ECONOMIC CURRENT DENSITY AND SELECTION OF OPTIMAL Al-Fe CONDUCTOR CROSS-SECTION FOR OVERHEAD 10 kV LINES

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ABSTRACT

This paper presents the manner of economic current density determination for overhead lines, as well as value determination of parameters on which it depends: line investments costs, maximal power losses equivalent duration time and electrical energy price. Economic current density value was calculated for real cases of two new projected overhead 10 kV lines, in all three possible variations of Al-Fe conductor cross-section: 50/8, 70/12 i 95/15 mm^2. For all these variants, complete technical calculations and equipment lists with corresponding price estimation were done.
The values of economic current density for overhead 10 kV line were determined depending on the range of maximal power losses equivalent duration time on this network element, and on the interval in which the electrical energy price is expected to increase in the next few years. In order to determine realistic range of maximal power losses equivalent duration time for overhead lines, registrated current loads of eleven overhead 10 kV lines were analized. The price of electrical power losses was varied from 3 €cent/kWh to 5 €cent/kWh.
Based on the range of economic current density, and also on relation between current density and maximal possible loads of overhead 10 kV lines (for three standard Al-Fe conductor's cross-section), the paper shows which cross-section are optimal for expected line loads.

INTRODUCTION

At the beginning of 1950s in Serbia the first researches about economic current density were done. Based on results obtained then, the conclusion was that building overhead lines with cross-section as small as it possible has been economicaly approved. Those researches, repeated during 1970s, Lit. [1], included all network elements, as well as determination of both – optimal cross-section (concerning feeders i.e. lines) and optimal voltage level of transmission network. That time, the researches of optimal characteristics of network elements, depending on economic current density, gave the results opposite to those obtained during 1950s; It was proved that, economicaly speaking, it was more efficient to build overhead lines with bigger cross-section. For overhead lines it was shown

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that economic current density varies between 1,0 to 1,2 A/mm^2. In the present circumstances of the changed Tariff System practice, it is necessary to repeat those researches. Namely, duration time of maximal load has been changed, and – consequently – maximal power losses equivalent duration time, too, from which the value of economic current density depends.
In the praxis, without necessary revision, engineers still use approximate, empiric formulas for maximal power losses equivalent duration time, τ, previously known from literature, f.e. Lit.[2]. However, depending on formula which has been used, very different results could be calculated. By determination of τ exact value, however, there are some problems, described in Lit. [3] and [4], and partially solved by methodology elaborated in Lit. [3].
Beside deficiency of literature related to this matter and non-existance of practicaly usefull results, as well as necessity checkout of the values obtained during previous researches, the argument for re-examination and repeated work on this topic also was the verification or validation of criteria, used by planners and project engineers in Al-Fe conductor's cross-section selection, for overhead 10 kV lines.

THEORETIC BASIS OF THE PROBLEM

Economic current density of overhead line. Optimal overhead line's current can be determined from the case when the costs dependent from cross-section equalize with the annual losses costs, [1]. Hence, economic current density of overhead line (derivation in detail is given in Appendix A), is:

$$\Delta_{Ve} = \frac{I}{s} = \frac{S}{\sqrt{3} \cdot U \cdot s} = \sqrt{\frac{c_V \cdot p_V}{3 \cdot \rho \cdot \tau \cdot c_{\Sigma e}}}, \qquad (1)$$

Analysis of the expression for economic current density (1) shows not only the independence on feeder's length, but also the indenpendence on circumstances on it's ends, i.e. economic parameters of incomming/outcomming cubicles. The very same exspression can be derived, too, in the case of expanding the problem with increasing the number of lines, as the variable of optimization.

Investment costs and costs per kilometer length and conductor cross-section unit of overhead line. In the numerator of expression (1) for economic current density of overhead line (in the following text: OHL), there is c_v – costs per line's kilometer and conductor's cross-section unit, in €/mm$^2\cdot$km. To calculate them, it is necessary to find building investment costs of OHL 10 kV with Al-Fe conductor, variantly – for three typical cross-sections (50/8, 70/12 i 95/15), used for this network voltage level. For two real OHLs, chosen as examples, technical calculations for poles selection on all pole positions were executed, other equipment selected, too, and complete equipment list with corresponding price estimation were done. Those procedures were repeated for all three variants of both OHLs, depending on used conductor's cross-section. For each line it was possible then to make linear regression for so obtained three values of investment costs, T_{gv}, i.e. to determine linear function $T_{gv}/L = c_v \cdot s + \text{const}$, where are: L – feeder's length, s – conductor's cross-section.
By mechanical load check of poles and other equipment, the calculations were done with adopted:

