INFLUENCE OF THE UNBALANCE FACTORS ON POWER AND ENERGY LOSSES FOR ELECTRIC LINES UNDER HARMONIC REGIME

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REZUMAT. Pierderile de energie electrică în sistemele de transport şi de distribuţie a energiei electrice reprezintă unul dintre indicatorii utilizaţi pentru evaluarea performanţei operatorilor din sistemul electroenergetic. Reducerea componentei tehnice a pierderilor este una idntre preocupările importante a specialiştilor din domeniu. Creşterea ponderii receptoarelor neliniare şi a nesimetriei curenţilor electrici, în special în zona tensiunilor medii şi joase, determină necesitatea evaluării nivelului pierderilor în prezenţa perturbaţiilor din reţea. În cadrul lucrării este dezvoltată o metodă de analiză a pierderilor de putere şi de energie, în regim sinusoidal dar nesimetric pentru reţele electrice de distribuţie.

Cuvinte cheie: indicatori de nesimetrie, pierderi de putere, pierderi de energie

ABSTRACT. Losses in electricity transmission systems and distribution of electrical energy is one of the indicators used to assess the performance of the electricity system operators. Reduction of losses technical component is one dintre major concerns of specialists in this field. Increasing share of non-linear receivers and unsymmetrical electric currents, particularly low and medium voltages, determined the need to evaluate the losses level in the presence of disturbances in the network. The work developed a method of analysis of the power and energy losses, but the sine nesimetric for electrical distribution networks.

Keywords: unbalance indicators, power losses, energy losses

1. INTRODUCTION

It is known that technical loss of power and energy are two subclasses: real and theoretical [1,2]. Technical component of energy losses can be optimized, by minimizing its objective function. Thus, the loss of electricity may be an indicator characterizing the performance of electrical network [3].

2. MATERIAL PARAMETERS ASSOCIATED WITH ELECTRIC NETWORKS

Material data required for Distribution Electrical Lines (DEL)

For the calculation of energy losses in a DEL is necessary to be known:

- topology or electric scheme (fig. 1);
- electric line rated parameters:

s – cross-section area of active conductors and neutral conductor;

L – line length;

ρ – electric line wires resistivity;

x_0 – rated reactance for electric line wires;

b_0 – transversal susceptance of the line;

g_0 – transversal conductance of the line.

The parameters of single-circuit electric line are calculated in sequel:

- Electric line resistance R_L

$$R_L = \frac{\rho \cdot L}{s}; \quad (1)$$

- Longitudinal reactance of line X_L

$$X_L = x_0 \cdot L; \quad (2)$$

- Transversal susceptance of line B_L

$$B_L = b_0 \cdot L; \quad (3)$$

Transversal conductance of line G_L

$$G_L = g_0 \cdot L; \quad (4)$$

and active losses on the line ΔP_L are

$$\Delta P_L = \Delta p_0 \cdot L, \quad (5)$$

where Δp_0 are active losses on lines' per unit.

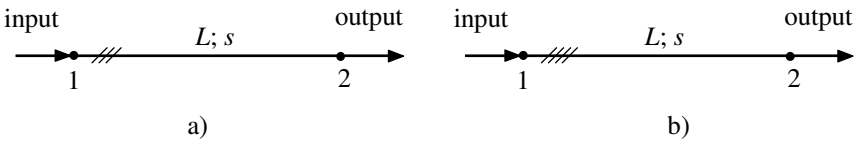

Fig. 1 – Electrical line simplified scheme:
a) symmetrical regime; b) non-symmetrical regime.

Rated data required for electric transformers.

For energy losses on a DEL, following parameters are required:

- topology or electric scheme (fig. 2);

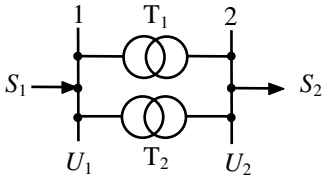

Fig. 2 – Scheme of a substation.

- rated characteristics of transformers.

3. LOAD CURVE

Assuming that the data acquisition system has an interface that can process at low voltage: the voltage U, electric current I, active power P, or energy active W_a, at time intervals Δt, reactive power Q or reactive energy W_r, then you can load curve charts, [1] for each phase and for the three phase system.

