LOAD ECONOMIC DENSITY OF MV LINES AND ASSET MANAGEMENT PROCEDURE OF THEIR CONDUCTORS OPTIMAL CROSS-SECTION SELECTION

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ABSTRACT

This paper presents the results of researches conducted during recent years in Electricity Distribution Company "Elektrodistribucija Beograd", in order to determine actual values of load (current) economic density of both overhead and underground medium voltage (MV) lines. This parameter is calculated from the equivalence of line's investment and its annual operational costs (i.e., minimization of summary costs). Therefore, it can be used as key parameter for making the most compatible decisions in asset management and optimal planning of MV network. Practical use of the approach based on load economic density is also illustrated in the paper.

INTRODUCTION

Comprehensive researches of load economic density, Δ_{ec}, were done in Serbia twice, during 1950s and 1970s, resulting with quite different conclusions concerning conductors' optimal cross-sections, for both kinds of feeders, overhead and underground. Since 2001 in Serbia, radically changed Tariff System for electricity sale has been introduced, followed by still increasing electricity prices. That made electricity consumption more rational. Consumers' changed behaviour intensively reduced not only the annual peak load values, but also propitiated ratio of maximum and minimum values in daily load charts (so called "chart ironing"). Consequently, the values of peak load equivalent duration time, T_{max}, and maximum power losses equivalent duration time, τ, increased. The latter parameter's growth led to the reduction of load economic density value, Δ_{ec}. All these reasons pointed out the necessity of new researches of Δ_{ec}. They were conducted in Electricity Distribution Company "Elektrodistribucija Beograd" (EDB), since 2005, [1], embracing, until 2009, all sorts and types of MV (35 and 10 kV) lines. The sample of more than 120 MV feeders has been analyzed, using their annual load charts' data, recorded in their supplying MV cubicles in substations (TS) X/MV, by EDB's Remote Control System (RCS).

The goals of these, recent researches, were following:
- To check conclusions achieved in previous research;
- To check and eventually modify empiric relations between T_{max} and τ;
- To find, as much as possible – accurate, average values of these two parameters and Δ_{ec}, for different sorts and types of MV lines, respectively;
- Evaluation of criteria previously used by electrical engineers in everyday practice of network planning and designing, by conductor's optimal cross-section selection;
- To create a practical procedure, based on achieved results, which could make easier the selection of optimal type and conductor's cross-section for MV feeders.

METHODOLOGY ELABORATION

Optimal current (i.e., load) of a line can be determined from the case when the costs dependent on its cross-section are equal with annual losses costs. (It is so called ***Kelvin's rule*** or ***Kelvin's economy***.) Load economic density depends also on several other variables, such as: maximum power losses equivalent duration time, τ(hours) and average electricity price c_e (¢€/kWh), according to:

$$\Delta_{ec} = \frac{I_{opt}}{s} = \frac{S_{opt}}{\sqrt{3} \cdot U \cdot s} = \sqrt{\frac{c_v \cdot p_v}{3 \cdot \rho \cdot \tau \cdot c_e}} \quad , \qquad (1)$$

where are:
s – conductor's cross-section (mm^2), U – voltage (kV),
I_{opt} – optimal current, i.e., optimal load, (A),
S_{opt} – optimal apparent power (kVA),
c_v – investment costs per line's kilometre and conductor's cross-section unit (€/km·mm^2),
p_v – total annual rate (of amortization, profit, maintenance) for a feeder (in Serbia its actual value is cca 9 %),
ρ – specific electrical resistance of conductor's material (Ω·mm^2/m),
τ - max. power losses equivalent duration time (hours),
c_e – total price of electrical energy (electrical power losses) on distribution level, including the price for peak load, (€/kWh).

