ELECTRICAL POWER LOSSES ESTIMATION IN 10 kV NETWORK

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ABSTRACT

This paper presents a new method for electrical power losses estimation in 10 kV network, based on accessible data. These data are resistance of network's element and annual electrical energy flow, passed through it, or the element's annual maximal power (current). This analysis treats thermic impulse, as the electrical power losses factor, caused by network element's operation. Method's elaboration presented in this paper shows that the linearization of network element's load duration curve (systemized annual load chart) gives a functionality of that particular network element's thermic impulse from annual electrical energy flow and from the trend of linearized load duration curve. An empiric functionality between that trend and annual electrical energy flow has been found, and – consequently – an algorithm for thermic impulse calculation, based on annual electrical energy flow data, only. It has been shown, also, that – based on empiric determined relation between maximal current (power) and electrical energy flow – exists a linear functionality of thermic impulse from maximal annual current (power) of the grid's element. Finally, empiric expressions of second degree for direct calculations of thermic impulse depending on peak power (current) or network element's annual electrical energy flow, has been determined. Elaborated method has been tested and compared on the sample of 26 branches of 10 kV network operated by "Elektrodistribucija-Beograd" (EDB) and the sample of 41 substation (TS) operated by "Elektrodistribucija-Niš" (ED Niš).

INTRODUCTION

A number of methods for estimation fo Joule losses in electrical power networks can be found in literature. Their main deficiency lies in the fact that they demand data which are usually unaccessible. In EDB, concerning 10 kV network operation, exist data about loads of starting sections of 10 kV feeders – taken every 15 minutes in their supplying cubicles in TS X/10 kV, comprised by Remote Control System (RCS), and local measurements of feeder's peak power (current), in other TS. Thereby, data about 15-minutes peak load are incomplete, due to insecurity of RCS. Within the project of EDB's 110 and 35 kV networks perspective development, data about supplying grid's elements for each customer are interposed in EDB's information system (so called »customer's coding«). By this data base searching it will be possible to determine annual energy flow through all network elements.

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The idea of this paper is to develop a method for estimation of annual power losses of operating network's elements, based on data about their annual peak power or annual electrical energy flow, and grid element's resistance, of course. Compared with mostly used, “τ method” [1], which demands three data: resistance, electrical energy flow and peak power, for appliance of this new method, only two data are sufficient – data about resistance and electrical energy flow, or peak power.

METHOD ELABORATION

Active energy losses (»Joule losses«) on a line with resistance R, caused by alternating load i(t), during period T, can be calculated according to equation:

$$\Delta W = 3R\int_0^T i^2(t)dt \qquad (1).$$

In expression (1), factor 3R can be observed, which is the characteristic of network's element, and factor $\int_0^T i^2(t)dt$, which is the characteristic of network element's operation and represents so called thermic impulse [2]. This paper will treat the value of thermic impulse, only:

$$A = \Delta W / 3R = \int_0^T i^2(t)dt \qquad (2).$$

Typical, systemized annual current chart (load duration curve) of 10 kV cubicle in TS X/10 kV is shown in Fig. 1.

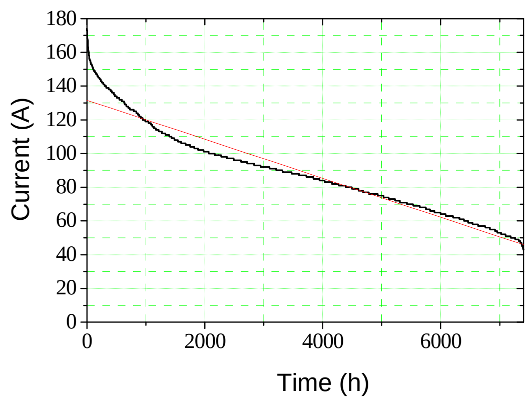


Figure 1 Linear regression of load duration curve

As it is possible to see from the Fig.1, load duration curve can be approximated (»fitted«) with a straight line, by the method of minimal sum of sqared deviations, between real and approximated data. The general form of approximation, considering decreasing trend of line, is:

$$I(t) = a - bt \qquad (3).$$

Consequently, there is:

$$A = \int_0^T I^2(t)dt = \int_0^T (a-bt)^2 dt = \int_0^T \left(a^2 - 2abt + b^2t^2\right)dt = T\left(a^2 - abT + b^2\frac{T^2}{3}\right) \qquad (4).$$

