

ANALIZA KVADRATNE JEDNAČINE ZA UGIB PROVODNIKA NA OSNOVU ZADANOG NAJVEĆEG UGIBA

ANALYSIS OF THE QUADRATIC EQUATION FOR THE CONDUCTOR SAG BASED ON A GIVEN MAXIMAL SAG

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Sažetak: Prilikom projektovanja nadzemnih vodova često je potrebno izračunati ugib voda u nekoj tački koja se razlikuje od sredine raspona. Za rješavanje tog zadatka koristi se jednačina ugiba pomoću koje se izračunava ugib provodnika u proizvoljnoj tački raspona. Ovaj rad prikazuje sveobuhvatnu analizu kvadratne jednačine za ugib koja se zasniva na zadanom najvećem ugibu parabole u ravnom rasponu. Zasebno su diskutirani ravni i kosi rasponi. Dobiveni rezultati pokazuju važne karakteristike kvadratne jednačine za ugib. Za raspone koji ne prelaze 400 metara uglavnom se koristi proračun prema modelu parabole, dok se za veće raspone preporučuje model lančanice.

Ključne riječi: parabola, lančanica, nadzemni vodovi, ugib, kriva voda, ravni raspon, kosi raspon

Abstract: In overhead line design it is often necessary to calculate the conductor sag at some point, which differs from the mid-span. To solve this task an equation for the conductor sag is used, by which the sag at an arbitrary point of the span can be calculated. This paper presents an entire analysis of the quadratic equation for the sag based on given maximal sag of the parabola in a levelled span. Both levelled and inclined spans are discussed separately. The provided results show important features of a quadratic equation for the sag. Generally, a parabola based calculation is acceptable for spans approximately up to 400 metres, while for longer spans a catenary based calculation is recommended.

Keywords: parabola, catenary, overhead lines, sag, conductor curve, levelled span, inclined span

INTRODUCTION

The conductor sag is a vertical distance between the conductor and the straight line (so called chord) connecting the suspension points of the conductor. The sag-tension calculation provides the maximal sag, which is necessary for the derivation of the sag equation. The latter is also called a sag formula and it is used to calculate the conductor sag at an arbitrary point of the span. Knowing the sag at a chosen point within the span, the conductor height can be calculated at that point. This paper shows an application of mathematics in order to analyze the sag equation, which is very important for overhead line (Figure 1) design [1], [2]. Firstly, the levelled span is discussed and the sag curve is shown for this case, then the sag equation is given in different forms of a quadratic (parabolic) equation. In the continuation the sag equation for inclined spans is separately obtained, i.e. in case of different elevations of the suspension points of the conductor. It is derived with the help of the conductor curve equation in levelled spans, by using some mathematical rules for functions [3]–[5].



Figure 1: Overhead line

The presented method is very practical for developing different algorithms useful for planning and designing electrical overhead lines, especially in finding solutions for rare unconventional tasks.

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Having got the equation for the conductor sag in inclined spans, it can be compared with the equation which concerns levelled spans and that comparison was the main goal of this paper. The conclusion is very clear, and the results are easy to understand for the readers. It helps to shed light on some basic differences between the parabola and catenary, whose curves are used during planning and constructing electrical overhead lines. Despite the fact that their curves are often very similar, the equations of the parabola and catenary are mathematically quite different [6].

1. LEVELLED SPANS

Figure 2 shows the conductor curve in the span with the suspension points on the same elevation. In this case the lowest point of the conductor (the vertex of the parabola) is located in the middle of the span. Data in Figure 2 are the following: the span length (a), height of the suspension points (h) and the maximal sag (f_{lev}).

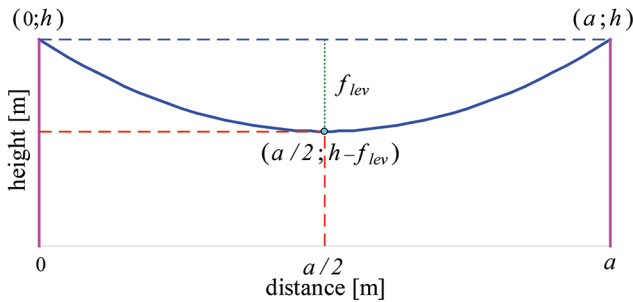


Figure 2: Conductor curve in a levelled span

It is obvious that the sag at the suspension points is equal to zero. In addition it is well seen that the sag has the largest value f_{lev} at the mid-span ($a/2$). According to these facts, the sag curve can be drawn as the Figure 3 shows.

