (I_{L1}+I_{L2}+I_{L3})>$.

Table 3. Power and energy loss values for LV line

Power and energy losses	Symmetrical load	Asymmetrical load
Power losses for peak load, during operation for 24 hours [kW]	0,873	1,060
Ratio of power loss for peak load	1,22	
Energy losses during one month, in [kWh]	110,81	132,90
Energy losses during 133 days, in [kWh]	488,06	585,34
Ratio of energy losses for load symmetry and asymmetry	1,20	

5. Conclusions

Load asymmetry for the simulation carried out at the beginning of the line, for its peak load, during 24 hours of its operation was $\alpha^*_{i2} = \alpha_{i2} \cdot 100\% = 18\%$ (for load symmetry the coefficient assumes value 0%)

On the basis of an analysis of the results obtained from exemplary simulations, it can be said that the increase in power and energy losses in the power line supplying residential and production customers caused by load asymmetry would be about 20% higher in comparison with energy losses for load symmetry, which is a significant value. The maximum loss increase that could be possible for the carried out simulation would be 64%. It would take place if the phases: most, medium and least loaded were assigned simultaneously at all customers, respectively to the line's first, second and third phase, which seems to be unreal with such a number of customers (n = 10).

In a given area covered by the power network and consisting of many lines, while making a general power and energy analysis involving determination of values of expected loads, the value of transmission capacity and additional costs connected with power transmission, it is necessary to take into account additional losses caused by load asymmetry.

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