Ranges determination of parameters of influence

Line's investment costs

Analyses of lines' investment costs have been conducted separately for: underground feeders, overhead lines with Al-Fe conductor and overhead lines with aerial bundle conductor (ABC), at 35 kV and 10 kV level, respectively. For each type of line, calculations of investment costs were done, for all variants of typical, standardized values of conductor's cross-section. For overhead 10 kV lines with Al-Fe conductors, following sub-variants were analyzed: with less or more poles per kilometre, i.e., for lines with longer or shorter spans between poles. (The latter case occurs if low voltage (LV) system should also be installed on the same poles. In these analyses, however, costs of LV conductors and equipment, were not taken into account.) The goal was to determine – for each MV line's type – its specific investment costs, c_v (in € per km and per mm^2 of cross-section). Figure 1 shows the principle of c_v determination, based on linear regression. Actual data are used, for overhead 10 kV lines with Al-Fe conductors, where: C_v – costs of new line, without cubicals in supplying TS at line's ends (€); L – line's length (km).

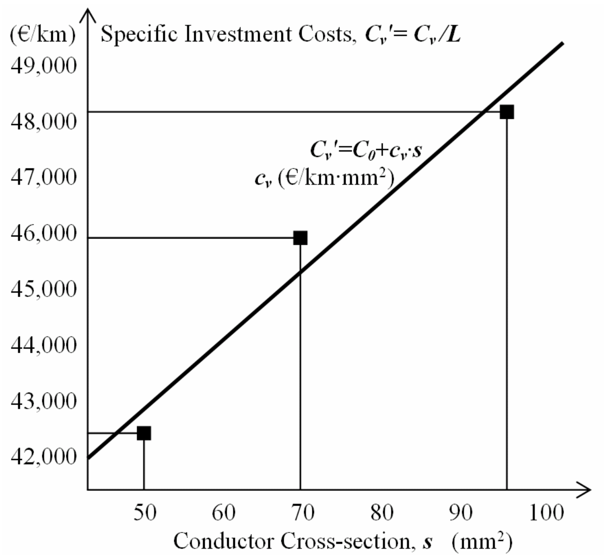


Fig. 1 Investment costs per kilometre of 10 kV overhead lines, for three typical Al-Fe conductors' cross-sections. Example: the line with shorter spans (with more poles).

Maximum power losses equivalent duration time

In order to conduct relevant sensitivity analysis, the range of another parameter of influence, maximum power losses equivalent duration time, τ, has been determined. So called ***integration method*** and real, actual loading data have been used, and τ calculated according to:

$$\tau = \frac{\int_0^T P_{ij}^2(t)\cdot dt}{P_{ij\,\max}^2} = \frac{\int_0^T I_{ij}^2(t)\cdot dt}{I_{ij\,\max}^2} \quad , \qquad (2)$$

where:

$P_{ij}(t)$ – load of MV cubicle i in the moment j;

$P_{ij\,max}$ – maximal annual load of cubicle i;

T=8760 hours for common, and 8784 hours for leap-year.

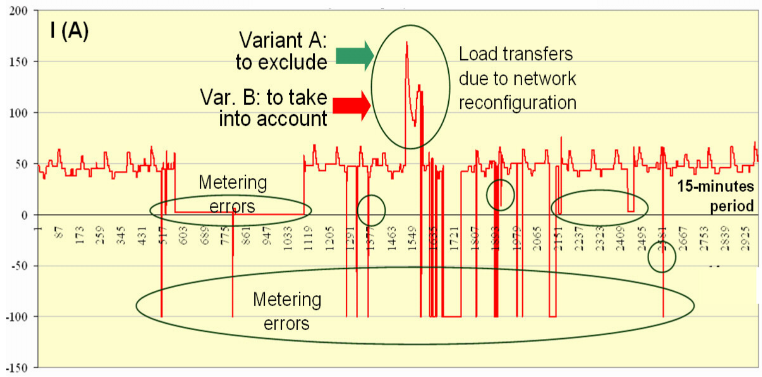
The sample of several dozens of recorded MV feeders' annual loading charts has been analyzed and used to obtain minimum, maximum and average (i.e., reference) value of τ. Researches and determination of τ were done in two basic variants: for all recorded regimes (*a.r.*) and for normal operation (*n.o.*), [2]. Results obtained during first research [1] for overhead lines (OHL) 10 kV with Al-Fe conductors and by further researches are shown in Table I. These results were used later as abscissa values in Fig. 3. Concerning normal operation, it has been restored by extraction (filtration) of load transfers (caused by faults and changes of supplying boundaries along analyzed feeders), from recorded annual loading charts. Other measuring and recording irregularities have been eliminated, too, in both variants. An example is shown in Fig. 2(a). All these data of I_{irr}, in periods of their appearance, have been replaced by average value of I_{av}, calculated from data values recorded during remaining, regular, periods. This principle and the manner of τ' and τ determination are illustrated in Fig. 2(b).