- normal additional load from mist, ice and snow: n_{do} = 1,6 g; where g has the following values:

  196 kg/km for Al-Fe 3x50/8, 284 kg/km for Al-Fe 3x70/12, 383 kg/km for Al-Fe 3x95/15;

- wind pressure: p_v = 75 daN/m^2 for 10 kV lines built with bare Al-Fe cords.

It was accepted and calculated with conductor's maximal working strain: σ_m = 7 daN/mm^2. For realistic spans between poles of both lines, flexure schedules were made, for all three cross-section cases. Forces selection at poles mechanical calculations were done according to Lit. [5] and [6].

Maximal losses equivalent duration time. In denominator of expression (1) for economic current density there is τ - maximal losses equivalent duration time. It can be determined in different ways, based on realistic load diagrams of grid elements, or by empiric formulas. Concerning deficiency of empiric formulas for τ mentioned in the Introduction, during this research precise determination of τ were done, using accessible measurements for corresponding electrical power distributing network elements. Regards of the fact that the 10 kV feeders – used here as examples for economic current density calculations – were not under the Remote Control System (RCS) of "Elektrodistribucija-Beograd" (EDB), their load diagrams were not accessible. Therefore the other feeders were chosen for τ calculations, according to criteria elaborated in Lit.[3]. Those lines are predominantly or purely overhead, fed from four 10 kV outcomming cubicles (cells) in substation (TS) 110/35/10 kV SREMČICA and seven 10 kV cells in TS 110/35/10 kV RALJA. For them the annual values of τ were calculated, on the way detaily explaned also in Lit.[3]. Minimal, maximal and average value of τ for those eleven 10 kV cells are shown in Schedule 1 (the part of Schedule IV from Lit.[3]).

SCHEDULE 1 – RANGES AND AVERAGE VALUES OF T_{max} AND τ FOR RURAL ZONE IN BELGRADE, BASED ON TEMPLATE OF ELEVEN 10 KV OVERHEAD LINES

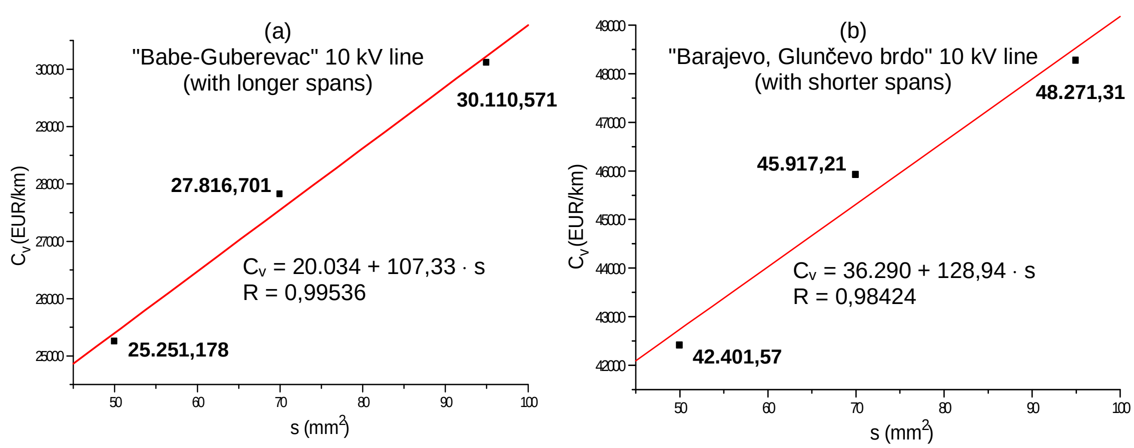
City zone / 10 kV network type		T_{max} (h)	τ (h)
Rural zone / overhead network	Minimal value	3872,16	1929,64
	Maximal value	5404,03	3465,87
	Average value	4783,22	2833,02

Based on results of the research presented in Lit.[3] and Schedule 1, economic current density, according to equation (1), should be varied depending on maximal power losses equivalent duration time, τ, which value lies in the range between 1900 and 3500 hours per year.