Concerning that the arithmetic average value of current, got by linear approximation, is:

$$I_{sr} = a - \frac{b}{2}T \qquad (5),$$

after re-arranging of previous equations, the expression for thermic impulse becomes:

$$A = I_{sr}^2 T + \frac{b^2 T^3}{12} \qquad (6).$$

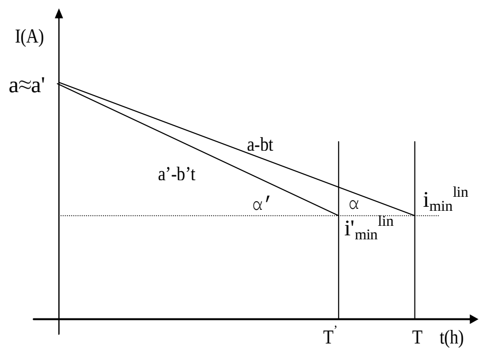
Total current impulse, therefore, consists of two parts; first is the current impulse by constant average current, and second one is the supplement of current impulse, caused by temporal change of annual current chart. With the approximation of constancy of voltage and average value of power factor, cos φ, average current is proportional to electrical energy flow (annual amount of consumptioned electrical energy, W):

$$I_{sr} = \frac{W}{\sqrt{3}U \cos\varphi} \qquad (7).$$

With T=8760 hours/year, it was necessary to determine empiricly a possible relation between linearized annual current chart's trend (b) from annual energy amount or peak power. This functionality was examined on the sample of 27 10 kV feeders supplied from cubicles in four TS X/10 kV (TS 35/10 kV »Zeleni venac«, TS 110/10 kV »Kaluđerica«, TS 110/35/10 kV »Sremčica« i TS 110/35/10 kV »Ralja«). During this research, two following problems occured:

1. The problem of data deficiency in annual load chart, caused by insecurity of remote control over TS,
2. The problem of changing customer supply boundaries on feeders, caused by outages.

The first problem has been solved with assumption that non-existing data behave due to the same regularity as existing ones, i.e. the current chart has been extended, according to Fig.2. All problems concerning this metter were elaborated in detail, in Lit. [3].



T' – equivalent time with existing data;

T – total annual period, 8760 hours.

Figure 2 Linearized load chart's extending principle

According to Fig. 2, the trend of straight line for T=8760 (h) was determined based on the trend of line for T<8760 (h), and with relation:

$$b \cong \frac{b'T'}{T} \qquad (8),$$

thereby following, realistic approximations were made: a ≈ a' and $i_{min}^{lin} \approx i'^{lin}_{min}$.
Because of the change of supply boundaries, caused by outages, the load duration curve refers to different consume areas, which gives a deviation of functionality of b from W, compared with situation without limits dragging. Such charts have been recognized visually, and only data related to one particular consume area, for normal operating conditions, were took into account (acc. to [3], too), with correction of parameter b according to equation (8).
Results of this research are presented in Fig. 3 and 4 and in Schedule 1.
In Schedule 1, T' presents the equivalent time i.e. total sum of 15-minute periods with existing, relevant data, b' – corresponding trend of fitted straight line, and b – trend of straight line, obtained by resetting on 8760 hours period.
In Fig. 3 and 4 it is observable that there is a correlation between the trend of cubicle's linearized annual load chart, from maximal annual current (and consequently – from maximal power), as well as from annual electrical energy flow. That functionality can be fitted with straight line, which has been done for both cases. Coefficient of correlation in the first case (left) is 0,95, and in second one 0,89. Analytic forms of those straight lines are given with expressions (9) and (10).