The most used indicators of load curves are:

- average apparent power S_{med};
- filling factor k_u ;
- form factor of the load curve k_f

$$k_f^2 = a + \frac{1-a}{k_u}, \qquad (6)$$

where a is a regression coefficient within the following interval $a \in [0{,}15\ ;\ 0{,}30]$.

4. POWER LOSSES IN ELECTRIC DISTRIBUTION NETWORKS

Power and energy losses in transformers

Starting from defining relations of these parameters associated to single-phase transformers, for a three-pahe transformers become [3]:

- Active power losses ΔP_T

$$\Delta P_T = \Delta P_0 + \Delta P_{sc} \cdot \frac{U_n^2}{S_n^2} \cdot \left(I_A^2 + I_B^2 + I_C^2\right); \qquad (7)$$

- Active energy losses ΔW_{aT}

$$\Delta W_{aT} = \Delta P_{0T} \cdot t_f + \Delta P_{scT} \cdot \frac{U_n^2}{S_m^2} \cdot \left(I_A^2 \cdot k_A^2 + I_B^2 \cdot k_B^2 + I_C^2 \cdot k_C^2\right) \cdot t_f \qquad (8)$$

In (8), I_A, I_B, I_C are average currents for transformer; k_A , k_B , k_C – form factor for load curves for each phase, S_m – maximum rated power, and t_f – utilizer average operating time. By taking into account symmetric voltages and unsymmetric and unbalanced currents, hypothesis valable for electric distribution systems with/without neutral, sequence currents are

- **zero** (homopolar)

$$\left(3 \cdot I^0\right)^2 = \sum_{u \in F} I_u^2 + 2 \cdot \sum_{u,v \in F} I_u \cdot I_v \cdot \cos\phi_{uv}; \qquad (9)$$

- **positive** (direct)

$$\left(3 \cdot I^+\right)^2 = \sum_{u \in F} I_u^2 + 2 \cdot \sum_{u,v \in F} I_u \cdot I_v \cdot \cos\left(\phi_{uv} + \frac{4 \cdot \pi}{3}\right); \qquad (10)$$

- **negative** (inverse)

$$\left(3 \cdot I^-\right)^2 = \sum_{u \in F} I_u^2 + 2 \cdot \sum_{u,v \in F} I_u \cdot I_v \cdot \cos\left(\phi_{uv} + \frac{2 \cdot \pi}{3}\right); \qquad (11)$$

The angles φ_{uv} belong to the collection:

$$\phi_{uv} \in \left(\phi_{AB}\,;\phi_{BC}\,;\phi_{CA}\right); \quad u, v \in F \qquad (12)$$

where F is the collection of transformer phases and the angles φ_{uv} are:

$$\begin{aligned} \phi_{AB} &= \phi_A - \phi_B; \\ \phi_{BC} &= \phi_B - \phi_C; \\ \phi_{CA} &= \phi_C - \phi_A. \end{aligned} \qquad (13)$$

With upper-mentioned values for currents, the relation (5) becomes:

$$\Delta P_T = \Delta P_{0T} + \Delta P_{scT} \cdot \left[1 + \left(k_I^-\right)^2 + \left(k_I^0\right)^2\right] \cdot \left(\frac{\sqrt{3} \cdot U_n \cdot I^+}{S_n}\right)^2 \qquad (14)$$

in which unsymmetry parameters k_I^0 and k_I^- are defined with relations(9)··· (11).

Parameters $U^+ = U_n$ and I^+ are completed with possitive sequence components of voltage an curreny, the latter being defined with (10).

By defining form factor k_f^2 with :

$$k_f^2 = \frac{I_A^2 \cdot k_A^2 + I_B^2 \cdot k_B^2 + I_C^2 \cdot k_C^2}{I_A^2 + I_B^2 + I_C^2}, \qquad (15)$$

then the equation (8) becomes:

$$\Delta W_{aT} = \left[\Delta P_0 + \Delta P_{sc} \cdot \frac{U_n^2}{S_n^2} \cdot k_f^2 \cdot \left(I_A^2 + I_B^2 + I_C^2\right)\right] \cdot t_f \,, \qquad (16)$$

which, by taking into account the unsymmetric factors (k_I^0, k_I^-) and the positive sequence components, the equation (16) leads to:

$$V_{aT} = \left\{\Delta P_0 + \Delta P_{sc} \cdot \left(\frac{\sqrt{3} \cdot U_n \cdot I^+}{S_n}\right)^2 \cdot \left[1 + \left(k_I^-\right)^2 + \left(k_I^0\right)^2\right] \cdot k_f^2\right\} \cdot t_f \qquad (17)$$