Electrical energy price. Except maximal power losses equivalent duration time, τ, as another variable in the denominator of expression (1) exists also the price of electrical power losses, i.e. the average price of delivered kWh. The EDB's financial income from electrical energy sold in 2004. was P_r=15.904.936·10^3 CSD, and annual electrical energy flow, took over from transmission network, was P_e=6.973·10^6 kWh. From there it can be calculated that the price of average kWh in that year was: $c_{\Sigma e} = P_r/P_e$ = 2,281 CSD/kWh = 0,03 €/kWh, where average rate in 2004 was 75 CSD/€. Therefore, for economic current density calculation, (1), as lower limit of the price for 1 kWh, 3 €cent/kWh can be accepted. Regards the nature of problems elaborated in this paper is of planning character and significance, as upper limit of $c_{\Sigma e}$ should be accepted the price of 5 €cent/kWh, which is considered as minimal economic electrical energy price, neccesery to reach in Serbia, in the next few years.

RESULTS OF ANALYSIS

The values of specific investment costs of overhead Al-Fe lines (per kilometer and conductor's cross-section). Overhead 10 kV lines chosed for this analysis are following: »Babe-Guberevac« (two tightened fields, 795 m in total length, with longer spans between poles) and »Glunčevo brdo« (one tightened field, 218 m in length, with shorter spans, i.e. more poles per kilometer). Their investment costs are calculated in the way previously described, and presented in Fig. 1, a and b, as points.



C_v - investment costs of overhead 10 kV line per kilometer, in (€/km);
c_v, – straight line trend, costs per line's run kilometer and conductor's cross-section unit, in €/mm²·km;
R – chart points overlapping with straight line obtained by linear regression

Figure 1 Functionality of investment costs per overhead line kilometer from conductor's cross-section

On each chart, respectively, through three obtained points, a straight line can be drown, by linear regression. Each line approximately represents depending relations between investment costs and conductor's cross-section value. Values on Fig. 1 are given in Euros (€), with remark that they were calculated in CSD, with rate of 83 CSD/€ in the time of calculation (August 2005.).Chart (b), right, for OHL with shorter spans, has a slightly larger trend of straight line. That means that the feeder has greater costs per line's run kilometer and conductor's cross-section unit, c_v, (cca 129 €/mm^2·km), matched with the line with longer spans (107,3 €/mm^2·km). Consequently, 10 kV line (b) will have also greater values of economic current density.

Economic current density values for overhead 10 kV lines with Al-Fe conductors, depending on maximal power losses equivalent duration time and on reached average electrical energy price. When previously calculated values for c_v incorporate in expression (1), and values for τ and $c_{\Sigma e}$ in it fluctuate within ranges explained above, for both tested lines it is possible to get adequate curve families, presented on Fig.2 and 3.

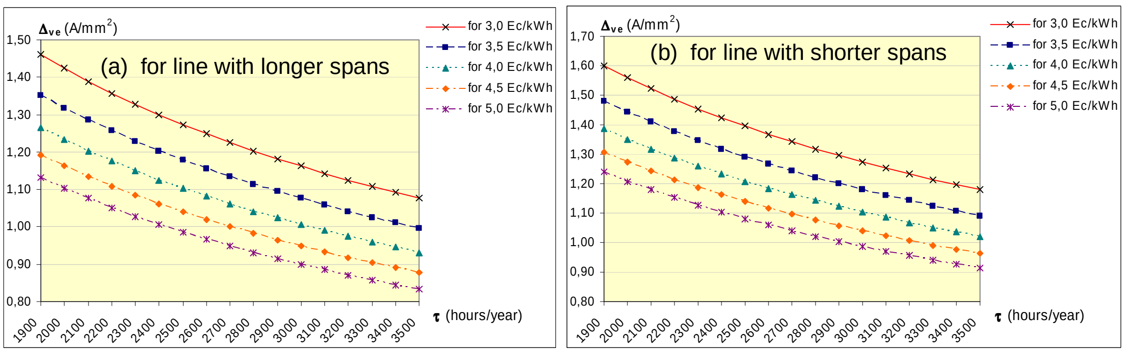


Figure 2 Economic current density depending on maximal power losses equivalent duration time