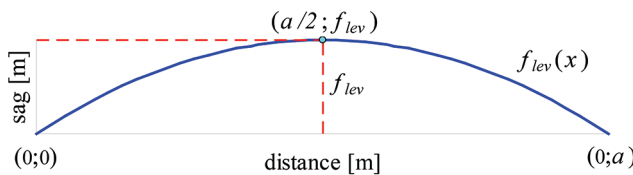


Figure 3: Sag curve for a levelled span

Thus, the conductor sag increases from zero to maximum then decreases to zero, going from the left-hand side support to the right-hand side one. It can be appropriately described by the sag equation $f_{lev}(x)$ as the function of x , where x varies from zero to the span length, $x \in [0, a]$. The conductor sag at an arbitrary point of the levelled span can be calculated by the following sag equation (1), based on a given maximal sag [7]:

$$f_{lev}(x) = \frac{-4f_{lev}}{a^2}(x^2 - ax) \quad x \in [0, a] \quad (1)$$

Coefficient A of the parabola defines its shape, it is given by (2):

$$A = \frac{-4f_{lev}}{a^2} \quad (2)$$

In the case of the sag curve, $A < 0$ (parabola opens downward and has a *global maximum*), while in case of the conductor curve, $A > 0$ (parabola opens upward and has a *global minimum*), but both parabolas open vertically. (Another type of the parabola opens horizontally, to the left or to the right.)

Some literatures [8], mainly Hungarian ones, give another sag equation (3) which can also be obtained from (1), by the use of the basic algebraic transformations.

$$f_{lev}(x) = f_{lev} \left[1 - \left(\frac{a-2x}{a} \right)^2 \right] \quad x \in [0, a] \quad (3)$$

The equation (3) is equivalent to (1). Naturally, as a parabola equation, (1) can also be transformed into the vertex form (4), or standard form (5).

$$f_{lev}(x) = \frac{-4f_{lev}}{a^2} \left(x - \frac{a}{2} \right)^2 + f_{lev} \quad x \in [0, a] \quad (4)$$

$$f_{lev}(x) = \frac{-4f_{lev}}{a^2} x^2 + \frac{4f_{lev}}{a} x \quad x \in [0, a] \quad (5)$$

Similarly any equation among (1), (3), (4) and (5) can be used for the sag calculation: the provided result will be the same.

The basic equation of the parabola in the standard form is given by (6):

$$y(x) = Ax^2 + Bx + C \quad (6)$$

Comparing (5) to the previous equation, it can be seen that coefficient C is zero and coefficient A is negative (since a and f_{lev} are always positive). The latter fact ($A < 0$) is the reason because the vertex ($a/2; f_{lev}$) of the sag curve is the maximum point. The coordinates of this point are easily recognizable in the equation (4).

2. INCLINED SPANS

In order to obtain the sag equation in inclined spans, at first the conductor curve equation will be defined in a levelled span. Knowing the coefficient A of the sag equation and the lowest point of the conductor curve in a levelled span, i.e. point ($a/2; h - f_{lev}$), it is easy to obtain the vertex form of the conductor curve equation in the levelled span [9], by the application (7).

$$y(x) = A(x - x_{MIN})^2 + y_{MIN} \quad (7)$$

The use of A from (4) or from (5), but now with a „+” sign, yields the equation (8). As shown in Figure 4, the conductor curve in a levelled span is the curve between the suspension points $A(0;h)$ and $B(a;h)$.

$$y_{lev}(x) = \frac{4f_{lev}}{a^2} \left(x - \frac{a}{2}\right)^2 + h - f_{lev} \quad x \in [0, a] \quad (8)$$

