# SENSITIVITY ANALYSIS OF INDUCED OVERVOLTAGE BY LIGTHNING STROKE NEAR DISTRIBUTION SYSTEM USING ATP-EMTP.

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Abstract. **In the present article the results of a study of sensitivity are analyzed focused to the induced overvoltage that take place by effect of atmospheric discharge in the proximity of a single-phase line. Such a study considers the physical parameters of the line (employees of the frequency) and the equations that represent those mentioned discharges. The main objective of this analysis is to observe the influence of the variables considered on the maximum magnitude of the overvoltage and its location along the line (COD). The analysis is made with the implementation of the Chowdhuri-Gross model in the ATP[1] and the use of a computer tool created to facilitate the handling of the necessary files to make such simulations[2]. The random variables that are considered in the analysis are: The amplitude of the return stroke current ($I_0$), The perpendicular distance between the discharge and the line ($Y_0$), the front time of the return stroke current ($T_f$), the relationship between the speed of the return stroke and the speed of the light ($\beta$) and the height of the conductor (h). Within the analysis considers the zone of attraction of the conductor (S), determining factor in the fixation of extreme values for the ranks of variation in some of the variables. As important results they stand out: the value of $Y_0$ is important in the location of the COD since it affect in the times of retard in the electromagnetic induction that happens in each point of the conductor; the value of $I_0$ has a lineal influence on the maximum magnitude of overvoltage; and the COD display a notorious insensibility respect to $I_0$**

**Keywords:** Transients, induced overvoltage, lightning, EMTP.

## I. INTRODUCTION.

One of the main studies of the induced overvoltage due to indirect discharge has been Pritinda Chowdhuri who has established a model [3] that represents the transitory phenomenon that happens in the phases of the distribution line when the lightning stroke take a place. This model has suffered different modifications from collaborators in the entire world and by the author, obtaining the deduction of a multiconductors line model considering this kind of induction[4].

For the implementation of the model mentioned (Norton equivalent) in the ATP, the equations that describe the model were developed and certain boundary conditions were stablished in this model [1]. In figure 1, the used scheme to represent the model of Chowdhuri can be appreciated and next are the used equations to represent the same one in ATP.

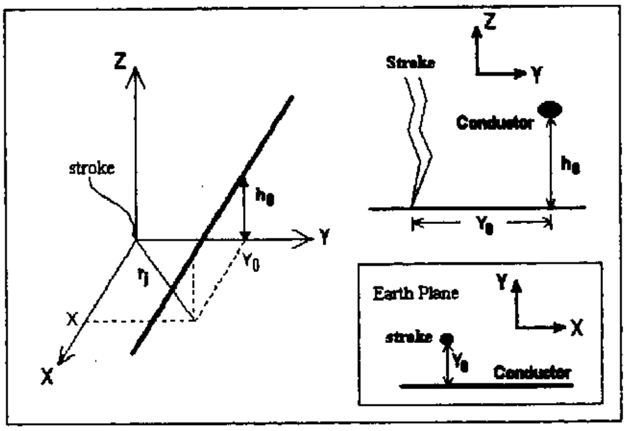


**Fig.1: Coordinates system of the line conductor and the lightning stroke.**

Equations for the equivalent current sources [1]:

$$i^{Norton}_{Chowdhuri}(t) = C \cdot \frac{d}{dt} v^{Thevenin}_{Chowdhuri}(t) \quad (1)$$

$$\frac{d}{dt}V_{ij} = \frac{d}{dt}V_{ij1} \cdot u(t-t_0) - \frac{d}{dt}V_{ij2} \cdot u(t-t_0-t_f) \quad (2)$$

$$\frac{d}{dt}V_{ij} = -\frac{60 \cdot \alpha_1 h_j}{\beta} \cdot \left(\frac{1-\beta^2}{\beta \cdot c}\right) \cdot \left(\frac{\sqrt{(t-t_0)^2 + a^2} + (t-t_0)}{(t-t_0) \cdot \sqrt{(t-t_0)^2 + a^2} + (t-t_0)^2 + a^2}\right) + \frac{60 \cdot \alpha 1 \cdot h_j}{\beta} \cdot \left(\frac{1}{\sqrt{h_c^2 + r_j^2}}\right) \quad (3)$$

$$\frac{d}{dt}V_{ij2} = -\frac{60\alpha_2 h_j}{\beta} \cdot \left(\frac{1-\beta^2}{\beta \cdot c}\right) \cdot \left(\frac{\sqrt{(t-t_0-t_f)^2 + a^2} + (t-t_0-t_f)}{(t-to-tf) \cdot \sqrt{(t-t_0-t_f)^2 + a^2} + (t-t_0-t_f)^2 + a^2}\right) + \frac{60\alpha_2 \cdot h_j}{\beta} \cdot \left(\frac{1}{\sqrt{h_c^2 + r_j^2}}\right) \quad (4)$$

Where (3) and (4) they only depend of physical variables.