Observing curve families $\Delta_{ve} = f(\tau)$ from Fig.2, a decline of economic current density value is remarkable with the growth of $c_{\Sigma e}$. Knowing that the electrical energy price will grow in the comming period – because it must reach the minimal economic value of 5 €cent/kWh – the value of economic current density will fall down, even below the values determined in previous researches (from 1 to 1,2 A/mm^2), Lit. [1]. Now, nevertheless, even for average value of τ from cca 2800 hours (see Schedule 1) and electrical energy price reached in 2004 (3 €cent/kWh), from Fig.2, it can be read exactly 1,2 A/mm^2 for line (a), and for (b) cca 1,3 A/mm^2.

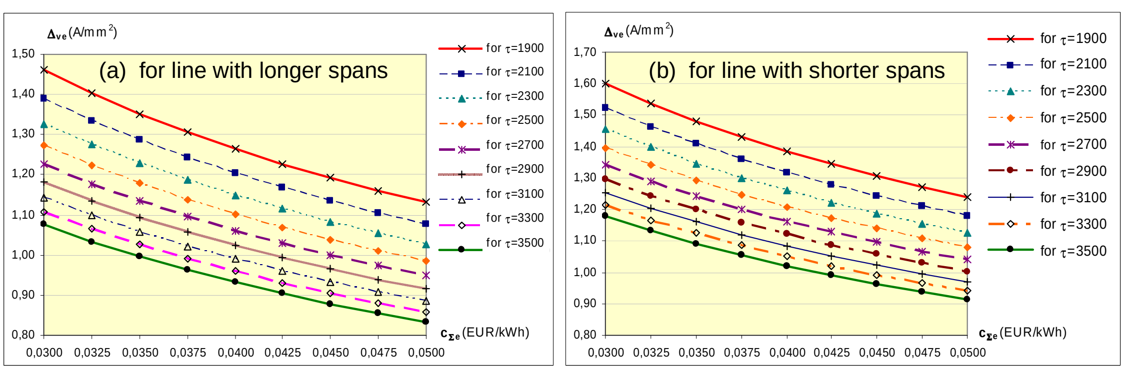


Figure 3 Functionality of economic current density from electrical energy (power losses) price

Beside that, the increase of electrical energy price and appliance of appropriate Tariff System make the electrical energy consumption more economic, which propitiate ratio of maximal and minimal values on realistic load charts of electrical power distributing network's elements (so called „chart ironning"). Consequently, the value of maximal load equivalent duration time increases, as well as maximal power losses equivalent duration time, while the value of economic current density decreases, according to relation (1). This is also clear by observing curve families on Fig. 2 and 3. It is obvious, namely, that even with present price per 1 kWh, economic current density decreases with the growth of maximal power losses duration time, τ, to the values determined in previous researches.

Determined economic current density values (depending on maximal power losses equivalent duration time and electrical energy power losses price) are slightly lower for 10 kV line (a), with longer spans (»Babe-Guberevac«), then those for line (b), with more poles per kilometer (»Barajevo, Glunčevo brdo«).

Determination of optimal Al-Fe conductor's cross-section for overhead 10 kV lines based on economic current density and expected load. As it was shown above with expression (1), functionality of economic current density on line's current load is given with following relation:

$$\Delta_V = \frac{I}{s} = \frac{S}{\sqrt{3} \cdot U \cdot s} \tag{2}$$

It is possible, therefore, to express the current density depending on expected load S (MVA) of Al-Fe 10 kV OHL, for all three characteristic conductor's cross-section, in the form of the straight lines family. In the further analysis, the range of possible load S is from zero to the load corresponding to permitted maximal current load of OHLs with Al-Fe conductors. Critical are the loads during winter period: 323 A i.e. 5,594 MVA for Al-Fe 50/8, 447 A (7,742 MVA) for Al-Fe 70/12 and 550 A (9,526 MVA) for Al-Fe 95/15. On the other hand, economic current density is presented with expression:

$$\Delta_{Ve} = \sqrt{\frac{c_V \cdot p_V}{3 \cdot \rho \cdot \tau \cdot c_{\Sigma e}}} \tag{3}$$

Lower and upper limits of economic current density were previously calculated on examples of two real 10 kV lines, and adopted value of specific resistance and feeder's annual rate were $\rho = 0{,}0265\ \Omega \cdot mm^2/m$ and $p_V = 9$ %, respectively. For each of both cases (a) and (b), it is possible to present the limits of Δ_{Ve} with two parallel, horizontal lines, as it is shown at Fig. 4.
The intersection of straight lines presented with expressions (2) and (3) determine lower and upper limit of economically reasonable (i.e. optimal) loads of 10 kV lines, for each of three possible conductor's cross-section (see the following Schedule and the chart on Fig. 4).