If it is noted with S^+ [2, 6]

$$S^+ = \sqrt{3} \cdot U_n \cdot I^+ \,, \qquad (18)$$

which may be defined as positive sequence rated power and if load factor is introduced, α_S, defined by[5]:

$$\alpha_s = \frac{S^+}{S_n} \,, \qquad (19)$$

then equations (16) and (18) become:

$$\Delta P_T = \Delta P_0 + \Delta P_{sc} \cdot \left[1 + \left(k_I^-\right)^2 + \left(k_I^0\right)^2\right] \cdot \alpha_{sk}^2 \,;$$
$$\Delta W_{aT} = \left\{\Delta P_0 + \Delta P_{sc} \cdot \left[1 + \left(k_I^-\right)^2 + \left(k_I^0\right)^2\right] \cdot k_f^2 \cdot \alpha_{sk}^2\right\} \cdot t_f \,. \qquad (20)$$

Choosing as variable α_s, the derivated of equations (20) become zero such:

- for ΔP_{Tk}, $\alpha_{s1}=0$;
- for ΔW_{aTk}, $\alpha_{s2}=0$.

Variations of the expressions from (20) with respect to load factor of rated power α_s, are presented in figure 3.

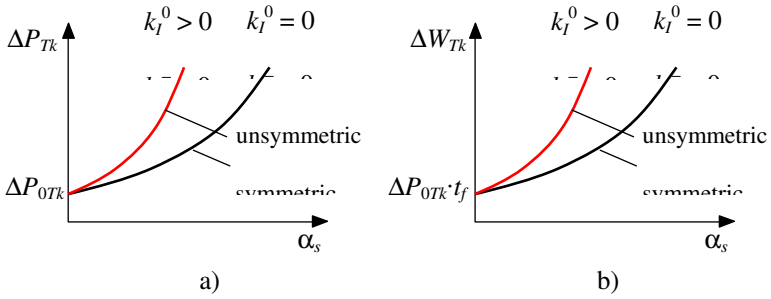

Fig. 3 – Power losses ΔP_T (a) and energy losses ΔW_{aT} (b), for symmetric and unsymmetric regimes.

From energy point of view [7-10]:

- power efficiency η_P

$$W = \frac{\alpha_W}{\alpha_W + \frac{\Delta P_0}{S^+} + \frac{\Delta P_{sc}}{S^+} \cdot \left[1 + \left(k_I^-\right)^2 + \left(k_I^0\right)^2\right] \cdot k_f^2 \cdot \alpha_W^2} \qquad (27)$$

.

Values for α_P and α_W variables for which values from (26) and (27) are maximum, are:

- for α_P

$$\eta_P = \frac{P_2}{P_1} \,, \qquad (21)$$

- energy efficiency η_W

$$\eta_W = \frac{W_2}{W_1} \,, \qquad (22)$$

Taking into account the singnificance of the power from figure 1, by replacing the active power and energy lossesfrom equation (20), the efficiency become:

- power efficiency η_P

$$\eta_P = \frac{P_2}{P_2 + \Delta P} = \frac{P_2}{P_2 + \Delta P_0 + \Delta P_{sc} \cdot \left[1 + \left(k_I^-\right)^2 + \left(k_I^0\right)^2\right] \cdot \left(\frac{P_2}{S_n}\right)^2} \,; \qquad (23)$$

- energy efficiency η_W

$$\eta_W = \frac{W_2}{W_2 + \Delta W} = \frac{W_2}{W_2 + \Delta P_0 \cdot t_f + \Delta P_{sc} \cdot \left[1 + \left(k_I^-\right)^2 + \left(k_I^0\right)^2\right] \cdot \left(\frac{W_2}{S_n \cdot t_f}\right)^2 \cdot k_f^2 \cdot t_f} \,. \qquad (24)$$