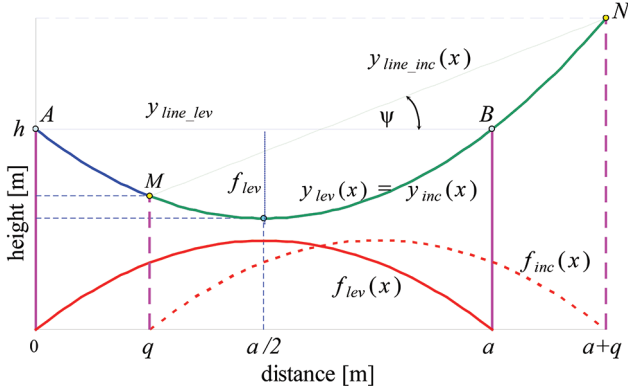


Figure 4: Conductor curves and sag curves in levelled and inclined spans with the same span length and A

The conductor curve on the interval $[q, a+q]$ has the same equation (9), but it concerns now to an inclined span with the suspension points $M(q; y_M)$ and $N(a+q; y_N)$. Only the interval has changed, but neither the span length nor coefficient A has changed.

$$y_{inc}(x) = \frac{4f_{lev}}{a^2} \left(x - \frac{a}{2}\right)^2 + h - f_{lev} \quad x \in [q, a+q] \quad (9)$$

This equation transformed into the standard form of the parabola equation gives (10).

$$y_{inc}(x) = \frac{4f_{lev}}{a^2} x^2 - \frac{4f_{lev}}{a} x + h \quad x \in [q, a+q] \quad (10)$$

Since the straight line connecting the suspension points of the formed inclined span in the interval $[q, a+q]$ is given by (11), the equation for the sag (13) can be classically obtained by (12).

$$y_{line_inc}(x) = \frac{y_N - y_M}{a} (x - q) + y_M \quad x \in [q, a+q] \quad (11)$$

$$f_{inc}(x) = y_{line_inc}(x) - y_{inc}(x) \quad x \in [q, a+q] \quad (12)$$

$$f_{inc}(x) = \frac{y_N - y_M}{a} (x - q) + y_M - \frac{4f_{lev}}{a^2} x^2 + \frac{4f_{lev}}{a} x - h \quad x \in [q, a+q] \quad (13)$$

In the following lines the difference $y_N - y_M$ (16) will be determined depending on q :

$$y_M = y(q) = \frac{4f_{lev}}{a^2} q^2 - \frac{4f_{lev}}{a} q + h \quad (14)$$

$$y_N = y(a+q) = \frac{4f_{lev}}{a^2} (a+q)^2 - \frac{4f_{lev}}{a} (a+q) + h \quad (15)$$

$$y_N - y_M = \frac{8f_{lev}}{a} q \quad (16)$$

Insertion of equations (14) and (16) into (13), yields (20).

The main steps are shown in (17) – (19):

$$f_{inc}(x) = \frac{-4f_{lev}}{a^2} [x^2 - ax + (a/2)^2 - 2qx + aq + q^2] + f_{lev} \quad x \in [q, a+q] \quad (17)$$

$$f_{inc}(x) = \frac{-4f_{lev}}{a^2} \left[\left(x - \frac{a}{2}\right)^2 - 2\left(x - \frac{a}{2}\right)q + q^2 \right] + f_{lev} \quad (18)$$

$$f_{inc}(x) = \frac{-4f_{lev}}{a^2} \left(x - \frac{a}{2} - q\right)^2 + f_{lev} \quad x \in [q, a+q] \quad (19)$$

$$f_{inc}(x) = f_{lev}(x - q) \quad x \in [q, a+q] \quad (20)$$

By replacing the sag curve for the inclined span, from interval $[q, a+q]$ to $[0, a]$, i.e. with the value of q toward y -axis, the replaced curve will be identical to the sag curve for a levelled span. It results the following identity [10]:

$$f_{inc}(x) \equiv f_{lev}(x) \quad \text{if } A_{inc} = A_{lev} \quad \wedge \quad a_{inc} = a_{lev} \quad (21)$$

Practically, the above identity with its conditions concerns the case when both conductor curves in levelled and inclined spans are parts of the same parabola curve, but in different intervals. It is shown in Figure 5 with the sag and conductor curves from two numerical examples, one for the levelled and the other for the inclined span. Both span length a and coefficient A are identical in two examples. The input data are given in Table I.