SCHEDULE 2 – APPROPRIATE CROSS-SECTION DEPENDING ON THE LOAD CORRESPONDING TO ECONOMIC CURRENT DENSITY

	line with longer spans		line with shorter spans	
	S (MVA)		S (MVA)	
s (mm^2)	min	max	min	max
50	0,7216	1,2643	0,7910	1,3859
70	1,0102	1,7701	1,1073	1,9403
95	1,3710	2,4022	1,5028	2,6332

The loads from Schedule 2 are economically reasonable loads for analized Al-Fe conductor's cross-sections. It can be seen that their maximal value for smaller cross-section is slightly greater than minimal economic load's value for the first next bigger cross-section. That means that for the consume areas for which – even in the future – it is not real to expect the load growth beyond, for example, 1,26 MVA, it is not necessary to use bigger Al-Fe conductor's cross-section than 50/8 (for instance – for some hamlet in rural area, fed over a 10 kV feeder's branch line). On the contrary, the main Al-Fe 10 kV lines should be built using the conductor's cross-section of at least 70 mm^2. Also, if the load growth is expected in some particular area, the smallest value of expected load, corresponding to 70/12 cross-section usage, is 1 MVA for the line with longer spans, and for 95/15 cross-section is 1,37 MVA. For OHL »Glunčevo brdo«, with shorter spans i.e. more closely situated poles, similar results were obtained as in the case of »Babe-Guberevac« 10 kV feeder. Therefore the conclusions are similar to previous, too. Single difference was this: overhead line with shorter spans has slightly bigger minimal and maximal load values correspondent to economic current density, for the same, adequate conductor's cross-sections. It is notable that even for S≥1,1 MVA (and expected load growth up to cca 2 MVA), the cross-section 70/12 should be used, and 95/15 for S≥1,5 MVA.
From Schedule 2 it is also notable that the ranges of optimal load for corresponding cross-sections are slightly bigger in the case of 10 kV OHL with shorter spans, than for the line with less poles per line's run kilometer.