Table I Results of τ determination (sample: 116 MV lines)

Line Type and Voltage level	τ_{min}^{ar} (h)	τ_{max}^{ar} (h)	τ_{av}^{ar} (h)	τ_{min}^{no} (h)	τ_{max}^{no} (h)	τ_{av}^{no} (h)	Consumption Type
cables 10 kV	886.61	3003.37	2070.68	1770.39	4570.16	2862.95	City centre
cables 35 kV	755.98	2460.20	1903.10	1870.28	3491.55	2529.16	Suburban
OHL 10 ABC	772.44	3282.06	2255.17	1691.60	3828.42	3091.24	Suburban
OHL 10 Al-Fe	-	-	-	1929.64	3465.87	2833.02	Rural zone
OHL 35 Al-Fe	364.38	3563.82	1796.59	2094.80	4095.35	2830.16	Rural zone

Average electricity price

Average electricity price, c_e (¢€/kWh), has been calculated as ratio between annual supplier's costs, C_w, for electrical energy taken from transmission network and its amount, W_{an}. Summary costs for both electrical energy and peak load were included in it. Calculations shown that minimal value of c_e was cca 3 ¢€/kWh, in 2004, with trend of slow growth until today, but still being amongst the lowest in wider region. Minimal, economic price of electrical energy in Serbia should be cca 5 ¢€/kWh, allowing simple reproduction and electrical power sector's operation without commercial losses. Therefore, the first research [1] was done with that value as accepted upper limit of c_e. However, the procedure described in this paper relates also to long-term peak load forecasts and network planning. Hence, for further analyses and researches of load economic density, conducted until 2009, accepted maximal value of average electricity price was 15 ¢€/kWh.



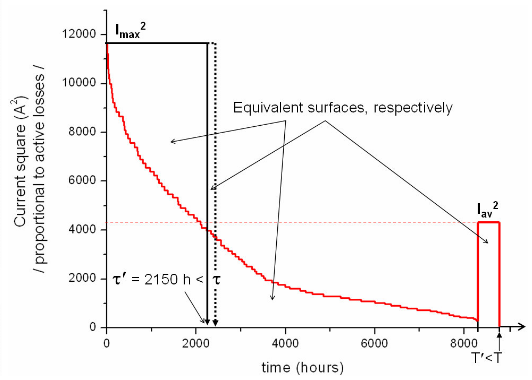


Fig. 2 (a) Example of monthly load chart filtration principle (b) Decreasing annual square load (current) chart

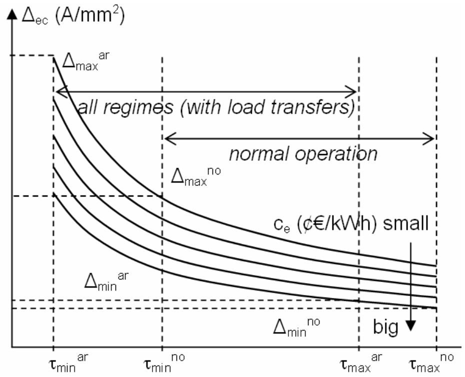


Figure 3 Load economic density Δ_{ec} (A/mm^2) versus maximum power losses equivalent duration time τ(h), by different average values of electricity price, c_e (¢€/kWh).

Sensitivity analysis

After determination of parameters of influence ranges, adequate sensitivity analyses of load economic density results have been done. Consequently, it resulted in load economic density forecast variants, for both types of MV lines. An example of the sensitivity analysis results is presented in Fig. 3. Each sensitivity analysis is done in two variants – for normal operation and for all regimes recorded during year. In the same time, these analyses present determination manner of load economic density range, $\Delta_{min} \div \Delta_{max}$, illustrated also in Fig. 3.

