Active and Reactive Power Losses in Distribution Transformers

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Abstract: The problem of energy quality has recently gained much recognition, one of the reasons being, that there is an increasing number of devices which require energy that meets high quality standards. An improvement in this respect, can be achieved by effective management of reactive power flow in the power system. Maintaining balance in active and reactive power is of key importance for the flawless functioning of the power system. This paper discusses theoretical issues underpinning calculations of active, reactive power and of energy loss in MV/LV transformers. Based on the parameters of transformers and data from consumer meters on active and reactive power, active and reactive power and energy loss was obtained, with the view to assess the efficiency of active power and energy transfer through MV/LV transformers.

Keywords: modelling; energy losses; active and reactive energy

1   Introduction

The flow of current through the elements of a power network, is accompanied by power and energy losses. Loss occurring at resistive elements is known as active loss, whereas the loss occurring at reactance elements is known as reactive loss. Both kinds of loss are detrimental due to a number of reasons: the extra amount of energy has to be generated in power plants, which requires additional devices and resources; the extra energy has to be transferred through all of the network elements, which requires increasing their transfer capacity; on Joule-Lenz law, energy turns into heat, which affects the dimensions of the network elements [1-4]. The consequences of losses vary depending on their type and place of their occurrence. As regards transformers, the key element is the core, which is

magnetized by means of inductive power, constituting reactive idle loss. This kind of loss can be greater than load loss and in the case of low power transformers, the ratio of idle to load loss can be about 4-5. Reactive idle loss in transformer cores is compensated for by means of capacitor batteries connected directly to the transformer [5-9]. The power of such capacitors should be equal to the power of the rated idle loss. Even though no energy resources are consumed for the generation of reactive power, which does not yield any work, it flows through the power system increasing its load. By this token, the detrimental effect of reactive power is multiplied. It is typically assessed by an equivalence coefficient of reactive power, by means of which it is possible to calculate the amount of active loss per unit of reactive power. The value of the coefficient depends on the location of the occurrence of reactive power. According to The Energy Efficiency Act [10], reducing reactive energy loss (art.19 par.1 pt. 5a) is one of the moves that should be implemented towards improving energy efficiency. In this respect, special attention should be paid to power transformers, which are one of the key elements of the power system [4, 7, 11]. Energy losses occurring in MV/LV transformers constitute from about 30 to 60% of total losses in LV networks [12-14]. At present, MV/LV transformers are typically not metered, but since the number of smart meters installed at end-consumers is continuously increasing, it is possible to measure the amount of energy flowing through MV/LV transformers with large precision [15-17].

2   Measurements of Energy Losses in a Two-Winding Transformer

Fig. 1 presents the measurement system, including an electronic meter of electrical energy, installed at the lower-voltage side of a two-winding transformer.
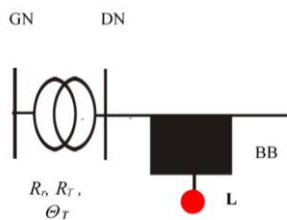

Figure 1

Measurement at the lower voltage side of a transformer

The following symbols are used in Fig. 1:

− GN   – higher-voltage side

− DN   – lower-voltage side

- BB – "black box" (voltage and current transformers); the following quantities are given for the transformers:

  - ϑ_U – winding ratio of the voltage transformer

  - ϑ_I – winding ratio of the current transformer

- **L**   – electronic meter

- R_r – idle resistance of the transformer

- R_T – rated load resistance of the transformer

- Θ_T –winding ratio of the transformer, equal to:

$$\Theta_T = \frac{U_{GN}}{U_{DN}}(1+0.01 \cdot \varDelta z) \tag{1}$$

where: U_{GN} – rated voltage of the transformer primary winding, U_{DN} – rated voltage of the transformer secondary winding, $\varDelta z$ – percentage correction of the transformer winding ratio.