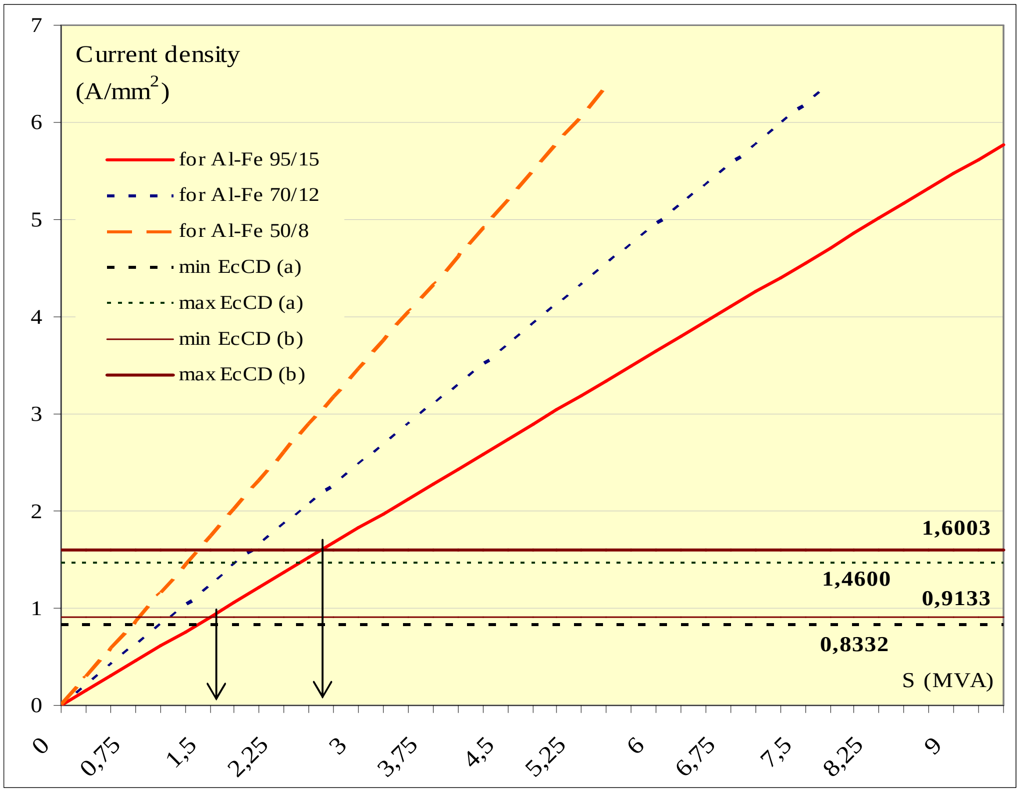


Figure 4 Current density of 10 kV OHL depending on expected load, for s=50, 70 and 95 mm^2 and economic current density range for OHL: a – with longer and b – with shorter spans

Finaly were done the comparation of obtained values of economic current density (EcCD on Fig. 4), with current density values, get from permanently allowed (thermic) currents, I_{td}, for analized, typical cross-sections, according to expression (4). Calculation of I_{td} , S_{td} is detaily explained in Appendix B.

$$\Delta_{td} = \frac{I_{td}}{s} = \frac{S_{td}}{\sqrt{3} \cdot U \cdot s} \qquad (4).$$

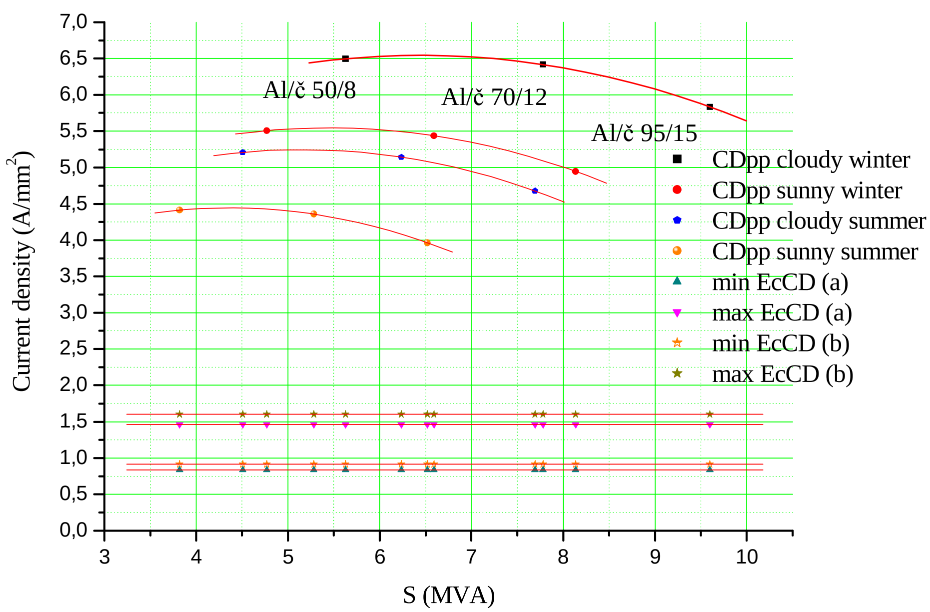


Figure 5 Value comparission of permanently permitted (pp) current densities, Δ_{td} and obtained economic (Ec) current densities, Δ_{Ve}

Such analysis can be made for all characteristic values of – for example – wind velocity, insolation conditions and seasons, but here are presented only the results of a few, characteristic cases. The most frequent wind speed of 0,6 m/s has been adopted, and the environmental conditions in winter and summer were varied, in two sub-cases: sunny and cloudy weather. That way, four extreme cases were obtained, for which – and for all three analysed cross-sections – permanently permitted current densities, Δ_{td}, (CDpp), form a family of four curves, expressed with square functions and presented on Fig. 5. The ranges of economic current densities for cases (a) and (b) - feeders with shorter and longer spans - determined during the research elaborated above, are also shown at Fig. 5 (horizontal lines).
From that Figure it is obvious in which rate overhead 10 kV lines will be overloaded beyond the upper economy limit, if they transmit the loads which values correspond to currents approximate to limits of permanently permitted thermic currents, I_{td}. This analysis, therefore, can be very workable and Fig. 5 useful for making planning decisions concerning building new or reconstructing existing lines, in order to unload them, if their already reached loads are significantly higher than economy ones.