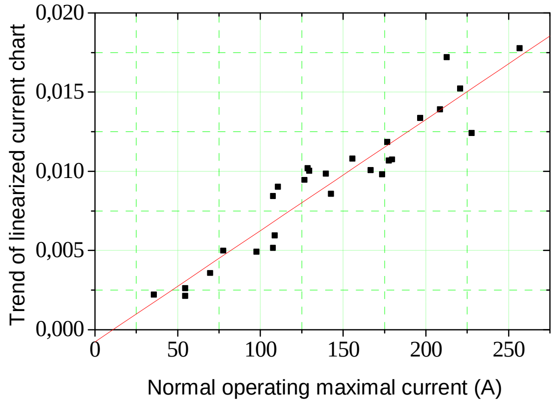


Figure 3 Correlation between trend of linearized current chart and maximal current

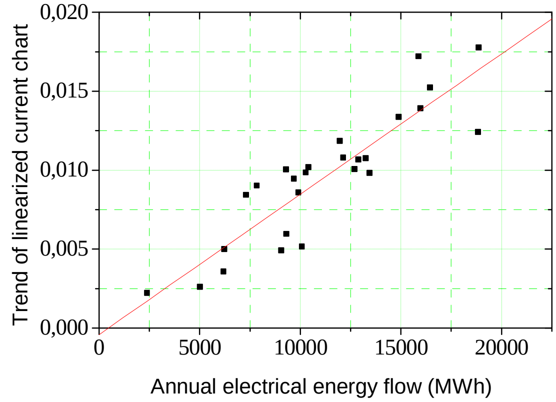


Figure 4 Correlation between trend of linearized current chart and electrical energy flow

$$b' = -0,00076 + 0,0007 \cdot I_{\max}(A) \qquad (9)$$

$$b' = -0,00042 + 8,89 \cdot 10^{-7} \cdot W(MWh) \qquad (10)$$

SCHEDULE 1 – RESEARCH SUMMARY RESULTS

Grid type	Supplying cubicle code	U_n	T'	Linearization of load duration curve		Measured data		Correct A (get from meas.data)	Estimated A via I_{max}		Estimated A via W_{god}	
									$I^2t = f(I_{max})$	Relat. error	$I^2t = f(W_{god})$	Relat. error
		kV	(h)	b' (A/h)	b (A/h)	I_{max}	I_{sr} (A)	I^2t ($A^2h\cdot10^3$)	I^2t ($A^2h\cdot10^3$)	(%)	I^2t ($A^2h\cdot10^3$)	(%)
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
Urban zone, underground grid	ZV05	10	8671,00	0,005	0,004949	78	41,24	16273,90	16785,72	3,15	16538,94	1,63
	ZV06	10	8362,50	0,01114	0,010635	178	85,14	70181,53	76923,49	9,61	70932,19	1,07
	ZV11	10	8007,75	0,01292	0,011811	177	79,08	62992,61	76105,11	20,82	61233,33	-2,79
	ZV17	10	8292,75	0,00887	0,008397	108	48,36	24679,13	30224,04	22,47	22862,49	-7,36
	ZV18	10	8304,75	0,00901	0,008542	143	65,47	41994,34	50888,68	21,18	42011,45	0,04
	ZV25	10	7402,75	0,01157	0,009777	174	88,79	74701,70	73676,29	-1,37	77111,16	3,23
	ZV26	10	8579,50	0,01002	0,009814	140	67,92	45183,12	48907,00	8,24	45212,92	0,07
Suburban zone, mixed network	KL28	10	6398,75	0,01229	0,008977	111	51,87	28301,22	31784,87	12,31	26331,69	-6,96
	KL30	10	7129,25	0,02178	0,017725	257	124,56	154384,30	155428,14	0,68	151177,48	-2,08
	KL31	10	6801,75	0,02212	0,017175	213	104,81	113120,46	108328,49	-4,24	107259,57	-5,18
	KL33	10	7345,25	0,0159	0,013332	197	98,40	95196,52	93305,58	-1,99	94613,06	-0,61
	KL34	10	7480,50	0,01625	0,013876	209	105,49	108768,34	104467,55	-3,95	108649,04	-0,11
	KL36	10	6494,50	0,01349	0,010001	130	61,45	38964,94	42586,35	9,29	37010,13	-5,02
	KL37	10	7335,00	0,01814	0,015189	221	108,61	116548,45	116260,79	-0,25	115137,43	-1,21
	KL39	10	7463,75	0,01105	0,009415	127	64,03	41057,83	40775,65	-0,69	40174,85	-2,15
Rural zones, overhead network	SR05	10	8126,25	0,00235	0,00218	36	15,91	2500,81	4600,42	83,96	1922,74	-23,12
	SR17	10	7625,00	0,01231	0,010715	180	87,52	74000,84	78573,40	6,18	74944,07	1,27
	SR22	10	8096,50	0,01085	0,010028	167	83,86	67403,63	68162,46	1,13	68836,00	2,13
	SR23	10	8093,50	0,01164	0,010754	156	80,16	63035,69	59931,86	-4,92	62907,06	-0,20
	RA07	10	6220,75	0,0143	0,010155	129	68,78	47262,72	41978,40	-11,18	46359,45	-1,91
	RA09	10	5667,75	0,00915	0,00592	109	61,61	35270,48	30739,94	-12,85	37201,27	5,47
	RA12	10	6251,75	0,00361	0,002576	55	33,29	10093,99	9154,95	-9,30	10634,17	5,35
	RA18	10	5992,00	0,0075	0,00513	108	66,63	40425,89	30224,04	-25,24	43502,31	7,61
	RA24	10	6273,50	0,00681	0,004877	98	59,87	32760,67	25306,22	-22,75	35126,21	7,22
	RA26	10	6296,50	0,00493	0,003544	70	40,97	15428,74	13868,51	-10,11	16322,63	5,79
	RA27	10	6286,25	0,01726	0,012386	228	124,30	144056,01	123431,71	-14,32	150561,34	4,52
	RA34	35	6448,50	0,00285	0,002098	55	37,17	12358,32	9154,95	-25,92	-	-
The lane of errors absolute values (%)										12,89		4,00

