MONITORING OF ELECTRIC POWER LOSSES IN MEDIUM VOLTAGE NETWORK OF POWER DISTRIBUTION COMPANY „ELEKTRODISTRIBUCIJA BEOGRAD” USING THE DATA FROM REMOTE CONTROL SYSTEM

Ljupče Mandić, M.Sc.EE.
“Elektrodistribucija Beograd”

1. INTRODUCTION

The losses of electrical energy in a network are the significant subject of research in all serious companies dealing with its distribution. Those losses are partly due to technical necessity of transporting electrical energy to its final consumers. The remaining part is the result of human factor and as such an index of efficiency in managing the electrical network.
The basic principle of solving the problem of electrical energy losses is distinguishing the two causes of the existing losses in a specific network as precisely as possible. That is required because the procedures of their reduction or total elimination are different. The principle should be that the quantity of electrical energy losses as a necessary result of its transport and distribution is defined as precisely as possible. Those losses are called technical losses. The remaining part of the registered losses is so-called commercial losses. This paper deals with technical losses exclusively.
The diagrams of medium voltage network load of the specific elements recorded by the remote control system of the “Elektrodistribucija Beograd” (EDB) section are used in the calculation. Namely, the data about fifteen-minute network loads are registered in the above-mentioned remote control system. The data are stored in database and can be used if necessary.
This paper provides the calculation of the complete technical losses in the network sections based on the use of the data from the remote control system together with data about physical characteristics of specific elements in the system of electrical energy distribution.
The purpose of this paper is to point out one of the ways in which the losses in medium voltage network can be precisely defined and to show how reliable the calculation of the losses is by making use if it.

2. DESCRIPTION OF METHOD

This method can be applied on the parts of medium voltage network that is in the system of remote control from EDB dispatching center. There are stored data about fifteen-minute network loads for each specific object.
By using those data it is possible to calculate directly the immediate power that is engaged by the specific object according to the following formula:

$$P = \sqrt{3}U \cdot I \cdot \cos\varphi \quad [W] \tag{2.1}$$

Instantaneous overhead line losses are calculated according to the formula:

$$P_{gV} = 3 \cdot I^2 \cdot R_V \quad [W] \tag{2.2}$$

Instantaneous transformer losses are:

$$P_{gT} = P_{Fe} + 3 \cdot I^2 \cdot R_T \quad [W] \tag{2.3}$$

From those data it is possible to calculate the total energy which is transported by that object in specific interval according to the formula:

$$E_{UK} = \sqrt{3}\, U \cos\varphi \sum_{n=1}^{N} I_n t_n \quad [kWh] \tag{2.4}$$

Overhead line energy losses are:

$$E_{gV} = \frac{3 \cdot R_V}{1000} \sum_{n=1}^{N} I_n^2 t_n \quad [kWh] \tag{2.5}$$

Transformer energy losses are:

$$E_{gT} = P_{Fe} \cdot t_{UK} + \frac{3 \cdot R_T}{1000} \sum_{n=1}^{N} I_n^2 t_n \quad [kWh] \tag{2.6}$$

If it is assumed that the time in which summation is carried out is one year (35.040 addends) the results received are absolutely correct data about the total energy which passed through that object and about total energy losses at that object.
This calculation is carried out exclusively for specific objects which have their own beginning and end with no branching. Those objects are:

- Overhead power lines 35 kV
- Transformers 35/10 kV
- Overhead power lines 10 kV with only one connected consumer (transformer substation)
- Transformers 10/0,4 kV which stand alone on a feeder

Examples of calculations of energy losses at 35 kV overhead power line and 35/10 kV transformer are given in Lit [1].
For all other 10 kV overhead lines and 10/0,4 kV transformers for which there is a database and which not individual objects are but more than one object (sections or divisions and therefore several transformer substations) at a single measurement, this method is applied with somewhat less reliability than with individual objects.
Objects of this kind are subject matter of this paper. The way in which the losses at one 10kV feeder with more sections and a number of connected transformers can be calculated and with what reliability, will be described later on. The same method will be used for the calculation of the losses at transformers.

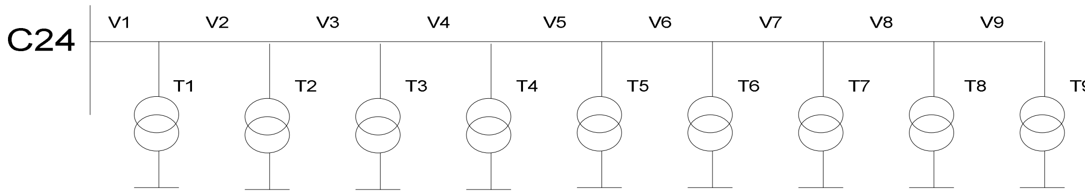
3. 10 KV OVERHEAD LINE POWER LOSSES

The calculation of 10kV overhead lines power losses was performed on two characteristic power lines.