CONCLUSIONS

The analysis of the results for economic current density of overhead lines, depending on maximal power losses equvalent duration time and electrical energy price, on examples of two particular, different feeders (with longer and shorter spans between poles), shows that similar ranges of economic current density values were obtained. Slightly greater values was determined for the line with more poles per kilometer, which is understandable – in that case, investment costs are higher, and also slightly increase with using bigger conductor's cross-section.
From functional relation between conductor's cross-section and optimal line's load (determined according to obtained economic current density), on the samples analized here, the following conclusions can be made:

- the loads in Schedule 2 represents economicaly reasonable loads for analized Al-Fe conductor;
- maximal values of economic load for smaller cross-sections are slightly higher than minimal values for the first next bigger specified cross-section;
- only in areas in which high load are not expectable, even in the future (in isolated, rural zones), it is reasonable to use smaller cross-section (50/8);
- on the contrary, the main branches of 10 kV feeders with Al-Fe conductors, should be built using minimal conductor's cross-section of 70/12 mm^2,
- in the case of area in which the estimated load growth is expected in the next few years, overhead 10 kV feeders with Al-Fe conductors should be built using bigger cross-section than it is neccesary in the present moment, respecting the economic current density value.

For the electrical energy price level, up to date reached in Serbia, and for the value range of maximal power losses equivalent duration time (calculated from annual measurings on eleven supplying cubicles of 10 kV predominantly overhead lines), following conclusion can be made: economic current densities values of overhead lines with Al-Fe conductors increased in the comparission with results obtained during researches in 1970s (its range now is between 1,07 and 1,6 A/mm^2).
Studying the way of change the economic current density depending on maximal power losses equivalent duration time and electrical energy price, next conclusion can be made, too:
In order to reach the values of economic current density of Al-Fe overhead lines, determined by previous researches (from 1 to 1,2 A/mm^2), the following should be done:

1) increase the price of kWh of electrical energy (which is already necessary, in order to reach minimal economic price of 5 €cent/kWh, which allows simple reproduction and operating of Electrical Power Industry of Serbia without commercial losses) and

2) increase the value of maximal power losses duration time, with appropriate changes of Tariff System.

Finaly, it is necessary to extend this research to number of overhead lines as great as it is possible, as well as on underground (cable) lines. That way, the results presented in this paper will be checked, and average values of economic current density for general overhead and undergroud line, respectively, will be obtained. To reach this goal, old equipment lists with prices estimations in EDB's projecting documentation should be inovated, in order to actualize investment costs. On the other hand, also the determination of maximal power losses equivalent duration time should be extended on more overhead and underground lines, in order to obtain average values of this parameter, as precise as it is possible, for both network types.

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APPENDIX A

According to Lit. [1], total annual line’s costs, T_g, including incomming/outcomming cubicles on both it’s ends and Joule losses costs, are:

$$T_g = \left(a_V + b_V \cdot U + c_V \cdot s\right)\cdot L \cdot p_V + 2\cdot\left(a_p + b_p \cdot U + c_p \cdot \frac{S}{U}\right)\cdot p_p + \frac{\rho \cdot L}{s}\cdot\left(\frac{S}{U}\right)^2 \cdot \tau \cdot c_{\Sigma e}, \qquad \text{(A.1)}$$

In relation (A.1) the meanings of characters are the following:

L - feeder’s length, s - conductor cross-section, in mm^2,
S - apparent power, in kVA, U - voltage, in kV,
a_V, b_V i c_V – constants for certain type of line
(a_V – includes also the costs of terrain, i.e. possible line’s run ridance),
c_V - costs per line’s kilometer and cross-section unit, €/mm^2·km,
p_V - total annual rate (of amortisation, profit, maintenance) for feeder (in Serbia it’s real value is ≈ 9%),
p_p - total annual rate (of amortisation, profit, maintenance) for feeder’s cubicle in substation,
a_p, b_p i c_p – constants related on supposed short circuit powers (currents), significant for equipment selection on selected network voltage level,
ρ - specific electrical resistance of conductor’s material (Aluminium for Al-Fe conductors), in Ω·mm^2/m,
τ - maximal power losses equivalent duration time, in hours,
$c_{\Sigma e}$ - total price of electrical energy (electrical power losses) on distribution level, including price for peak-power, in €/kWh.