The meter records [19] the following data:

- *power profile*, including active consumed power $\{P+\}_{Tn}$, reactive consumed (inductive) power $\{Q_L+\}_{Tn}$, reactive returned (capacitive) power $\{Q_C-\}_{Tn}$ at the *n*-th calculation period T_n, and possibly also active returned power $\{P-\}_{Tn}$, reactive returned (inductive) power $\{Q_L-\}_{Tn}$, and reactive consumed (capacitive) power $\{Q_C+\}_{Tn}$),

- *energy losses* at the end of the *n*-th calculation period for the *z*-th zone, including losses of the active consumed energy SP_{nz}, of reactive consumed (inductive) energy $SQ_{L,nz}$, reactive returned (capacitive) energy $SQ_{C,nz}$, and possibly also energy states corresponding to the power profile, as enumerated above; *n* – index of the calculation period, $z = 1, 2, …, Z, Z$ – the number of zones within 24 hours,

- *indications of the loss counters*: $S(V^2h)_n$, $S(I^2h)_n$ at the end of a *n*-th calculation period without dividing it into time zones. The values are given for the whole 24-h period and the meter does not register, unfortunately, the indications of the loss counters for each measuring cycle.

On the basis of the *indications of the loss counters,* the following values are obtained for the current *n*-th calculation period:

$$\varDelta S(V) = S(V^2h)_n - S(V^2h)_{n-1} \tag{2}$$

$$\varDelta S(I) = S(I^2h)_n - S(I^2h)_{n-1} \tag{3}$$

Let us turn to active energy. At the resistance R_r there are voltage energy losses and at the resistance R_{TN} there are load energy losses. The two resistances are obtained from the formulas:

$$R_r = \frac{U_{GN}^2 \cdot 10^3}{\Delta P_{FeN}} \tag{4}$$

$$R_T = \Delta P_{CuN} \frac{U_{GN}^2}{S_N^2} \cdot 10^3 \tag{5}$$

where: ΔP_{FeN} – rated loss of the active power in the transformer core, kW, ΔP_{CuN} – rated loss of the active power in the transformer windings, kW, S_N – rated power of the transformer, kVA, U_{GN} – rated voltage (see above), kV.

The voltage loss of active energy occurs in accordance with the formula (2):

$$U_{D(h)}^2 = \Delta S(V)\vartheta_U^2 \text{, [V}^2\text{h]} \tag{6}$$

$$U_{G(h)}^2 = \Delta S(V)\vartheta_U^2 \Theta_T^2 \text{, [V}^2\text{h]} \tag{7}$$

As follows from the formula $\Delta P_{FeN} = \dfrac{U_{GN}^2 \cdot 10^3}{R_r}$, the voltage energy loss ΔE_U is equal to (cf. (7))

$$\Delta E_U = \frac{\Delta S(V)\vartheta_U^2 \Theta_T^2}{R_r \cdot 10^3} \text{, [kWh]} \tag{8}$$

After substituting (4) into (8)

$$\Delta E_U = \frac{\Delta S(V)\vartheta_U^2 \Theta_T^2 \Delta P_{FeN}}{U_{GN}^2 \, 10^6} \text{, [kWh]} \tag{9}$$

The load (current) loss of the active energy occurs in accordance with (cf. (3))

$$I_{D(h)}^2 = \Delta S(I)\vartheta_I^2 \text{, [A}^2\text{h]}. \tag{10}$$

On the basis of (10) and by analogy to $\Delta P_{CuN} = 3I_N^2 R_T \cdot 10^{-3}$, the current energy loss ΔE_I equals

$$\Delta E_I = \Delta S(I)\vartheta_I^2 R_{T(DN)} \cdot 10^{-3} \text{, [kWh]} \tag{11}$$

where: $R_{T(DN)}$ – load resistance of the transformer at the voltage DN, equal to (cf. (1), (5))

$$R_{T(DN)} = R_T \cdot \frac{1}{\Theta_T^2} = \Delta P_{CuN} \frac{U_{GN}^2}{S_N^2} \cdot \frac{10^3}{\Theta_T^2} \tag{12}$$

After substituting (12) into (11)

$$\Delta E_I = \Delta S(I) \vartheta_I^2 \Delta P_{CuN} \frac{U_{GN}^2}{S_N^2} \cdot \frac{1}{\Theta_T^2} \text{ , [kWh]} \tag{13}$$

Active energy in the *z*-th zone equals

$$E(P)_z = (SP_{nz} - SP_{n-1,z})M \text{ , [kWh]} \tag{14}$$

where: M – constant (multiplier) of the meter, depending on the winding ratio: ϑ_U , ϑ_I .