Based on expressions (9) and (10), equation (8) and data about T' presented in Schedule 1, values of b can be calculated, with setting on 8760 hours period. After that, based on relation (6), corresponding values of thermic impulse were estimated by using feeder's maximal current values or annual electrical energy flow. These calculation results are presented in columns *10* and *12*, in Schedule 1. In the columns *11* and *13* of the same Schedule, there are error values, calculated against accurate value, from column 9. As correct value is addopted in fact the value of thermic impulse calculated from original 15-minute currents, obtained by RCS of EDB. Finaly, the arithmetic average value of relative error's absolute values is also given in Schedule 1. As it is possible to see from it, much better power losses estimation is from annual electrical energy flow, than from maximal current (power). This conclusion is logical, because data about electrical energy flow is implicitely the data about arithmetic average of 15-minute currents, i.e. average data about whole year.
Concerning the fact that functionality of the trend of linearized load duration curve, from maximal current (power) and annual electrical energy flow can be approximated with linear function, it is clear that also the function of indipendent variables can be linearized, as it is shown in Fig. 5.
This empiric correlation is convenient for calculations of power losses on 10 kV network's sections, for which the peak power is unknown, but the data about consumption of consumers, supplied from that particular section – on the contrary – is accessible. This correlation can also be used for calculations of power losses in TS 10/0,4 kV.