Optimal loads determination

Further researches embraced comparison of previously determined load economic density ranges with expected values of load density, Δ_l, for each kind and type of line, l, with standardized cross-section, s_l, given by:

$$\Delta_l = \frac{I}{s_l} = \frac{S}{\sqrt{3} \cdot U \cdot s_l} = k_l \cdot S \ , \qquad (3)$$

where k_l=*const*., for each typical cross-section, s_l, and $l=1,2,...,n$. For our research, we have chosen several types and standard cross-sections' values, s_l, of overhead conductors and underground cables, used in MV grids' planning and construction in Serbia. As the result, the ranges of optimal loads for typical conductors' cross-sections have been achieved. Determination principle of optimal load range for one particular, typical conductor's cross-section is illustrated in Fig. 4. Horizontal lines in that figure have been obtained as result of described sensitivity analysis, and calculated according to (1). The family of three unparallel straight lines have been determined according to (3). Intersections of mutually correspondent geometrical lines of types (1) and (3), determine ranges of optimal load, S_{opt}, along particular sort and type of power line. This procedure was repeated for all sorts and types of MV power lines, conductors and standard values of their cross-sections. Results achieved by this procedure, Fig. 5, made easier conductor's typical cross-section value's (s_l) selection, depending on particular consumption area, its characteristics and load forecast.

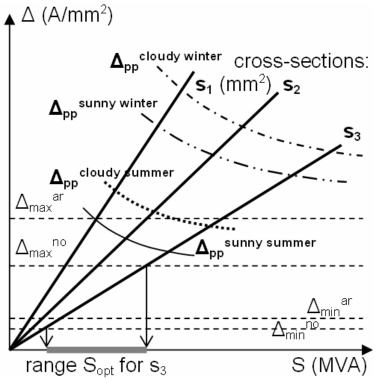


Figure 4 Comparison of load densities: economic (i.e., optimal, $\Delta_{min} \div \Delta_{max}$), permanently permitted (Δ_{pp}^{ws}) and expected ($\Delta_l = f(S) = k_l \cdot S$). Example: ABC overhead lines.

Comparison with permanently permitted loads

The comparison between economic and permanently permitted load densities is also done during researches and illustrated here in Fig. 4. Permitted load densities, Δ_{pp}^{ws}, were calculated for several, different weather and season conditions, as well as for all kinds and types of MV lines:

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

Consequently, permanently permitted current (load), I_{pp}, in (4) has been calculated using different relations. For overhead lines, it is calculated according to:

$$I_{pp} = k_{load} \cdot k_\theta \cdot k_w \cdot k_{sun} \cdot I_{np} \ . \qquad (5)$$

In the case of overhead lines with Al-Fe conductors:

$$k_\theta = 1.0 + 0.009 \cdot (40 - \theta_{air}) \ . \qquad (6)$$

For overhead lines using ABC, there is:

$$k_\theta = 1.0 + 0.008 \cdot (30 - \theta_{air}) \ . \qquad (7)$$

For underground lines, permanently permitted current is given by:

$$I_{pp} = k_{load} \cdot k_{\theta g} \cdot k_{\rho g} \cdot k_{nc} \cdot I_{np} \ , \qquad (8)$$

$$k_{\theta g} = 1.0 + 0.007 \cdot (20 - \theta_{ground}) \ . \qquad (9)$$

In (5)-(9), coefficients are:
k_{load} – loading (k_{load} =1 for changeable, distribution load);
k_θ – related to air temperature, θ_{air};
$k_{\theta g}$ – related to ground temperature, θ_{ground};
k_w – related to wind velocity; k_{sun} – related to insolation;
$k_{\rho g}$ – related to ground's specific thermal resistance;
k_{nc} – depends on number of cables in the trench;
I_{np} – nominal permitted current (for normal conditions).

The points on lines (3) in Fig. 4, which in the same time content (4) and (5) or (8) with subjected relations (6), (7) or (9), define the family of curve lines Δ_{pp}, illustrated in the same figure.