The total energy is a summation (cf. (14))

$$E(P) = \sum_{z=1}^{Z} E(P)_z \tag{15}$$

Electronic meters equipped with loss recording modules are typically installed at a large energy user's, with measurements performed at the DN (lower voltage) circuit of a transformer. The consumer pays, among other things, for energy consumed and energy loss occurring in the transformer, the tariffs being different for the particular zones. Therefore, the problem arises how to assign voltage and current energy losses to the particular zones. The total loss should be distributed correctly over the time zones, in order to add an appropriate value to the energy obtained (14).

3   Calculating Power/Energy Losses in a Transformer on the Basis of Load

A meter installed at the lower-voltage side of the transformer takes measurements at 15-minute intervals. On the basis of these measurements, mean active and reactive power, i.e. the power profile is energy QL(+)t, reactive capacitive returned energy QC(–)t, reactive inductive returned energy QL(–)t, reactive capacitive consumed energy QC(–)t can be obtained [15]:

$$P_t = P(+)_t - P(-)_t ; \ Q_t = Q_L(+)_t - Q_C(-)_t - Q_L(-)_t + Q_C(+)_t \tag{16}$$

Active energy in the *h*-th hour is equal to the *active power* $\overline{P}_h$ averaged over an hour

$$\overline{P}_h = \sum_{t(h)=k(h)-3}^{k(h)} P_{t(h)} \tag{17}$$

and reactive energy in the *h*-th hour is equal to the *reactive power* $\overline{Q}_h$ averaged over an hour

$$\overline{Q}_h = \sum_{t(h)=k(h)-3}^{k(h)} Q_{t(h)} \tag{18}$$

where: $k(h)$ – number of the last quarter of the *h*-th hour, h – number of the hour, h = 1, 2,…, H, H – number of hours analyzed in the period under scrutiny.

Active power P_t and reactive power Q_t for the *t*-th 15 minute cycle are, respectively:

$$P_t = 3U_{ft}I_t \cos\varphi_t = 3U_{ft}I_{ct} \qquad\qquad Q_t = 3U_{ft}I_t \sin\varphi_t = 3U_{ft}I_{bt} \tag{19}$$

where: U_{ft} –phase voltage for the *t*-th cycle, I_{ct}, I_{bt} active and reactive current components for the *t*-th cycle, respectively, equal to:

$$I_{ct} = \frac{P_t}{3U_{ft}} \qquad\qquad I_{bt} = \frac{Q_t}{3U_{ft}} \tag{20}$$

In a 60-minute period consisting of four 15-minute cycles, the active component I_c and the reactive component I_b of the current are (cf. (20)):

$$I_c = \sum_t I_{ct} = \frac{1}{3}\sum_t \frac{P_t}{U_{ft}} \qquad\qquad I_b = \sum_t I_{bt} = \frac{1}{3}\sum_t \frac{Q_t}{U_{ft}} \tag{21}$$

and their resultant sum I is

$$I = \sqrt{I_c^2 + I_b^2} \tag{22}$$

Substituting (21) into (22)

$$I = \frac{1}{3}\sqrt{(\sum_t \frac{P_t}{U_{ft}})^2 + (\sum_t \frac{Q_t}{U_{ft}})^2} \tag{23}$$

On the basis of mean power/hour (por. (17), (18); the index *h* was dropped), the apparent power is obtained

$$S = \sqrt{\overline{P}^2 + \overline{Q}^2} \tag{24}$$

On the basis of (24) and the formula $S = \sqrt{3}\,\overline{U}I$, the *mean line-to-line voltage in an hour* is obtained

$$\overline{U} = \frac{\sqrt{3[(\sum_t P_t)^2 + (\sum_t Q_t)^2\,]}}{3I} \tag{25}$$

which, after (23) is taken into account, is equal to

$$\overline{U} = \sqrt{\frac{3[(\sum_t P_t)^2 + (\sum_t Q_t)^2\,]}{(\sum_t \frac{P_t}{U_{ft}})^2 + (\sum_t \frac{Q_t}{U_{ft}})^2}} \tag{26}$$