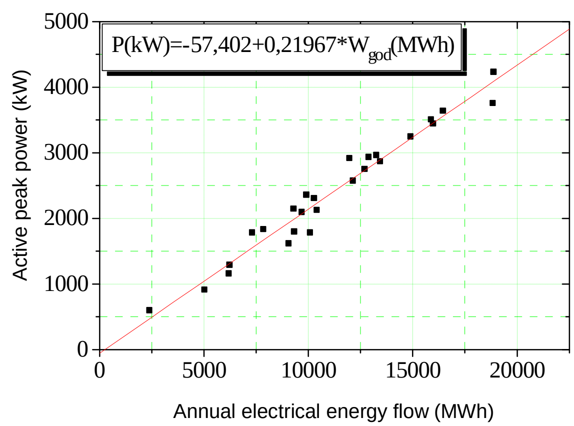


Figure 5 Relation between annual electrical energy flow and active peak power

DIRECT FUNCTIONALITY OF THERMIC IMPULSE FROM ELECTRICAL ENERGY FLOW OR PEAK POWER

It has been interesting to try to constitute a direct functionality of thermic impulse from annual peak power (current, I_{max}) or electrical energy flow, W, on particular supplying 10 kV cubicles. This can be done by creating charts A=*f*(I_{max}) and A=*f*(W) and by »fitting« measured values with corresponding curve. Such procedure is shown in Fig. 6, 7, 8 and 9.
On the charts presented by Fig. 6 and 8 the functionality has been shown with logarithmic division of axis, and in Fig. 7 and 9 – with linear. From Fig. 6 and 8 it is obvious that the functionality in logarithmic presentation can be fitted with linear function, which means that the fitting curve, correspondent to the chart with linear axis division, has the form:

$$A = m \cdot I_{max}^{n}, \quad \text{i.e.} \quad A = m \cdot W^{n} \qquad (11).$$

Parameters m and n should be determined for each case, respectavely. As the result, analitic expressions of the fitting functions, are presented also in Fig. 7 and 9.
Based on the analitic expressions presented on Fig. 7 and 9, it is possible to calculate directly the value of 10 kV feeder's thermic impulse, corresponding to data about cubicle's maximal annual current or annual electrical energy flow. From Figures above it is observable that data dispersion is smaller around the curve fitted in the second analyzed case (Fig. 8 and 9, functionality of thermic impulse from annual electrical energy flow), than in the case of functionality from maximal current (Fig. 6 and 7). Such result is logical, concerning the fact that the annual electrical energy flow is the characteristic of

whole year, compared with maximal current, registrated during that year, which is therefore the characteristic of a particular moment. Beside that, in the case of functionality from anual electrical energy flow, supposed power degree function (11) is, in fact, approximately second degree function (see the equation on the Fig. 9).