Table I: Input data for numerical examples

Example 1 levelled span ($h_1 = h_2$)		Example 2 inclined span ($h_1 < h_2$)	
a [m]	200	a [m]	200
h_1 [m]	18	h_1 [m]	10
h_2 [m]	18	h_2 [m]	26
f_{lev} [m]	8	f_{inc} [m]	8

The parabola coefficient and equations from two examples are the following:

1. The levelled span:

Parabola coefficient

$$|A_{lev}| = \frac{4f_{lev}}{a^2} = 8 \cdot 10^{-4} \quad (22)$$

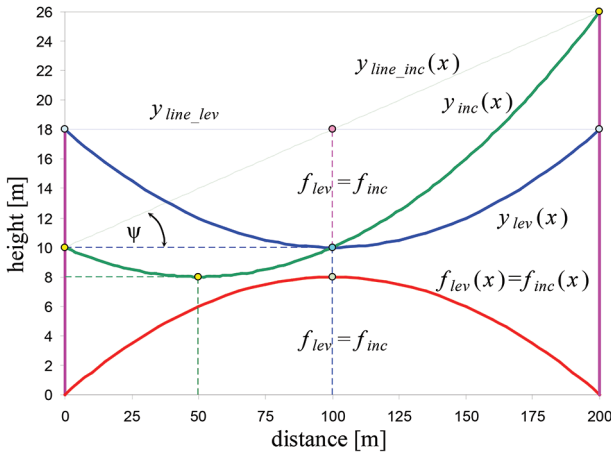


Figure 5: Sag and conductor curves from given numerical examples

Equation for the conductor curve

$$y_{lev}(x) = 8 \cdot 10^{-4} (x - 100)^2 + 10 \quad x \in [0, 200] \quad (23)$$

Equation for the straight line

$$y_{line_lev} = h_1 = h_2 = 18 \text{ m} \quad (24)$$

Equation for the sag curve

$$f_{lev}(x) = -8 \cdot 10^{-4} (x - 100)^2 + 8 \quad x \in [0, 200] \quad (25)$$

2. The inclined span:

Parabola coefficient

$$|A_{inc}| = \frac{4f_{inc}}{a^2} = 8 \cdot 10^{-4} \quad (26)$$

Equation for the conductor curve

$$y_{inc}(x) = 8 \cdot 10^{-4} (x - 50)^2 + 8 \quad x \in [0, 200] \quad (27)$$

Equation for the straight line

$$y_{line_inc}(x) = 8 \cdot 10^{-2} x + 10 \quad x \in [0, 200] \quad (28)$$

Equation for the sag curve

$$f_{inc}(x) = -8 \cdot 10^{-4} (x - 100)^2 + 8 \quad x \in [0, 200] \quad (29)$$

3. THE USE OF $1/\cos\psi$ MULTIPLIER

The parabola is an approximation of the catenary. It is a well known fact that the catenary sag in an inclined span is bigger than the sag in an equivalent levelled span. Thus the catenary equation for the conductor sag in a levelled span is different from the appropriate one which concerns to the inclined span. On the contrary, in the previous chapter the feature of the parabola is shown and mathematically proved that the same equation for the sag can be used in levelled and inclined spans as

well. Considering that the parabola sags are equal (30), if both a and A are identical in two cases.

$$f_{inc}(x) = f_{lev}(x) \quad \forall \quad 0 \leq x \leq a \quad (30)$$

The revealed contradiction between the catenary and parabola sags is partly compensated using $1/\cos\psi$ multiplier [11] to increase the parabola sag in the inclined span in comparison to the sag in the levelled span. The following formula (31) is used:

$$f_{inc\psi}(x) = \frac{1}{\cos\psi} f_{lev}(x) \quad x \in [0, a] \quad (31)$$

After application of $1/\cos\psi$ the maximal sag in the inclined span is denoted as $f_{inc\psi}$. It is obvious that the previous expression concerns not only to the mid-span sag, but to a sag at any point within the span. The ψ is an angle between the chord and horizontal line (see in Figure 5). The calculation of $1/\cos\psi$ can be done in different ways, any of the following formulas (32), (33) can be used.

$$\frac{1}{\cos\psi} = \sqrt{1 + g^2 \psi} = \sqrt{1 + \left(\frac{h_2 - h_1}{a}\right)^2} \quad (32)$$

$$\frac{1}{\cos\psi} = \left\{ \cos \left[\arctg \left(\frac{h_2 - h_1}{a} \right) \right] \right\}^{-1} \quad (33)$$

h_1 – height of the left-hand side suspension point,
 h_2 – height of the right-hand side suspension point.