The first subpart on the right side of equation (A.1) represents investment costs of the line itself, the second one – costs of cubicles in substations (on feeder’s ends), and the third – of Joule losses. With bigger conductor cross-section the permanent costs rise, and variant (power losses) costs diminish. Therefore it is realistic to expect that by certain voltage and cross-section (current density) the value of total annual costs are minimal.

Economic current density of overhead line can be determined by equalizing with zero the partial derivation per cross-section of function (A.1):

$$\frac{\partial T}{\partial s} = c_V \cdot L \cdot p_V - \frac{\rho \cdot L}{s^2}\cdot\left(\frac{S}{U}\right)^2 \cdot \tau \cdot c_{\Sigma e} = 0\,, \qquad \text{(A.2)}$$

Re-arranging relation (2) gives:

$$c_V \cdot p_V \cdot L \cdot s = 3 \cdot \frac{\rho \cdot L}{s} \cdot I^2 \cdot \tau \cdot c_{\Sigma e}\,, \qquad \text{(A.3)}$$

so-called Kelvin's rule, i.e. Kelvin's economy: optimal current of overhead line can be calculated from the case when the costs depending on conductor's cross-section are equal to annual losses costs. Thenceforth, finaly, the economic current density of overhead line is:

$$\Delta_{Ve} = \frac{I}{s} = \frac{S}{\sqrt{3} \cdot U \cdot s} = \sqrt{\frac{c_V \cdot p_V}{3 \cdot \rho \cdot \tau \cdot c_{\Sigma e}}}, \tag{A.4}$$

APPENDIX B

In equation (4): $I_{td} = I_{doz} = K_{op} \cdot K_{\theta} \cdot K_v \cdot K_s \cdot I_{nd}$ (A) (B.1),

is really allowed load current, in supposed conditions, for which correspondent coefficients are:

K_{op} – load coefficient (for changeable, distributing network load: $K_{op} = 1{,}0$),

K_{θ} - thermic coefficient: $K_{\theta} = 1{,}0 + 0{,}009\ (40 - \theta_a)$ (B.2),

(in winter conditions:: $\theta_a = 0\ ^oC$, in summer: $30\ ^oC$)

K_v – for corresponding wind in m/s, chosen from Schedule 3,

K_s – for corresponding weather and insolation, chosen from Schedule 3,

I_{nd} – nominal allowed load current, assigned to particular conductor's type and cross-section, acc. to Schedule 4.

SCHEDULE 3 – COEFFICIENTS OF WIND AND INSOLATION INFLUENCE ON CURRENT CAPACITY OF OVERHEAD LINES WITH Al-Fe CONDUCTORS

v(m/s)		0	0,6	1	2	3	4	5	6
Al - Fe	k_v	1	1,191	1,295	1,459	1,567	1,648	1,713	1,799
	k_{sz}	1,291	1,180	1,146	1,109	1,092	1,083	1,076	1,068
k_{sz}=1 if the line is directly exposed to solar radiation									

SCHEDULE 4 – PERMITTED CURRENT LOADS VALUES FOR OVERHEAD LINES WITH Al-Fe CONDUCTORS

Al-Fe conductor's specified cross-section (*mm²*)	I_{nd} *(A)*	I_{dozz} *(A)*	I_{dozl} *(A)*
50/8	170	323	220
70/12	235	447	305
95/15	290	550	377
$\theta_p = 80^oC$, k_{op}=1			
I_{nd} – specified value of permitted current load for θ_v=40 ^oC, v=0m/s			
I_{dozz} – permitted current load during winter period, for θ_v=0 ^oC, *v=0,6m/s* without direct solar radiation			
I_{dozl} – permitted current load in summer period, for θ_v=30 ^oC, *v=0,6m/s* sa with direct solar radiation			

The permanently allowed apparent power is then: $S_{td} = S_{doz} = \sqrt{3}\, U_n\, I_{doz}$ (B.3).