For each MV/LV transformer the following quantities are known:

1) Rated values: S_N, ΔP_{FeN}, ΔP_{CuN}, $\Delta u_{z\%}$, $I_{0\%}$, U_{GN}, U_{DN} and the windings ratio correction $\Delta z_\%$, performed by means of a tap changer,

2) $\overline{DT}_h$ (date and time, i.e. the timestamp), $\overline{P}_h$, $\overline{Q}_h$, $\overline{U}_h$ (B.11), $h = 1, 2, ., H$.

Below a method of calculating power/energy losses in an hour-period is presented for an r-th transformer (r = 1, 2, …, R, R – number of transformers under scrutiny; a transformer index is omitted in further discussion). The following losses are obtained:

ΔP_{Uh} – voltage loss of active power in the transformer core

ΔP_{Ih} – current loss of active power in the transformer windings

ΔQ_{Uh} – voltage loss of reactive power in the transformer core

ΔQ_{Ih} – current loss of reactive power in the transformer windings

The voltage loss of active power in the transformer core is obtained from the formula:

$$\Delta P_{Uh} = \Delta P_{FeN} \frac{\overline{U}_{Gh}^2}{U_{GN}^2} \tag{27}$$

where: $\overline{U}_{Gh}$ –mean voltage in the *h*-th hour at the primary side of the transformer, obtained from the formula:

$$\overline{U}_{Gh} = \overline{U}_h (1 + 0{,}01 \cdot \Delta u_{T\%h})\Theta \tag{28}$$

where: $\overline{U}_h$ – voltage in the *h*-th hour at the secondary side of the transformer, $\Delta u_{T\%h}$ – relative voltage drop in the transformer for the *h*-th hour, Θ – real voltage winding ratio of the transformer (constant throughout the analysis), equal to:

$$\Theta = \frac{U_{GN}}{U_{DN}}(1+0,01\cdot\Delta z_{\%})$$

The relative voltage drop in the transformer for the *h*-th hour is obtained from the formula:

$$\Delta u_{T\%h} = (\Delta u_{RN\%}\cos\varphi_h + \Delta u_{XN\%}\sin\varphi_h)\beta_h \tag{29}$$

where:

$$\beta_h = \frac{\sqrt{\overline{P}_h^2 + \overline{Q}_h^2}}{S_N} \tag{30}$$

is the load coefficient of the transformer.

The current loss of active power in the transformer windings ΔP_{Ih} is obtained from the formula:

$$\Delta P_{Ih} = \Delta P_{CuN}\beta_h^2 k_{Th} \tag{31}$$

where: k_{Th} – *temperature coefficient,* allowing for the change in the resistance in the transformer windings depending on the load, equal [3] to:

$$k_{Th} = 0.3179\cdot\beta_h^2 - 0.082\cdot\beta_h + 0.77 \tag{32}$$

The voltage loss of reactive power in the transformer core ΔQ_{Uh} is obtained from the formula:

$$\Delta Q_{Uh} = \sqrt{(0.01\cdot I_{0\%}S_N)^2 - \Delta P_{FeN}^2}\cdot\frac{\overline{U}_{Gh}^2}{U_{GN}^2} \tag{33}$$

The current loss of reactive power in the transformer windings ΔQ_{Ih} is obtained from the formula:

$$\Delta Q_{Ih} = 0.01\cdot\Delta u_{XN\%}S_N\beta_h^2 \tag{34}$$

4   Results

The analysis was carried out on the basis of data from the year 2016, obtained from a distribution company in Poland. The data from consumer meters with active and reactive load for one year periods and transformers MV / LV were collected. The MV / LV transformer load data is shown in Table 1. Using the data on recipients' loads, the active energy load in transformers was calculated for every month of the year on the basis of formula (17) and reactive – on the basis of formula (18).