If chousen as variables

$$\alpha_P = \frac{P_2^+}{S_n} \,;$$
$$\alpha_W = \frac{W_2^+}{S_n \cdot t_f} \,, \qquad (25)$$

then the efficiencies (23) and (24) become:

- power efficiency η_{Pcp}

$$\eta_P = \frac{\alpha_P}{\alpha_P + \frac{\Delta P_0}{S^+} + \frac{\Delta P_{sc}}{S^+} \cdot \left[1 + \left(k_I^-\right)^2 + \left(k_I^0\right)^2\right] \cdot \alpha_P^2} \,; \qquad (26)$$

- energy efficiency η_W

$$\alpha_P = \sqrt{\frac{\Delta P_0}{\Delta P_{sc}}} \cdot \frac{1}{\sqrt{1 + \left(k_I^-\right)^2 + \left(k_I^0\right)^2}} \,; \qquad (28)$$

- for α_W

$$\alpha_W = \sqrt{\frac{\Delta P_0}{\Delta P_{sc}}} \cdot \frac{1}{k_f \cdot \sqrt{1 + \left(k_I^-\right)^2 + \left(k_I^0\right)^2}} \,, \qquad (29)$$

the maximum for each equation (28) and (29) is:

- efficiency η_P

$$\eta_P = \frac{P_2^+}{P_2^+ + 2\cdot\sqrt{\Delta P_0 \cdot \Delta P_{sc}}\cdot\sqrt{1+\left(k_I^-\right)^2+\left(k_I^0\right)^2}}\ ; \qquad (30)$$

- efficiency η_W

$$\eta_W = \frac{P_2^+}{P_2^+ + 2\cdot k_f \cdot\sqrt{\Delta P_0 \cdot \Delta P_{sc}}\cdot\sqrt{1+\left(k_I^-\right)^2+\left(k_I^0\right)^2}}\ ; \qquad (31)$$

Functions $\eta_P = f(\alpha_P)$ and $\eta_W = f(\alpha_W)$ are presented in figure 4.

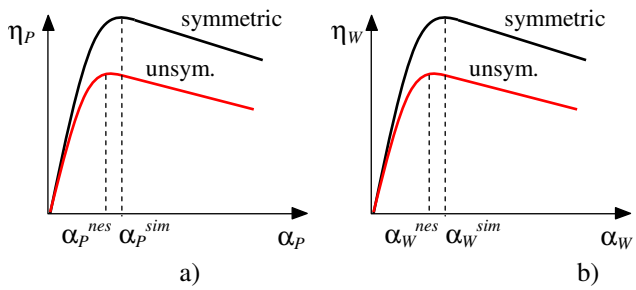

Fig. 4 – Efficiencies η_P (a) and η_W (b) for symmetric and unsymmetric regimes.

Power and energy losses in electric lines

Starting from defining relations of the parameters associated to the single-pahse line , for a three-phase symmetrical line without neutral (fig. 1 a)), these become [7]:

- Active power losses ΔP_L

$$\Delta P_L = \Delta P_{0L} + R_L \cdot \left(I_A^2 + I_B^2 + I_C^2\right); \qquad (32)$$

- Active energy losses ΔW_{aL}

$$\Delta W_{aL} = \Delta P_{0L}\cdot t_f + \Delta P_{sarL}\cdot\frac{U_n^2}{S_n^2}\left(I_A^2\cdot k_A^2 + I_B^2\cdot k_B^2 + I_C^2\cdot k_C^2\right)\cdot t \qquad (33)$$

.

With upper notations, equation (32) becomes:

$$\Delta P_L = \Delta P_{0L} + \Delta P_{sarL}\cdot\left[1+\left(k_I^-\right)^2+\left(k_I^0\right)^2\right]\cdot\left(\frac{\sqrt{3}\cdot I^+\cdot U_n}{S_n}\right)^2 \qquad (34)$$

in which factors k_I^0 and k_I^- are determined based on equations (9)···(11).