Using the mentioned multiplier the parabola gets an important feature of the catenary given by the following relation for the parabola sags in levelled and inclined spans:

$$f_{inc\psi}(x) > f_{lev}(x) \quad \forall \quad 0 < x < a \quad (34)$$

It can be seen in Figure 6. Naturally, a larger inclination (i.e. bigger angle ψ) of the span causes bigger increase of the sag.

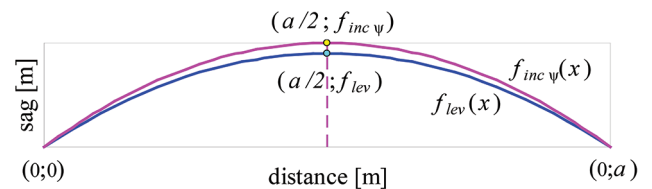


Figure 6: Sag curves in levelled and inclined spans with the application of $1/\cos\psi$ for the latter

By the use of $1/\cos\psi$ the quadratic equation for the sag in inclined spans gets the following form (35):

$$f_{inc\psi}(x) = \frac{-4f_{inc\psi}}{a^2} \left(x - \frac{a}{2} \right)^2 + f_{inc\psi} \quad x \in [0, a] \quad (35)$$

In comparison to the catenary equation for sag the previous equation gives better results than (19). This is very important for the clearance calculation between the live overhead conductors and the ground or objects.

Using input data for the sag equation (29) in an inclined span from the previous chapter ($h_1=10\text{m}$; $h_2=26\text{m}$; $a=200\text{m}$; $f_{\text{inc}}=8\text{m}$), but now with the application of (31), i.e. $f_{\text{inc}\psi}=8,0256\text{m}$ ($\psi=4,5739^\circ$), the sag equation in an inclined span (29) becomes (36):

$$f_{\text{inc}\psi}(x) = -80256 \cdot 10^{-8} (x-100)^2 + 8,0256 \quad (36)$$

The changes are present both in coefficient A and the vertex. To summarize, the comparison of the sag equation in inclined spans (36) with the appropriate equation (29), which does not contain $1/\cos\psi$, or with (25) since it is identical to (29), results the following conclusions:

- the parabola coefficient A has decreased,
- the x -coordinate of the vertex point has not changed,
- the y -coordinate of the vertex point has increased.

The consequence of $1/\cos\psi$ application in quadratic equation for the sag is the following: in comparison to a levelled span, the maximal sag in an inclined span has slightly increased, but its location is still at the mid-span ($x_{f_{\text{inc}\psi}} = x_{f_{\text{inc}}} = x_{f_{\text{lev}}} = a/2$). So, $1/\cos\psi$ cannot provide the movement of the maximal sag from the mid-span. On the one hand the maximal sag of the catenary in inclined spans is slightly moved from the mid-span toward the higher suspension point [12]. On the other hand the maximal sag of the parabola is always located at the mid-span both in levelled and inclined spans. It can be so complemented now that this feature of the parabola is even independent of the application of $1/\cos\psi$.

Taking into the consideration the above presented, the following equation (37) in the vertex form is usable for sag calculation at any point within the inclined span by the given maximal sag in a levelled span (f_{lev}).

$$f_{\text{inc}\psi}(x) = \frac{-4f_{\text{lev}}}{a^2 \cos\psi} \left(x - \frac{a}{2}\right)^2 + \frac{f_{\text{lev}}}{\cos\psi} \quad x \in [0, a] \quad (37)$$

The previous equation is derived from the case of $y_M < y_N$ (see in Figure 4). It is very important to emphasise that the use of another case of the inclined span ($y_M > y_N$) produces just the identical equation, since the cosine is an even function (38):

$$\cos(-\psi) = \cos(\psi) \quad (38)$$

Furthermore, the sag equation (37) is universal, since it can also be used for a sag calculation at any point within a levelled span. In that case $\psi=0$ and then the equation (37) becomes (4), since $\cos(0)=1$.