Also were necessary made a series of adjustments that adapted the model to a format that was understood by the simulation program ATP.

The use of the LINE CONSTANTS and JMARTI SETUP subroutines for the calculation of the physical parameters of the line, some TACS tools, and other characteristic elements of the ATP-EMTP are necessary for the creation of the files to make such simulations.

The files to make the simulation has a distribution of nodes throughout 7 km over the line to both sides of the discharge, that is to say, 14 km altogether, among which the physical parameters calculated (distributed or frequency dependent ones) are placed, and for each one are placed the corresponding Chowdhuri's current source [1]. The distribution of nodes mentioned and therefore the distribution of equivalent sources, are the shown on the figure 2. Altogether, considering both sides of the discharge, 167 nodes are obtained. It is important to indicate that this distribution of sources was not the initial and had to modify itself until obtaining more precise results.

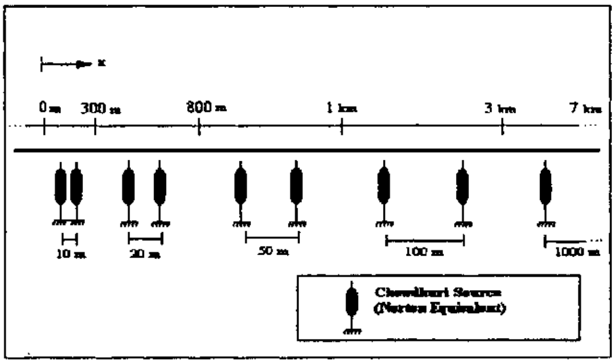


**Fig.2: Distribution of Chowdhuri sources for representation of the phenomenon of induced overvoltage.**

The mentioned thing in the previous paragraph is translated in the tedious processing to prepare the entrance file for the simulation of the induced overvoltage in the ATP, implying a great investment of hours to make only a few cases. It becomes necessary the use of a computer tool (CHDATP) [2] to make faster this process and flexible the user's interaction with the ATP to do the required simulations, covering the ranges of variation of the variables considered in quick and precise form, main factors for this analysis.

The cases that are considered in this study are the following ones: variation of the return stroke current ($I_0$), variation of the perpendicular distance between the discharge and the line ($Y_0$), variation of the front time of the return stroke current ($T_f$), variation of the relationship between the speed of the return stroke and the speed of the light ($\beta$) and variation of the conductor height (h), all this for an single line.

## II. METHODOLOGY.

The analysis method is based in the use and advantage of the program CHDATP [2] created specifically to make this study. The same one facilitates the work in two senses; by a side it creates the necessary files for the calculation of the physical parameters of the line (distributed or dependent of the frequency) and by the other prepares the file necessary to make the simulation of the overvoltage induced like so. That is to say, after known the location characteristics of the line and the nominal data of manufacture of the conductor ($R_{ac}$ or $R_{dc}$, GMR, height of the line, etc) and the atmospheric discharge data such as the return stroke current ($I_0$), approximated height of the cloud ($h_c$), perpendicular distance between the lightning stroke and the conductor ($Y_0$), the front time and the tail time of the return stroke ($T_f$ and $T_h$), and the relation between the speed of the light and the speed of the return stroke ($\beta$), the CHDATP make the calculations, the reading and location of the parameters of the line (that have to calculate previously to prepare the overvoltage file), the definition of each Chowdhuri's current source and finally this program call the ATP and make the overvoltage calculation. The user only have to defines the values of each variable required by the program and indicate in which nodes he want to register the behavior of the overvoltage wave.

Once defined the ranks of variation of the variables and the increase steps around these ranks, Some cases by each variable were executed and later with the aid of graphical processor TPPLOT [7], all the overvoltage wave were registered for each case and each defined node to found the maximum peak around all the line and the place where it was appear . Finally every case have associated a maximum overvoltage value in kV and a distance where it were appear (COD) in meters .