$U^+ = U_n$ and I^+ are positive sequence components for voltage and current, the latter being defined by equation (10). With these, equation (34) becomes:

$$\Delta W_{aL} = \left[\Delta P_{0L} + \Delta P_{sarL}\cdot\frac{U_n^2}{S_n^2}\cdot k_f^2\cdot\left(I_A^2 + I_B^2 + I_C^2\right)\right]\cdot t_f\ , \qquad (35)$$

in which, by taking into account (k_I^0, k_I^-) and positive sequence components expressions from equation (10) it results

$$\Delta W_{aL} = \left\{\Delta P_{0L} + \Delta P_{sarL}\cdot\left(\frac{S^+}{S_n}\right)^2\cdot\left[1+\left(k_I^-\right)^2+\left(k_I^0\right)^2\right]\cdot k_f^2\right\}\cdot t_f\ , \qquad (36)$$

If equation (18)is used [2, 6] and if electric current load factor is introduced α_I :

$$\alpha_I = \frac{I^+}{I_n}, \qquad (37)$$

after replacement in equations (18) and (37), then (34) and (36) become:

$$\Delta P_L = \Delta P_{0L} + \Delta P_{sarL}\cdot\left[1+\left(k_I^-\right)^2+\left(k_I^0\right)^2\right]\cdot\alpha_I^2\ ;$$

$$\Delta W_{aL} = \left\{\Delta P_{0L} + \Delta P_{sarL}\cdot\left[1+\left(k_I^-\right)^2+\left(k_I^0\right)^2\right]\cdot k_f^2\cdot\alpha_s^2\right\}\cdot t_f\ . \qquad (38)$$

With equation (38), power and energy losses in electric lines are obtained.

5. STUDY FOR TWO-WINDINGS TRANSFORMERS

Using mathematical model presented in the first part, a mathematic model was proposed for power losses determination, given in table 1.

Table 1.

Equipment and load characteristics for 630kVA transformer

U_{np} / U_{ns} , kV/kV	20 / 0,4	I_n , A	1500
ΔP_0 , kW	1.27	ΔP_{sc} , kW	6.5

Using upper-mentioned equations, the values presented in table 2 were obtained, which shows the unbalanced load of the transformer for which this analysis was intended.

Table 2.

Unsymmetric loads for 630kVA transformer

I_A	I_B	I_C	φ_A	φ_B	φ_C	I^0	I^-	I^+	k_I^0	k_I^-
A	A	A	°	°	°	A	A	A		
300.0	425.0	275.0	5	250	125	49.3	45.6	333.0	0.15	0.14
320.0	470.0	290.0	6	252	126	59.7	54.7	359.5	0.17	0.15
340.0	515.0	305.0	7	254	127	70.1	63.8	386.0	0.18	0.17
360.0	560.0	320.0	8	256	128	80.8	73.0	412.3	0.20	0.18
380.0	605.0	335.0	9	258	129	91.6	82.1	438.7	0.21	0.19
400.0	650.0	350.0	10	260	130	102.6	91.4	464.9	0.22	0.20
420.0	695.0	365.0	11	262	131	113.7	100.6	491.1	0.23	0.20
440.0	740.0	380.0	12	264	132	125.1	110.0	517.2	0.24	0.21
460.0	785.0	395.0	13	266	133	136.6	119.4	543.2	0.25	0.22
480.0	830.0	410.0	14	268	134	148.4	128.9	569.1	0.26	0.23
500.0	875.0	425.0	15	270	135	160.3	138.5	594.9	0.27	0.23
520.0	920.0	440.0	16	272	136	172.5	148.1	620.6	0.28	0.24
540.0	965.0	455.0	17	274	137	184.8	157.9	646.2	0.29	0.24

Power losses in symmetrical and unsymmetrical schemes are presented in table 3. It is underlined the fact that the variation of active power and energy losses with respect to the load factor has no impressive dependency, the reason being that as the unsymmetrical regime is reduced, losses from the symmetrical regime will overlay over the unsymmetrical regime.

The table shows the losses of electricity and symmetrical and unsymmetrical schemes.

These case studies were performed for various form factor values k_f^2 for various load curves and for values of power factor.

6. CONCLUSIONS

The analysis model presented is useful for the ellaboration of detaliated measures and technical points of view, which validate and justify the financial strategy for electricity distribution.