3.1 10 kV overhead line losses, feeder 24, from TS 35/10 kV "Novi Beograd 1"

This object was chosen as a typical representative of 10 kV overhead lines that supplies electrical energy to the blocks of flats in Novi Beograd. Nine transformer substations are connected on it with total power of

630 kVA. The network was created rather generously so the overhead power lines and transformers are loaded less than 50% of nominal load of the installed transformers. There are about 1500 consumers connected to these nine transformer substations, almost exclusively households with remote heating and individual supply of hot water. The engaged power of this feeder in maximum load is about 2 MW.
Scheme of this overhead line is shown in picture 1.



Picture 1.

There are data about fifteen-minute electrical energy loads of this overhead power line in the period from 1.1.2005. at 00.00 o'clock to 31.12.2005. at 23.45 o'clock, this represents the total of 35.040 data. The only certain thing is that the electric current in its total amount flows through the first section and it is possible to calculate the exact values in that part. For other sections, the distribution of power flows is relative and it can be calculated in different ways. In that case, the electric current of the second and other sections is reduced compared to the entering current, so the power of the total losses in the whole section can be calculated according to the following formula:

$$P_{gV} = 3 \cdot \left(I_1^2 \cdot R_{V1} + I_2^2 \cdot R_{V2} + I_3^2 \cdot R_{V3} + \ldots + I_9^2 \cdot R_{V9} \right) \quad (3.1)$$

$$P_{gV} = 3 I_1^2 \left(\frac{I_1^2}{I_1^2} R_{V1} + \frac{I_2^2}{I_1^2} R_{V2} + \frac{I_3^2}{I_1^2} R_{V3} + \ldots + \frac{I_9^2}{I_1^2} R_{V9} \right) \quad (3.2)$$

$$P_{gV} = 3 I_1^2 \left(R_{V1} + R_{V2} \cdot K_1^2 + R_{V3} \cdot K_2^2 + \ldots + R_{V9} \cdot K_9^2 \right) \quad (3.3)$$

$$P_{gV} = 3 I_1^2 \left(R_{V1} + R_{V2}^* + R_{V3}^* + \ldots + R_{V9}^* \right) \quad (3.4)$$

$$P_{gV} = 3 I_1^2 \cdot R_V^* \quad (3.5)$$

where it is:

$$R_V^* = R_{V1} + R_{V2}^* + R_{V3}^* + \ldots + R_{V9}^* \quad (3.6)$$

The total electrical energy losses at the overhead power line at a specific time are calculated according to the formula:

$$E_{gV\,uk} = \frac{3 \cdot R_V^*}{1000} \sum_{n=1}^{N} I_{1n}^2 t_n \quad (3.7)$$

For the calculation of the losses in the period of one year, the formulas are the following:

$$E_{UK} = \sqrt{3}\, U \cdot \cos\varphi \cdot 0{,}25 \sum_{n=1}^{35040} I_n \quad [kWh] \quad (3.8)$$

$$E_{gV} = \frac{3 \cdot R_V^*}{1000} \cdot 0{,}25 \sum_{n=1}^{35040} I_n \quad [kWh] \tag{3.9}$$

where it is:

P_{gv} .... power losses of power line
E_{gv} .... energy losses of power line in a specific period of time
I_n .... electrical current of n^{th} section
$R_{v\,n}$ .... resistance of n^{th} section distribution
R_{vn}^* .... resistance of the n^{th} section reduced to power of the first section
R_v^* .... total resistance of a power line reduced to the electrical energy in the first section
K_n .... factor of reduction
0,25 .... correction coefficient due to introduction of fifteen-minute electrical energy values in the calculation

As it was mentioned before, the total registered electrical energy flows through the first section and the calculated losses in that section are exact. The distribution of power flows from the second section to the end of the network can only be assumed. However, in order to receive as correct as possible results, we calculated the distribution of power flows in four variants by:

- transformer powers of each transformer substation
- DMS group method for the distribution of power flows in EDB network
- number of consumers of each transformer substation
- maximum realized power of each transformer substation

After the calculation, coefficients of reduction for specific sections have the following values:

TABLE 1 – REDUCTION COEFFICIENT PER SECTIONS

Variant	**K_1**	**K_2**	**K_3**	**K_4**	**K_5**	**K_6**	**K_7**	**K_8**	**K_9**
Transformer power	1,000	0,889	0,778	0,667	0,556	0,444	0,333	0,222	0,111
DMS group method	1,000	0,901	0,738	0,608	0,555	0,441	0,310	0,201	0,106
Number of consumers	1,000	0,878	0,776	0,654	0,558	0,455	0,319	0,211	0,112
Maximum power	1,000	0,869	0,790	0,662	0,569	0,423	0,336	0,227	0,124

After the calculation with these coefficients, the results received at a particular overhead power line are the following:

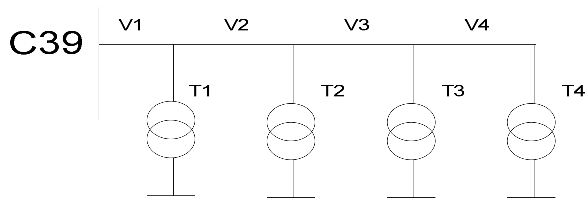
TABLE 2 – JOULE'S LOSSES OF OVERHEAD POWER LINE IN VARIATIONS

Variant	**E_S [kWh]**	**$E_{g\,S}$ [kWh]**	**$E_{g\,S}$ [%]**	**Deviation [%]**
Transformer power	9.602.436	37.222	0,3876	+ 1,07
DMS group method	9.602.436	35.940	0,3742	- 2,42
Number of consumers	9.602.436	37.091	0,3863	+ 0,73
Maximum power	9.602.436	37.067	0,3860	+ 0,65
Average	**9.602.436**	**36.830**	**0,3835**	

3.2. 10 kV overhead line losses , feeder 39, from TS 110/10 kV "Kaluđerica"

This network is chosen as a typical representative of 10 kV overhead power lines which supplies the consumers in the Belgrade suburb with electrical energy. There are four 10/0,4 kV transformer substations connected to a power line, two of which have the power of 1000 kVA (T2 and T4) and the other two of 630 kVA (T1 and T3). The complete network is loaded above average values, so on maximum load it exceeds 70 % of nominal power of the installed transformers. These four transformer substations supply electrical energy to about 420 household consumers. The consumers are mainly households and there is no remote heating, so many of these use electric heating. The engaged power on maximum load is about 2,3 MW.

Scheme of the described network is shown in picture 2.



Picture 2.

The choice of variants of power flow calculations in sections for this overhead power line was based on somewhat different data about the network from those in 2.1 since these data were available.
The variants are entered in the table with results.
After the calculation was done in the same way as in 2.1, the results obtained are the following:

TABLE 3 - COEFFICIENTS OF ELECTRICAL ENERGY REDUCTION IN SECTIONS

Variant	**K_1**	**K_2**	**K_3**	**K_4**
Transformer power	1,000	0,807	0,500	0,307
DMS group method	1,000	0,823	0,511	0,300
Number of household plug-ins	1,000	0,868	0,571	0,316
Maximum registered power	1,000	0,867	0,465	0,285
Measured values of electrical energy	1,000	0,849	0,443	0,252

After the calculation with these coefficients the results about electrical energy losses at all the transformers at the specific overhead power line are the following:

TABLE 4 – JOULLE'S LOSSES OF OVERHEAD POWER LINE IN VARIANTS

Variant	**E_S [kWh]**	**$E_{g\ s}$ [kWh]**	**$E_{g\ s}$ [%]**	**Deviation [%]**
Transformer power	9.625.595	58.328	0,6060	- 1,72
DMSgroup method	9.625.595	59.251	0,6156	- 0,16
Number of household plug-ins	9.625.595	60.107	0,6245	+ 1,28
Maximum registered current	9.625.595	60.000	0,6233	+ 1,09
Measured values of current	9.625.595	59.054	0,6135	- 0,50
Average	9.625.595	59.348	0,6166	

3.3 Research results of losses on 10 kV overhead lines

From the noted mathematical descriptions, insights in network schemes and results in tables, following can be concluded:

- Estimation of losses for the first section is correct since total registered current runs through it,
- The first section of overhead lines are usually the longest,
- The first section take part in losses estimation with full resistance, considerably contributing to the total losses, mostly over 50 % of total losses of the complete feeder,
- Reduction coefficients for the following section of different variants are approximately the same and differ only in few percents, especially in the first sections,

- Reduction coefficient is included in estimation to the power 2, which means that reduced resistance of first sections has respectable value, but to the end of the line it suddenly decreases, in that way insignificantly affecting total losses from the fourth section on.