Table 1. Active and reactive energy flowing through MV/LV transformers for every month of the year.

Table 1

Active and reactive energy flowing through MV/LV transformers for every month of the year

	Active energy [MWh]			Reactive energy [Mvarh]		
	160 [kVA]	250 [kVA]	400 [kVA]	160 [kVA]	250 [kVA]	400 [kVA]
I	341	869	1847	74	145	400
II	294	739	1601	66	129	373
III	294	758	1610	73	140	397
V	272	678	1466	75	130	389
V	271	675	1419	82	145	409
VI	256	624	1304	83	143	390
VII	242	640	1361	80	183	470
VIII	246	640	1358	81	182	463
IX	250	674	1425	68	147	417
X	272	744	1625	69	154	469
XI	286	779	1681	67	148	424
XII	340	875	1824	75	148	404

On the basis of the data, voltage and current losses of active and reactive energy were calculated. Results for the particular months are shown in Table 2. Voltage loss of active energy is obtained from formula (27) and reactive from formula (33). Current loss of active energy is obtained from formula (31) and reactive from formula (34).

As can be seen in Table 2 reactive energy loss in transformers is significantly higher than active energy loss. Besides, voltage losses, both of active and reactive energy are higher than current losses. The low amount of current losses is due to relatively low load coefficients of MV/LV transformers, varying from 0.138 for the group 160 kVA to 0.148 for the group 400 kVA.

Table 2

Active and reactive energy losses flowing through MV/LV transformers

	Power kVA]	Number of transf.	β	Active energy losses		Reactive energy losses	
				Voltage [MWh]	Current [MWh]	Voltage [Mvarh]	Current [Mvarh]
I	160	18	0.163	4.8	0.90	48.3	3.2
	250	30	0.158	15.5	2.17	111.0	8.8
	400	47	0.172	23.3	5.90	194.7	22.9
II	160	18	0.156	4.4	0.75	43.7	2.7
	250	30	0.149	14.0	1.73	100.2	7.1
	400	47	0.165	21.1	4.86	176.2	19.0
III	160	18	0.142	4.8	0.70	48.3	2.5
	250	30	0.138	15.4	1.69	110.8	6.9
	400	47	0.151	23.2	4.52	194.2	17.8
IV	160	18	0.136	4.7	0.65	46.9	2.3
	250	30	0.128	14.8	1.44	106.2	5.9
	400	47	0.142	22.6	3.86	188.8	15.3
V	160	18	0.132	4.9	0.64	48.6	2.3
	250	30	0.124	15.7	1.39	112.3	5.7
	400	47	0.134	23.7	3.52	198.8	14.0
VI	160	18	0.130	4.7	0.60	47.0	2.2
	250	30	0.119	15.2	1.28	108.7	5.2
	400	47	0.128	23.0	3.14	192.5	12.5
VII	160	18	0.119	4.8	0.56	48.3	2.0
	250	30	0.119	15.5	1.35	111.1	5.5
	400	47	0.131	23.3	3.27	195.2	13.1
VIII	160	18	0.121	4.9	0.59	48.3	2.1
	250	30	0.119	15.5	1.35	111.1	5.5
	400	47	0.130	23.3	3.31	195.1	13.2
IX	160	18	0.125	4.7	0.58	46.9	2.1
	250	30	0.128	15.0	1.43	107.7	5.8
	400	47	0.139	22.6	3.60	189.2	14.3
X	160	18	0.131	4.9	0.64	48.4	2.3
	250	30	0.136	15.5	1.66	111.1	6.8
	400	47	0.153	23.4	4.57	195.5	18.0
XI	160	18	0.142	4.7	0.71	46.7	2.5
	250	30	0.147	15.0	1.85	107.4	7.6
	400	47	0.163	22.6	5.09	189.0	19.9
	160	18	0.163	4.8	0.92	48.3	3.3