Table 3

Power losses for 630kVA transformer under symmetrical and unsymmetrical regimes

Electric current			Power losses							
			Symmetrical				Unsymmetrical			
I_A	I_B	I_C	α_{SP}	S_{optPs}	$\Delta P_T'$	η_{Ps}	α_{SP}	S_{optPns}	$\Delta P_T'$	η_{Pns}
A	A	A		kVA	kW	%		kVA	kW	%
300.0	425.0	275.0	0.37	104.04	2.18	99.1	0.29	99.97	2.18	98.3
320.0	470.0	290.0	0.40	112.85	2.34	99.1	0.32	107.41	2.34	98.4
340.0	515.0	305.0	0.42	121.71	2.51	99.1	0.34	114.78	2.51	98.5
360.0	560.0	320.0	0.45	130.60	2.70	99.1	0.37	122.09	2.70	98.6
380.0	605.0	335.0	0.48	139.52	2.90	99.1	0.40	129.34	2.90	98.7
400.0	650.0	350.0	0.51	148.46	3.12	99.0	0.43	136.54	3.12	98.8
420.0	695.0	365.0	0.54	157.41	3.35	99.0	0.46	143.67	3.35	98.8
440.0	740.0	380.0	0.57	166.39	3.59	99.0	0.49	150.75	3.59	98.9
460.0	785.0	395.0	0.60	175.38	3.85	99.0	0.52	157.77	3.85	99.0
480.0	830.0	410.0	0.63	184.37	4.12	99.0	0.55	164.72	4.12	99.0
500.0	875.0	425.0	0.65	193.38	4.40	98.9	0.58	171.62	4.40	99.1
520.0	909.0	440.0	0.68	200.84	4.65	98.9	0.61	177.73	4.65	99.1
540.0	909.0	455.0	0.71	203.52	4.74	98.9	0.64	181.57	4.74	99.1

Table 4.

Energy losses for 630kVA transformer under symmetrical and unsymmetrical regimes

Electric current		Active energy losses							
		Symmetrical				Unsymmetrical			
I_{mp}	I_n	α_{SW}	S_{optns}	$\Delta W_{aT}'$	η_{Ws}	α_{SW}	S_{optWns}	$\Delta W_{aT}'$	η_{Wns}
A	A		kVA	kWh	%		kVA	kWh	%
340	909	0.37	78.35	24066.3	98.8	0.29	76.49	89835.85	94.65
369	909	0.40	85.16	26000.3	98.8	0.32	82.97	96503.82	95.05
397	909	0.42	92.05	28038.0	98.8	0.34	89.48	103203.88	95.39
426	909	0.45	99.00	30173.3	98.8	0.37	96.02	109929.49	95.69
456	909	0.48	106.01	32400.4	98.8	0.40	102.57	116675.78	95.96
485	909	0.51	113.09	34714.3	98.8	0.43	109.15	123439.02	96.19
514	909	0.54	120.22	37110.4	98.8	0.46	115.73	130216.31	96.40
543	909	0.57	127.41	39584.4	98.8	0.49	122.33	137005.40	96.59
573	909	0.60	134.64	42132.4	98.7	0.52	128.94	143804.47	96.76
602	909	0.63	141.92	44751.0	98.7	0.55	135.55	150612.06	96.91
631	909	0.65	149.24	47436.8	98.7	0.58	142.18	157426.98	97.05
656	909	0.68	155.96	49587.2	98.7	0.61	147.66	163068.23	97.16
665	909	0.71	160.75	49925.4	98.7	0.64	149.63	165093.45	97.19

Among these measures, the relevant ones are:

- the choice of transformers parameters (ΔP_0 and ΔP_{sc}) to meet the needs of users with minimum losses (power and energy);
- ensure the symmetrical load which allow, for the same transit of electricity, high yields and minimal loss of power and energy;
- appropriate tariff measures for a better flattening factor of graphs of load which, under a symmetric (and unbalance), leads to loss of strength and energy.

Thus, in order to increase economic efficiency of electricity distribution systems few technical measures are recommended:

- efficient positioning of symetrization devices;
- technical and economic design for symetrization devices;
- efficient positioning of the devices used for distortion regime mitigation – harmonic filters;
- technical and economic design for harmonic filters.

All these elements are known and have been included in all the standards, which must be supplemented with studies for load-type graphics that will allow for the development of new regulations adapted to tariffs for energy efficiency increase.

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