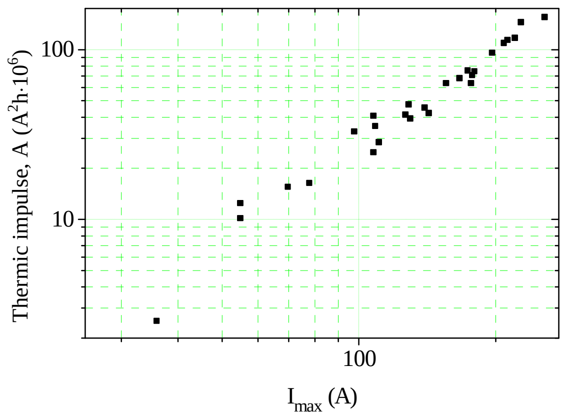


Figure 6 Function A=f(I_{max}) with logarithimic scale

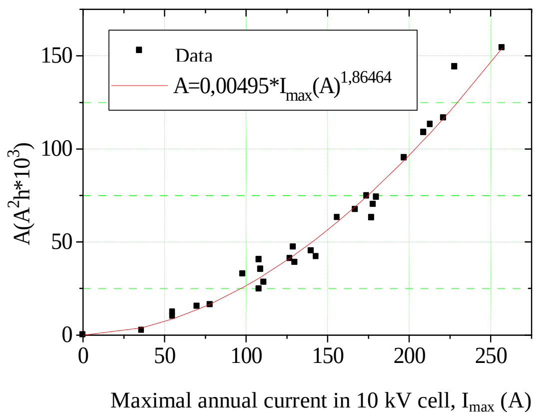


Figure 7 Function A=f(I_{max}) with linear scale

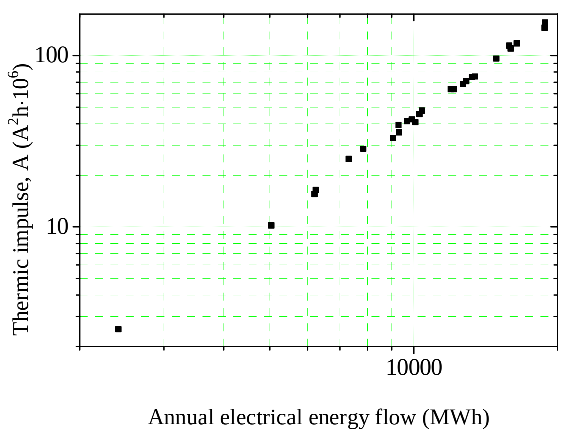


Figure 8 Function A=f(W) with logarithimic scale

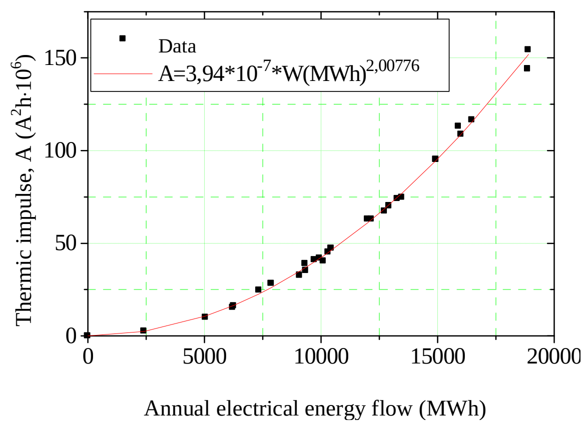
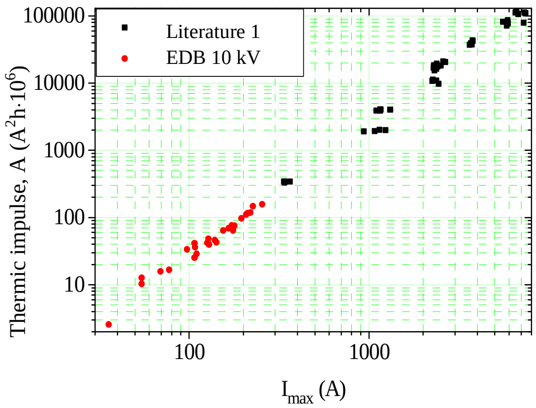


Figure 9 Function A=f(W) with linear scale

It was interesting to check if the second degree functionality of thermic impulse from peak power or electrical energy flow could be generalized on the bigger sample. Therefore, data from Lit. [1], related to 41 annual load chart of supplying TS operated by »Elektrodistribucija Niš« (ED Niš), has been analyzed, too. Thermic impulse was calculated from those data, supposing that each TS was the source of 10 kV voltage. Therefore the measured currents [1], were re-calculated on 10 kV voltage level. Those results, together with results from Belgrade (left), are presented in Figures 10, 11, 12 and 13. Corresponding losses of the »source« with voltage level different from 10 kV, should be calculated with resetting of corresponding network element's resistance on 10 kV, reference voltage level.
It is observable that data dispersion around fitted curve is greater in the case presented in Figure 11, i.e. there is – as well as in the case of Belgrade's data analysis – stronger functionality of thermic impulse from annual electrical energy flow than from maximal current.
From the analitic form of the charts presented in Fig. 9 and 13 it is obvious that there is a relationship between thermic impulse and annual electrical energy flow, for a wider load range, concerning the fact that by this analysis were comprised the network elements with peak power from 0,62 to 127 MW, and even from two different electrical power distributing systems. Beside that – and especialy related to electrical energy flow functionality – the accuracy of fitted curve compared with measured data, is extremely high. Average error of fitted curve related to exact data in Fig. 13 is 3,3%, and average error of fitted curve related on exact data in Fig. 9 is 3,28%. Comparing curve analitic expressions, used for data fitting, respectively for EDB only and for EDB and ED Niš, [1], summary data, it is obvious that

those equations are very similar. It should be marked that the power degree of annual electrical energy flow, W, is very close to second degree in the function used for fitting. Namely, the annual electrical energy flow is proportional to sum of I·t, and thermic impulse to sum of I^2·t, therefore thermic impulse is proportional to second degree of annual electrical energy flow. Power of second degree should be expected also by powering maximal current, done for curve fitting according to maximal current. Due to higher level of data dispersion in this case (because maximal current characterizes one specific moment during year, and thermic impuls represents the whole year), however, by fitting towards maximal current, obtained power degree is more distored from second degree, compared with the case of fitting towards annual electrical energy flow.