From the noted mathematical descriptions and insights in table 2 and table 4 it can be concluded that each of these variants gives reliable results which differ from average values by only ± 2 %. That value is, in any case, in the limits values of the instrument accuracy and can be considered reliable. As for household areas, the author recommends to employ method considering number of consumers, if available. The simplest thing is to use method considering capacity of the applied transformer.

4 10/0,4 kV TRANSFORMER LOSSES

The studies where done on transformers connected to overhead lines which were examined

4.1 Losses **on transformers connected to 10 kV overhead lines, feeder 24, from the TS 35/10 kV "Novi Beograd 1"**

The description of this area and operation method is shown in 3.1.
Mathematical formulas to estimate transformer losses during one year are as follows:

$$E_{UK} = \sqrt{3}\,U \cdot \cos\varphi \cdot 0{,}25 \cdot K_T \sum_{n=1}^{35040} I_n \quad [kWh] \tag{4.1}$$

$$E_{gT} = P_{Fe} \cdot 8.760 + \frac{3 \cdot R_T}{1000} \cdot 0{,}25 \cdot \mathrm{K_T} \sum_{n=1}^{35040} I_n \quad [kWh] \tag{4.2}$$

As to variants employed to estimate currents run by each transformer the special same ones are those used in 2.1 and defining coefficients defined by currents entering each transformer (K_T).
The results of the studies are show in table 5.

TABLE 5 – CURRENT PARTICIPATION COEFFICIENTS OF EACH TRANSFORMER IN TOTAL CURRENT

Variant	**K_1**	**K_2**	**K_3**	**K_4**	**K_5**	**K_6**	**K_7**	**K_8**	**K_9**
Transformer power	0,111	0,111	0,111	0,111	0,111	0,111	0,111	0,111	0,111
DMS group method	0,099	0,163	0,130	0,053	0,144	0,101	O,109	0,095	0,106
Number of consumer	0,122	0,102	0,122	0,096	0,103	0,136	0,108	0,099	0,112
Maximum power	0,131	0,079	0,128	0,093	0,146	0,087	0,109	0,103	0,124

Estimation with these coefficients having been done, we had the following results about losses in all transformers on a certain overhead line:

TABLE 6 – JOULLE'S LOSSES AT TRANSFORMERS IN VARIANTS

Variant	**E_{uk} [kWh]**	**$E_{g\ uk}$ [kWh]**	**$E_{g\ uk}$ [%]**	**Deviation [%]**
Transformer power	9.582.642	129.168	1,3479	- 0,51
DMS group method	9.582.642	130.732	1,3642	+ 0,69
Number of consumer	9.582.642	129.437	1,3507	- 0,41
Maximum power	9.582.642	129.959	1,3562	+0,10
Average	**9.582.642**	**129.824**	**1,3584**	

4.2 Losses on transformers connected to 10 kV overhead lines, feeder 39, from the TS 110/10 kV "Kaluđerica"

Everything stated in chapter 3.2 can be applied to this network, and coefficients are defined in the some way as in chapter 4.1. Having estimated power currents the some way as in 3.2 for coefficients K_T we got the following values:

TABLE 7– CURRENT PARTICIPATION COEFFICIENTS OF EACH TRANSFORMER IN TOTAL CURRENT

Variant	K_1	K_2	K_3	K_4
Transformer power	0,193	0,307	0,193	0,307
DMS group method	0,177	0,312	0,201	0,310
Number of household plug-ins	0,132	0,297	0,252	0,319
Maximum registered current	0,133	0,402	0,180	0,285
Measured values of current	0,151	0,406	0,191	0,252

Estimation with these coefficients having been done, we had the following results about losses in oil transformers on a certain overhead line:

TABLE 8 – JOULLE'S LOSSES AT TRANSFORMERS IN VARIANTS

Variant	E_S [kWh]	$E_{g\ S}$ [kWh]	$E_{g\ S}$ [%]	Deviation [%]
Transformer power	9.566.244	107.687	1,1256	- 1,87
DMS group method	9.566.244	107.972	1,1287	- 1,60
Number of household plug-ins	9.566.244	109.353	1,1432	- 0,34
Maximum registered current	9.566.244	112.117	1.1720	+ 2.17
Measured values of current	9.566.244	111.521	1,1658	+1,63
Average	**9.566.244**	**109.739**	**1,1471**	

4.3 Results of 10/0,4 kV transformer losses studies

From the noted mathematical descriptions, insights in network schemes and results from the table 6 and table 8 the following can be concluded:

- Losses on transformers are due to permanent losses caused by magnetizing transformer core and variable losses caused by heating of a transformer because of transformer electric current running,
- It can be seen that percentage losses in lightly loaded transformers are higher than those in average loaded transformers,
- The author recommends loading transformers up to 85 % since the losses are optimal,
- It can be noticed that percentage losses in transformers, no matter how big loading is, doesn't differ much and reach the value of 1, 20 %.