With these data it is possible to build graphics of the behavior of the magnitude of the maximum overvoltage and their location along the line in function of the variable that is analyzed.

In such sense and considering that the atmospheric discharge are a transient phenomenon of high frequency, one of the used criteria is the consideration of the dependency in frequency of R, L, and C for the equivalent circuit of the line. It is to considerate the attenuation and deformation [1] of the overvoltage wave by high frequency effect over the conductor, of course; within the limitations established by the model and ATP program. For that reason, the frequency model were tuned in 10 kHz, in a range from 0.01 Hz to 1 MHz(9 decades). At the same time we used the Carson correction to consider the earth effect over the R, L, C line parameters.

The conductor attraction zone (S) is defined as the cover radius that appears around the conductors before an atmospheric discharge of certain magnitude of current (ec 5).

$$S = 10 \cdot I^{0.65} \qquad (5)$$

(S in meters and the magnitude of the current of the discharge I in kA).

The previous expression determines the limit among direct and indirect atmospheric discharges as it can be appreciated in the figure 3. Their use is very important to limit the ranges of study of the maximum magnitude of the current (this magnitude defines a limit of approach of the ray toward the line) and of the perpendicular distance between the discharge and the line (equally this approach between the line and the discharge allows a maximum of current so that the same one is not attracted toward the conductor).

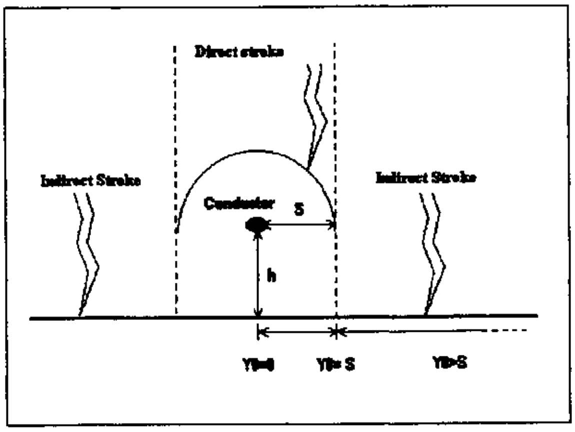


**Fig.3: Area of attraction of the conductor before atmospheric discharges.**

### II.1. CONSIDERED VARIABLES.

The Chowdhuri -Gross model consists approximately of 11 variables. Additionally the conductor's characteristics contribute with 4 and 5 more variables for 15 or 16 possible candidates to be manipulated. In the present article we make a variations over four (4) of these variables. Next the selected variables are described briefly:

*a) $I_0$ ( Amplitude of the return stroke current):* The selected rank was from 10 to 150 kA. It is important to emphasize that the probability of an atmospheric discharge exceeds 10 kA is of a 96% approximately, and to exceed 150 kA is 0,5% [5]. It indicate that the most realistic situation will be for values of current around 10 kA.

b) *$Y_0$ (Perpendicular distances from the discharge to the line)*: The minimum value of the rank to consider is established by S (the conductor attraction zone). The superior limit for this variable was defined in a maximum of 1500 m; distances for which still the waves of induced overvoltage could present magnitudes that could make damage on the insulation of the equipment in distribution systems.

c) $T_f$ (Time front of the wave): The typical rank for the fronts waves in the atmospheric discharge was considered statistical value that go from 0,5 to 10,5 μs.

d) h (Height of the conductor over the earth): they took possible values for distribution posts from the 4 until the 25 m.

### II.2. CONDITION INITIALS.

The initial data for the conductor and for the discharge, those shown respectively in the tables I and II.

**Table I: Initial Data of the Conductor.**

| LINES (conductor type AAAC, #2) | | | |
|---|---|---|---|
| Height (h)<br>M | Resistance (R)<br>Ohm/km | Diameter<br>cm | GMR<br>cm |
| 10 | 0.768 | 1.015 | 0.5255 |

**Table II: Characteristic of the Discharge Atmospheric initial.**

| DISCHARGES ATMOSPHERIC | | | | | | |
|---|---|---|---|---|---|---|
| $I_0$<br>kA | β | $Y_0$<br>m | $T_F$<br>s | $T_H$<br>s | f<br>Hz | $h_C$<br>km |
| 10 | 0.3 | 10 | 2 | 75 | 60 | 3 |

### III. STUDIES CASES: RESULTS AND ANALYSIS.

The measurement nodes for the record overvoltage were located (in the simulation file for ATP) each 100 m between 500 and 2500 m, and in 0, 3, 4 and 5 km, with a total of 25 mensuration points.