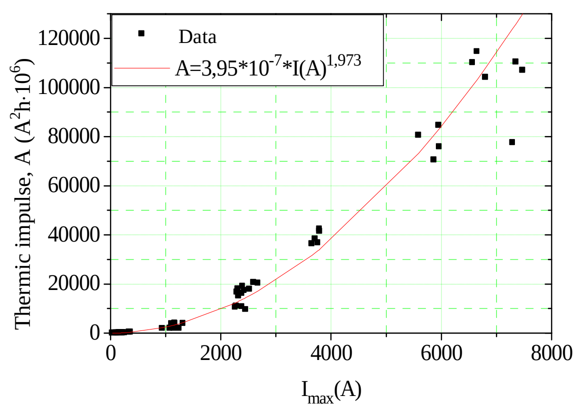
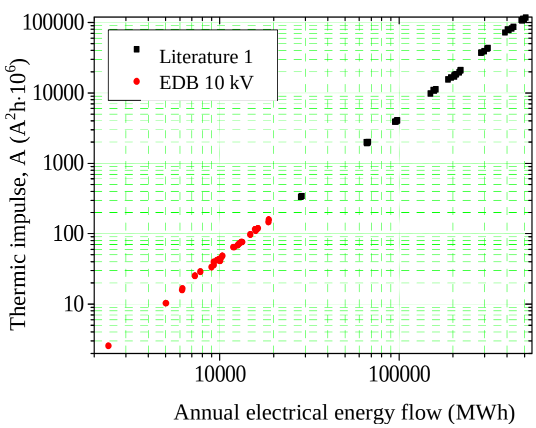


Figure 10 Function A=*f*(I_{max}) with logarithimic scale

Figure 11 Function A=*f*(I_{max}) with linear scale

Summary results from EDB (10 kV cubicles) and ED Niš (TS 110/X kV)



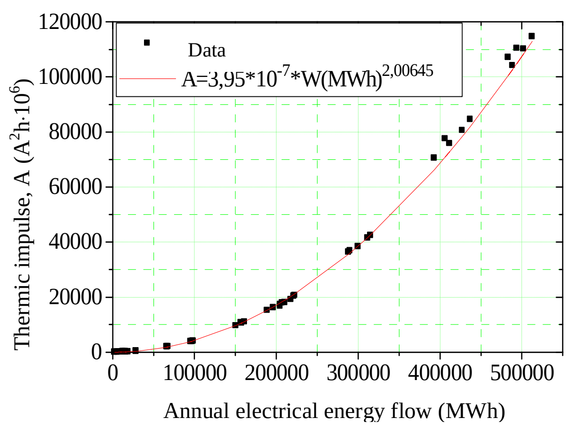


Figure 12 Function A=*f*(W) with logarithimic scale

Figure 13 Function A=*f*(W) with linear scale

Summary results from EDB (10 kV cubicles) and ED Niš (TS 110/X kV)

CONCLUSIONS

Based on previous analysis and calculations, the following can be concluded:

1. Based on known values of particular 10 kV network elements resistance and annual electrical energy flow transmitted through them, or the values of their peak powers (currents), by the methodology presented above it is possible to estimate electrical power losses on those elements. Thereby, average error is cca 13%, if the estimation has been done according to peak current, and only cca 4% if it has been done based on the annual electrical energy flow. Electrical energy flow is accessible from customer's data base, if there was a data about supplying network elements for each customer, in it (so called "customers coding").

2. There is a direct, empiric functionality between thermic impulse of 10 kV network elements and annual electrical energy flow through them, i.e. their peak power (current). This relation can be approximated with following type of power function: $A=m \cdot W^n$, i.e. $A=m \cdot I_{max}^n$.

3. Elaborated functionality can be generalized on higher voltage levels, for wide network elements range (with loads from under 1 MW to over 100 MW), with determination of thermic impulse, using current value re-calculated on reference voltage level of 10 kV.

4. In further researches it should be checked if this functionality can be generalized on TS 10/0,4 kV and 0,4 kV network elements, too.

LITERATURE

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