Using procedure and equations presented above, comparison between Δ_{ec} and Δ_{pp} could be done for overhead lines as well as for underground cables, leading to quite different conclusions for those cases, Fig. 5. The main achievement of this kind of comparison is following:

RESULTS

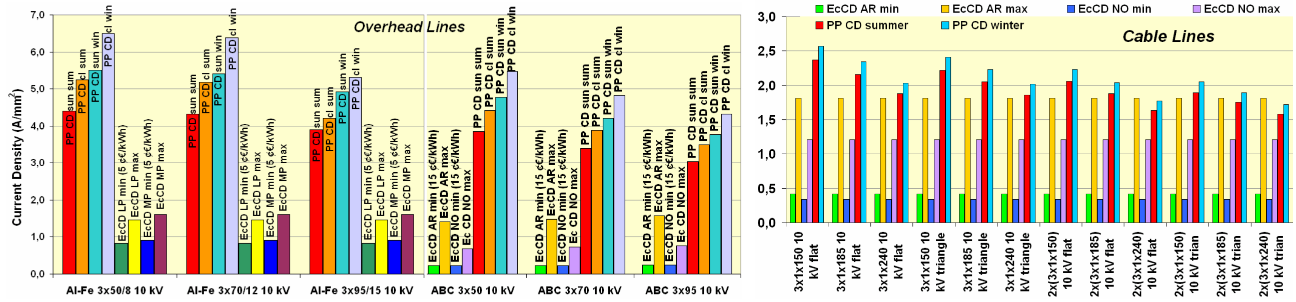


Figure 5 Comparison of economic and permanently permitted load (current) densities for various 10 kV lines' types

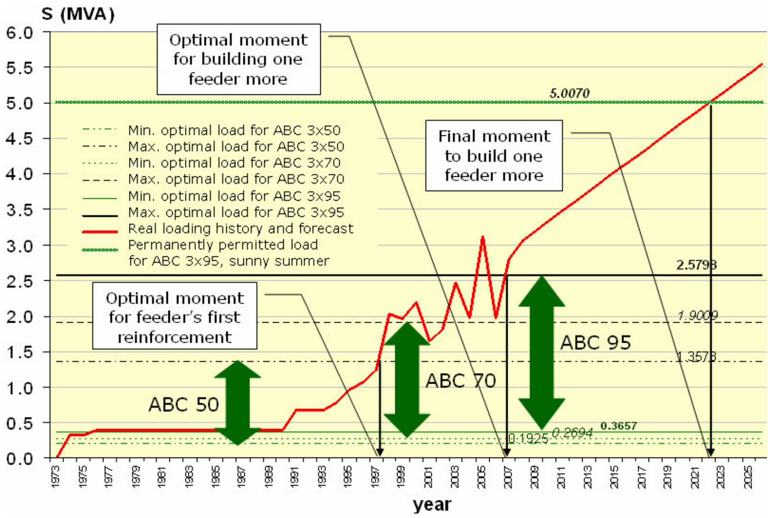


Figure 6 Loading history and forecast of one suburb area in Belgrade, supplied by single feeder 10 kV, made with aerial bundle conductor (ABC). Their comparison with optimal loads (i.e., *min*{$S_{opt}^{\,l}$} and *max*{$S_{opt}^{\,l}$}, based on economic load density ranges) and with permanently permitted load for ABC 95 mm^2 per phase, in the most critical conditions (the highest horizontal line), points out the optimal investment variants and the moments of their implementation.

If it exists (as it is the case in Fig. 4), the zone over Δ_{max}, up to Δ_{pp}, represents the zone of non-economical (non-optimal) loading of MV line type in consideration. If in reality, some MV line operates in such mode, it would be the signal to react, with asset management or network planning measures and activities. The last section of the paper elaborates how described approach, based on load economic density, can also help asset managers and planning engineers in searching for optimal solution.

PROPOSED PROCEDURE PRACTICAL USE

Practical use of previously described approach, based on load economic density, is illustrated here in Fig. 6, by an example of a suburban area of Belgrade, still in developing state. From its loading history and the peak load forecast, compared with economic (i.e., optimal) load range, an asset manager or planning engineer can easily conclude which action is better: reconstruction and reinforcement of existing feeder or building another, new one. Also the proper moment for each investment activity can be clearly seen out, and they are remarked in Fig. 6.

Ranges of optimal load, read out on abscissa of charts like that one in Fig. 4, are the same ranges, presented by three pairs of parallel lines in Fig. 6. By simple comparison of these values and real, recorded or forecasted values of maximum (or peak) load, S_m (MVA), in some particular area, asset manager or planning engineer can conclude which scenario should be the optimal one.

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