In the case of the mid-span ($x=a/2$), the equation (37) changes into a much simpler form (39) presenting the

relationship between the maximal sags of the parabola in inclined and levelled spans:

$$f_{\text{inc}\psi} = \frac{f_{\text{lev}}}{\cos\psi} \quad (39)$$

It has to be mentioned that the previous relationship is mathematically incorrect for a catenary, its use is recommended only in the parabola based calculation.

Finally, putting (39) into (40) [10] instead of f_{inc} , the modified equation for the conductor curve in inclined spans can be written both in the standard (41) and vertex form (42), based on a given maximal sag in a levelled span (f_{lev}).

$$y_{\text{inc}}(x) = \frac{4f_{\text{inc}}}{a^2} x^2 + \frac{h_2 - h_1 - 4f_{\text{inc}}}{a} x + h_1 \quad x \in [0, a] \quad (40)$$

$$y_{\text{inc}\psi}(x) = \frac{4f_{\text{lev}}}{a^2 \cos\psi} x^2 + \frac{1}{a} \left(h_2 - h_1 - \frac{4f_{\text{lev}}}{\cos\psi} \right) x + h_1 \quad x \in [0, a] \quad (41)$$

$$y_{\text{inc}\psi}(x) = \frac{4f_{\text{lev}}}{a^2 \cos\psi} \left[x - \frac{a}{2} \left(1 - \frac{h_2 - h_1}{4f_{\text{lev}}} \cos\psi \right) \right]^2 + h_1 - \frac{f_{\text{lev}}}{\cos\psi} \left(1 - \frac{h_2 - h_1}{4f_{\text{lev}}} \cos\psi \right)^2 \quad x \in [0, a] \quad (42)$$

Two previous equations for the conductor curve are valid for both cases of inclined spans, $h_1 < h_2$ and $h_1 > h_2$. In a levelled span ($\psi=0$ and $h_1=h_2=h$) the equations (41) and (42) become (10) and (8) retrospectively, in the interval $[0, a]$. The advantage of the conductor curve equation (42) in comparison to (41) is that it directly provides the coordinates of the lowest point $MIN_{\psi}(x_{\text{MIN}\psi}; y_{\text{MIN}\psi})$ of the parabola conductor curve, which contains $1/\cos\psi$ multiplier. These coordinates are given by (43) and (44).

$$x_{\text{MIN}\psi} = \frac{a}{2} \left(1 - \frac{h_2 - h_1}{4f_{\text{lev}}} \cos\psi \right) \quad (43)$$

$$y_{\text{MIN}\psi} = h_1 - \frac{f_{\text{lev}}}{\cos\psi} \left(1 - \frac{h_2 - h_1}{4f_{\text{lev}}} \cos\psi \right)^2 \quad (44)$$

The vertex points, i.e. the lowest points of the conductor curves $y_{\text{inc}}(x)$ and $y_{\text{inc}\psi}(x)$ are shown in Figure 7. The catenary curve $y_{\text{inc cat}}(x)$ has been drawn too.

Using input data for the conductor curve equation (27) in an inclined span from the previous chapter (example 2), but now with the application of $1/\cos\psi$ multiplier, the conductor curve equation (27) becomes (45):

$$y_{\text{inc}\psi}(x) = 80256 \cdot 10^{-8} (x - 50,1592)^2 + 7,9808 \quad (45)$$

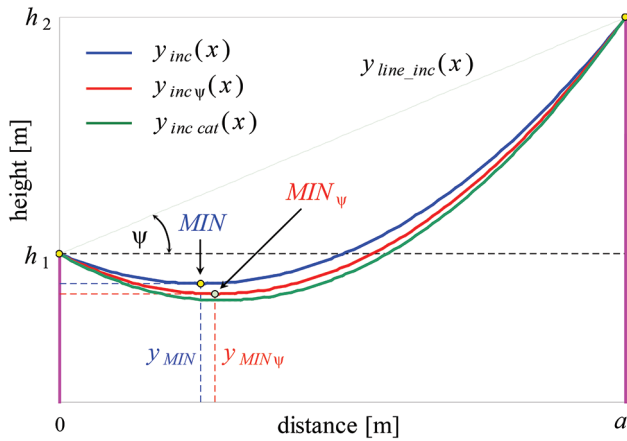


Figure 7: Conductor curves in the inclined span, i.e. the catenary and its parabolic approximation with and without the application of $1/\cos\psi$