XII	250	30	0.159	15.4	2.25	110.6	9.1
	400	47	0.170	23.2	5.77	193.8	22.5
Year			**0.142**	**516**	**79**	**4182**	**313**

Using the formula:

$$\eta_E = \frac{E_c}{E_c + \Delta E_{cU} + \Delta E_{cI}}$$

the average efficiency of active energy transfer was obtained. The results are presented in Fig. 2.
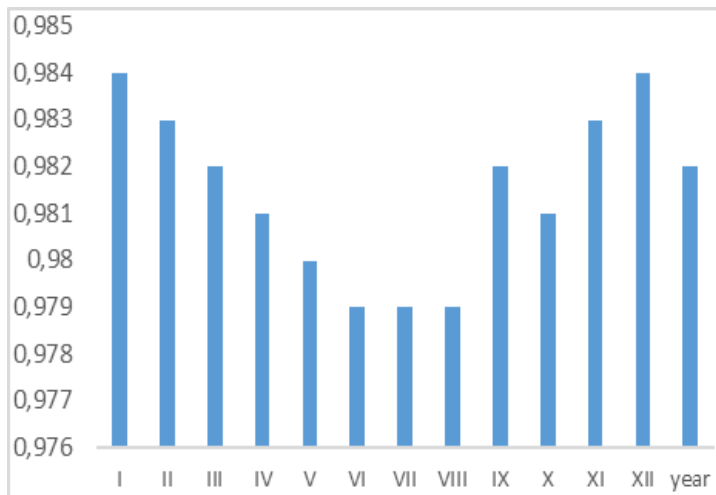

Figure 2
Average efficiency of energy transfer

The highest efficiency of energy transfer in MV/LV transformers occurs in winter and the lowest in summer. This is connected, among other factors, with voltage losses, which are practically constant throughout the year, so when the amount of energy flowing through transformers is lower as it is in summer, the network efficiency is also lower.

Extremely low transformer load coefficients generate high active and reactive energy loss. Taking this into consideration, a simulation experiment was carried out for the period of a year, in which the transformer load was adjusted to the amount of energy flowing through them. The results are presented in Table 3.

Table 3

Active and reactive energy loss after the transformer power has been adjusted to load

Current condition						
Power [kVA]	Number of transf.	β	Active energy losses		Reactive energy losses	
			Voltage [MWh]	Current [MWh]	Voltage [Mvarh]	Current [Mvarh]
160	18	0.138	57.723	8.291	570.299	29.972
250	30	0.135	183.208	19.642	1308.847	80.583
400	47	0.148	275.788	51.450	2303.423	203.312
total	516.719	79.383	4182.569	313.867	516.719	79.383
Transformer power adjusted to load						
Power [kVA]	Number of transf.	β	Active energy losses		Reactive energy losses	
			Voltage [MWh]	Current [MWh]	Voltage [Mvarh]	Current [Mvarh]
63	22	0.351	31.910	9.2199	352.674	19.977
75	31	0.451	95.76	75.997	580.455	191.412
160	42	0.37	118.652	106.546	1172.281	385.164
total	246.323	191.762	2105.410	596.552	246.323	191.762

It follows that when the transformer power was adjusted to the load, the active energy loss was reduced by 26.5%, and the reactive energy loss by 40%.

Conclusions

It has been demonstrated that transformers are characterized by a low load coefficient, which is evidenced by high voltage energy loss, significantly exceeding current energy loss.

The highest value of the power coefficient (*cosφ*), equal to 0.952 (tg*φ* = 0.323) was attested in December and the lowest value equal to 0.916 (tg*φ* = 0.437) in June. For the whole year, these values for the primary transformer winding are (respectively) *cosφ* = 0.932, tg*φ* = 0.390. The relatively high power coefficient is affected by the batteries of parallel capacitors connected to the low voltage side of MV/LV transformers as compensation for the idle state.

The study has found that the low efficiency of energy distribution is caused by low load in MV/LV transformers. The extremely low load coefficient contributes to high reactive energy loss, thereby lowering the network efficiency. It follows that transformer power should be adequately adjusted to the load, which will significantly reduce the energy losses.

Acknowledgement

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