For the accuracy of the method, similar to chapter 3, no matter which method has been used total results about losses of all transformers in one feeder are almost the same. Deviation from average value is again ± 2 % which means that noted results are very reliable.
The same as in chapter 3 it is recommended to use the variant considering the number of consumers, but in a case of lacking this fact, the transformer power variant is quite reliable.

4. TESTING OF THE METHOD

The method was tested in the consumer area of TS 110/10 kV "Kaluđerica". This is suburban residential zone, supplied by 8 feeder of 10 kV network about 40 kilometers in length. As for this underground cable there have been installed 17 km of IPO 13 3x150 mm^2 cable, about 15 km of ABC cable, type XHP 48/0 3x70mm^2 and about 8 km of bare Al and Cu conductor. 68 transformer substations of 37 MVA of the total

installed power where connected to this network. The maximum of the engaged power of this region realized in 2005. was 24,43 MW and consumption was 105.801.080 kWh.
Table 9 shows the results examining total losses on medium voltage on this network.

Table 9 – JOULLE'S LOSSES AT OVERHEAD POWER LINE AND TRANSFORMERS ON THE TS 110/10 kV "KALUĐERICA"

Order number	Feeder number	I [A]	R_v* [Ω]	E_S [kWh]	E_{gOL} [kWh]	E_{gOL}[%]	E_{gTS} [kWh]	E_{gTS} [%]
1.	"28"	24 - 110	0,7485	4.427.096	38.913	0,88	54.330	1,24
2.	"30"	47 – 271	1,2782	18.318.809	639.791	3,49	208.221	1,18
3.	"31"	33 – 227	1,0029	16.686.589	416.637	2,50	190.077	1,18
4.	"33"	41 – 207	0,5867	14.761.110	184.368	1,25	207.574	1,42
5.	"34"	63 – 207	0,6088	15.806.490	215.316	1,36	195.603	1,25
6.	"36"	23 – 137	0,7760	10.029.643	129.167	1,29	119.873	1,21
7.	"37"	51 – 227	0,5581	16.677.980	124.410	1,35	188.279	1,15
8.	"39"	22 - 140	0,4413	9.625595	58.328	0,61	107.808	1,27
SUM				**106.333.312**	**1.906.931**	**1,79**	**1.271.765**	**1.17**

5. CO N C L U S I O N

The activities to promote the method of estimating precise losses on medium voltage network of power in the area of "Elektrodistribucija Beograd" using data obtained by remote control system were started in [1]. This work describes procedure considering single electric power stations with current measuring at the entrance, with no feeders, which means that the whole electric current comes to the end of the station. In that case the procedure of estimating losses is rather simple, and the final result absolutely correct. These stations are 35 kV overhead power lines and 35/10 kV transformers.
The work also elaborates 10 kV overhead lines where registered current runs fully only through the first section and later this disperses into feeders. To estimate how much current is taken by each feeder and what the loss in the feeder is, as well as in a certain 10/0,4 kV transformer there are some variant which can be practically realized.
It is shown that power losses can be estimated by this method with the accuracy of ±2%, which is certainly more correct than any other method.
It is also shown how big losses on overhead lines are, that′s to say on transformation considering one example in a suburban zone.
How much these data are precise, it can be seen from comparing them considering total consumption on this consumer area. Measuring devices registered the consumption of this area from 105.801.080 kWh in 2005. Studying and summing up dispatchers facts the consumption is 106.333.312 kWh, as shown in table 9. It can be seen that deviation is less than 0, 5 %, and that is under the accuracy limit of measuring instrument.
In this way it is possible to estimate correctly the power losses in the medium voltage network in great part of the consuming area of "Elektrodistribucija Beograd".

6. B I B L I O G R A P H Y

[1] Mr Lj. Mandić, M. Nikolić: "Optimal method of estimating electrical power losses on electro energetic system elements of ″Elektrodistribucije Beograd" ″ELEKTRODISTRIBUCIJA″ No.3. 2001.