*a) Variation of $Y_0$.*

In this case the variable who defined the $Y_O$ variation rank was $I_O$. Three different $I_0$ values were used; 50 kA, 100 kA and 150 kA. For these values of current the S associated value were 127 m, 200 m and 260. Therefore they were chosen like minimum $Y_0$ to 140 m, 200 m and 300 m respectively, executing a total of 75 different cases to cover the corresponding ranks. The other parameters were considered in initial conditions.

**Table III: Range of Variation for $Y_O$**

| Distance<br>m | $I_O$<br>kA |
|---|---|
| 140-1500 | 50 |
| 200-1500 | 100 |
| 300-1500 | 150 |

**Table IV: Increase Step for $Y_O$**

| $\Delta Y_O$<br>m | Distance<br>m |
|---|---|
| 20 | 140-200 |
| 50 | 250-800 |
| 100 | 900-1500 |

As it is possible observed in the graph shown in figure 4, the three curves show a greatest dependency the overvoltage magnitude with respect to $Y_O$, in zones near minimum $Y_0$ for each case. The maximum magnitudes happen while more near the line falls the discharges and they are attenuated as $Y_0$ increases, thus for greatest distances above 1000 m the magnitude of the maximum overvoltage does not surpass 180 kV.

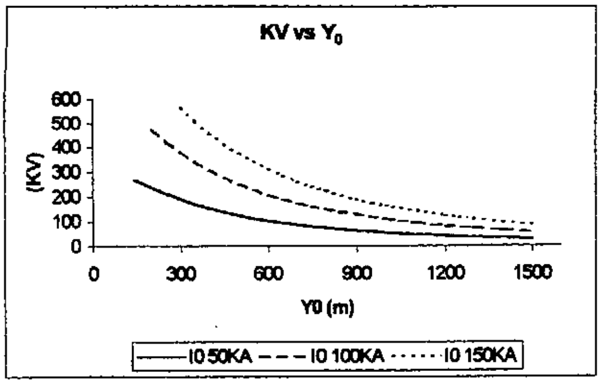


**Fig. 4: Maximum overvoltage vs. $Y_0$ for $I_0$ : 50, 100 and 150 kA.**

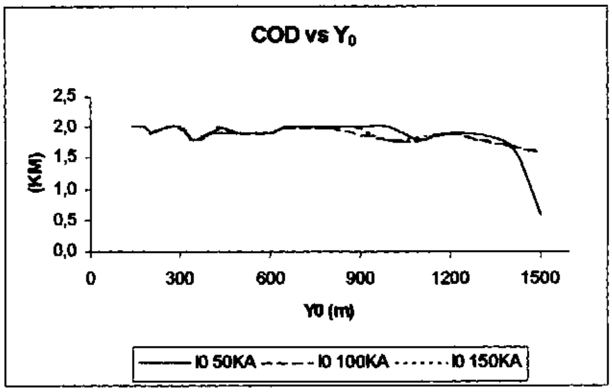


**Fig.5: Location of the COD vs. $Y_0$ for $I_0$ of 50, 100 and 150 kA.**

The behavior of the maximum overvoltage obey basically the relation between the trip time of the charge of the ray to each point on the conductor and the times that take each one of the travelling waves in moving by the same one, which will determine the location of the COD. This relation involves the speed of the wave in the conductor, the speed of the wave in the earth plane and the behavior of the magnitude of each wave (attenuation).

Then, as $Y_0$ is increased from their minimum value, the COD tends to move away from X = 0 m to finding a point stable where the superposition of the waves will be greater. After this point the COD stays more or less constant because the superposition of the waves and the magnitudes of the same ones therefore determine it, until overvoltage wave begins towards smaller values. Such reduction must that the induction in the points (on the conductor) more distant to the lightning stroke is diminished and the travelling waves associated are become despicable, reason why the point of convergence of these tends to run itself towards the zones nearest the discharge, that is to say, tends to run itself towards X= 0 m.