Again the changes are noticeable both in coefficient A and the vertex, but here in a different way in comparison to the appropriate research of the sag equation. In this case the concrete conclusions are the following:

- the parabola coefficient A has increased,
- the x -coordinate of the vertex point has increased in the case of $h_1 < h_2$, and vice versa (it has decreased in the case of $h_1 > h_2$),
- the y -coordinate of the vertex point has decreased.

Finally, taking into the consideration all conclusions provided in this chapter in connection with the equations for the sag and for the conductor curve, the following general relations can be written concerning to the application of $1/\cos\psi$ multiplier versus ignoring it, in inclined spans:

$$|A_{inc\psi}| > |A_{inc}| \quad (46)$$

$$f_{inc\psi} > f_{inc} \quad (47)$$

$$x_{f_{inc\psi}} = x_{f_{inc}} = a/2 \quad (48)$$

$$x_{MIN\psi} > x_{MIN} \quad \text{if} \quad h_1 < h_2 \quad (49)$$

$$x_{MIN\psi} < x_{MIN} \quad \text{if} \quad h_1 > h_2 \quad (50)$$

$$y_{MIN\psi} < y_{MIN} \quad (51)$$

4. CONCLUSION

This paper has analysed in details the quadratic equation for the conductor sag. It is also shown the universal sag equation applicable for the sag calculation at any point of the span both in case of levelled and inclined spans. This equation is based on a given maximal sag of the parabola in a levelled span, which can be obtained by using the well known sag-tension calculation [11], [13] or taken from the available sag-tension tables.

Since the parabola definition is based on its parameter p , but does not contain the maximal sag, knowing the mathematical relationship (52) between the parameter p and the coefficient A , then by developing (53), the quadratic equation for the sag can also be written depending on p . The standard form of this equation is (54), while the vertex form is (55):

$$p = \frac{1}{2|A|} \Rightarrow |A| = \frac{1}{2p} \quad (52)$$

$$\frac{4f_{inc\psi}}{a^2} = \frac{1}{2p} \Rightarrow f_{inc\psi} = \frac{a^2}{8p} \quad (53)$$

$$f_{inc\psi}(x) = -\frac{1}{2p}x^2 + \frac{a}{2p}x \quad x \in [0, a] \quad (54)$$

$$f_{inc\psi}(x) = -\frac{1}{2p}\left(x - \frac{a}{2}\right)^2 + \frac{a^2}{8p} \quad x \in [0, a] \quad (55)$$

Beside these two forms of the equation for the sag, four other forms have been presented too. Each of these can have a specific use depending on a concrete task to be solved. For plotting the sag curve or for the sag calculation at an arbitrary point of the span, any of the shown equations is applicable as well. But if it is necessary to replace the curve within the x - y coordinate system, for example in order to develop a new algorithm in connection with planning and designing overhead lines, the vertex form of the equation is more preferable than the others.

The following very important feature of the parabola is identified: the quadratic sag function of its curve replaced from interval $[0, a]$ to $[-a/2, a/2]$ is an *even* function both in case of levelled and inclined spans.

The previous feature of the parabola characterizes the catenary too, but only in levelled spans, not in inclined spans. This especial difference between the parabola and the catenary will be separately discussed and proved in the next paper as the continuation of the actual one.

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BIOGRAPHY

Alen Hatibović was born in 1966 in Tuzla (Bosnia-Herzegovina). He graduated from the University of Tuzla, Faculty of Electrical Engineering, in 1992. He has been working for *Électricité de France* in Hungary, for a company called *EDF DÉMÁSZ* since 1998. As an electrical design engineer he has been planning and designing electrical network. Now he is doing big projects for development of MV network using *PRAO* software from *EDF*. He is mostly interested in applying mathematics in planning overhead power lines in order to achieve high precision in calculations and usefulness in practice; he also helps the education of electrical design engineers. He is the author of 20 scientific and professional papers (mainly on overhead line design) and presently is a PhD student at the University of Budapest.