It is important to emphasize that when considering the zone of attraction of the conductor (S), the behavior of the COD is limited a rank of stabilization and a later reduction for increases of $Y_0$ as it is possible to be observed in fig.5

*b) Variation of $I_0$.*

For this case $Y_0$ it is who make the limits in the rank of variation of $I_0$, not to fall in smaller distances that could be into the zone of attraction (S), considering the values of 100 m, 1000 m and 1500 m like interesting values of $Y_0$. For the first case, when fixing $Y_0$ = 100 m obtains 35 kA for $I_0$ max, like at limit value to guarantee an indirect stroke near the conductor. For the other two cases we obtained 1194 and 2228 kA for $Y_0$ of 1000 and 1500 m respectively, being this value biggest than 150 kA, which is the maximum value in the study rank. A total of 50 different cases was executed.

**Table V: Variation range of $I_0$**

| $Y_0$ m. | $I_0$ kA. |
|---|---|
| 100 | 10-33 |
| 1000 | 10-150 |
| 1500 | 10-150 |

**Table VI: Increase step of $I_0$**

| $Y_0$ m. | $\Delta I_0$ kA. |
|---|---|
| 100 | 3 |
| 1000 | 10 |
| 1500 | 10 |

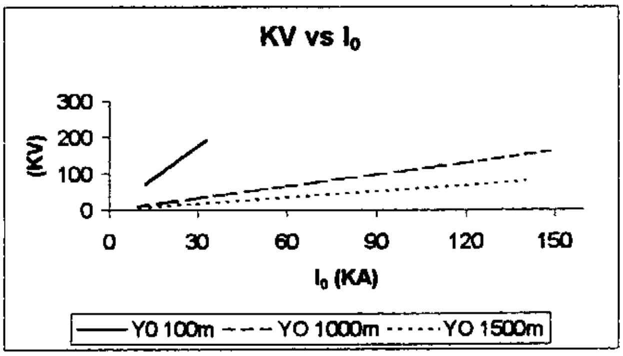


**Fig.6: Maximum overvoltage vs. $I_0$ for $Y_0$: 100, 1000 and 1500 m.**

We can see in figures 6 and 7 exist a linear dependency of the maximum overvoltage with respect to $I_0$ and the COD didn't show any change with respect to increases of $I_0$. we can also observed the influence of S in the reduction of the rank of study for $Y_0$ = 100 m. On the other hand $Y_0$ has a considerable weight in the COD location. How we can see in figure 7, when $Y_0$ move away from the line, the COD tends to go to the point X = 0 m.

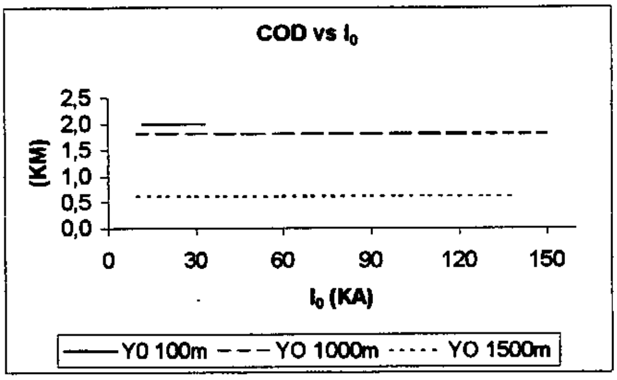


**Fig.7: Location of the COD vs. $I_0$ for $Y_0$ of 100, 1000 and 1500.**

This linear dependency reflected in the behavior of the maximum overvoltage for each one of $Y_0$ selected (fig.6), it is due to the model only represent the increase of the lightning stroke current and their effect in each point on the line will stay proportional to this current when other parameters keep their values constants. By such reason it is to hope that the COD stays constant for variations of $I_0$ because the trip times of the return stroke waves and the trip time of the travelling waves don't change.

*c) Variation of $T_f$*

For this variable three cases were considered in those a current value inside a probable range was assigned, after that a $Y_0$ take a close value of S associated to this currents. The $I_0$ chosen were 10 kA, 30 kA and 80 kA and 50 m, 100 m and 200 m for the $Y_0$ respective. Variation range: 0.5–10.5 µs, TF: steps of 0.5 µs in the whole range.

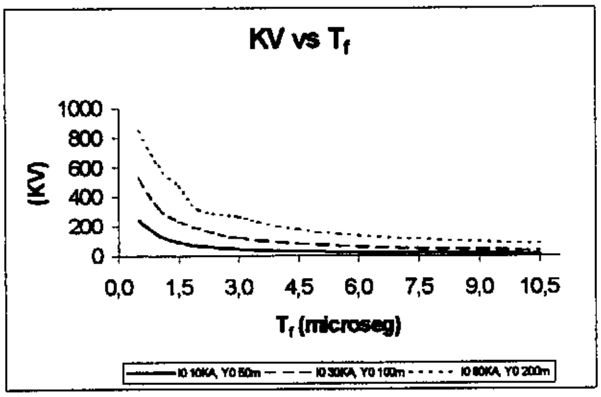


**Fig.8:Maximum Overvoltage vs. $T_f$ for $I_0$-$Y_0$ combinations.**

The maximum overvoltage appear in the range from 0.5 to 2 µs (fig. 8). The difference between this three overvoltage curves is due to the difference $I_0$ and $Y_0$ considered values, where the curve of more current (80 kA) it registers the highest overvoltage values.

About the behavior of the COD, it is possible to be observed in the figure 9, that in the three selected cases exists a zone of growth until arriving at the stabilization. This happens more quickly if these two values ($I_0$, $Y_0$) are smaller; if both values increase the COD it stabilizes in greatest values of $T_f$.

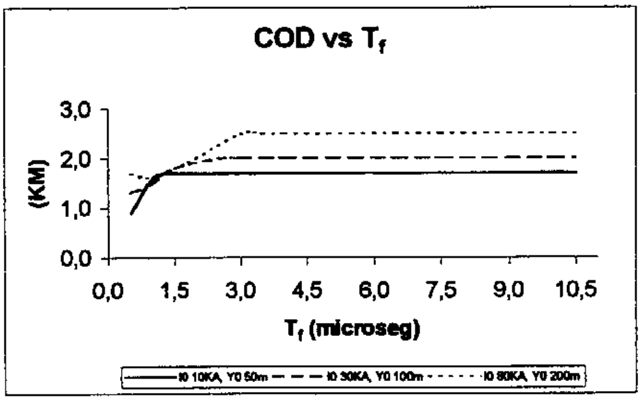


**Fig.9: Location of the COD vs. $T_f$ for different combinations of $I_0$-$Y_0$.**

The behavior of the Maximum overvoltage with respect to $T_f$ variations is similar to the described one for variations of $Y_0$; When $T_f$ is increased from their smaller value (0,5 µs) the maximum values of the overvoltage descend from their higher value in exponential form. This behavior could be attributed to the fact that small front times (between 0,5 and 2 µs in fig 8) are related with big rates of current growth $\left(\frac{di}{dt}\right)$, with which is being forced to the system to increase the effect of the induction in shorter times $\left(\frac{\text{kV}}{\mu seg}\right)$. In other words, small return stroke current fronts imply more severe currents injection to the system by the to earth capacitances and the immediate effect is the increase in the variation of voltage that happens in the terminals the same ones, that is to say, between the line and the plane of earth.

*d) Variation of h.*

Four cases were taken such that the previous point with the other variables fixed to the initial conditions. A total of 50 different cases was executed to cover the respective ranks. Variation range: 4 - 25 meters. Δh: steps of 3 meters.

It is observed that as the conductor is higher with respect to earth the magnitude of the maximum overvoltage increases proportionally as we can see in figure 10. The difference between slopes of these four straight lines $\left(\frac{\Delta kV}{\Delta h}\right)$ obey to the differences in magnitude of current (different $I_0$); greater current implies greater slope and for a greater current the increases in h are translated as well in biggest increases in the magnitudes of the overvoltage.

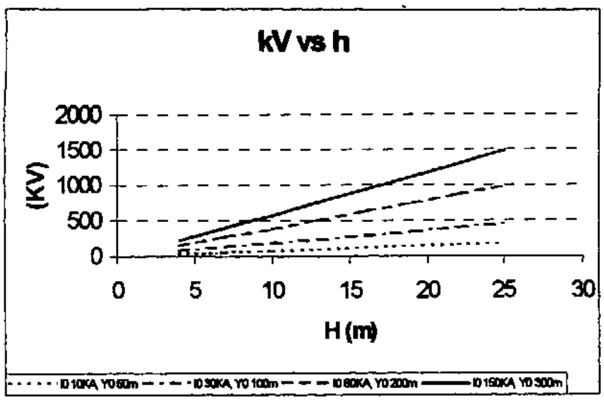


**Fig.10: Maximum overvoltage vs. h for combinations of $I_0$-$Y_0$.**

Also a stepped growth can be observed (fig.11) that experiences the COD as h increases.

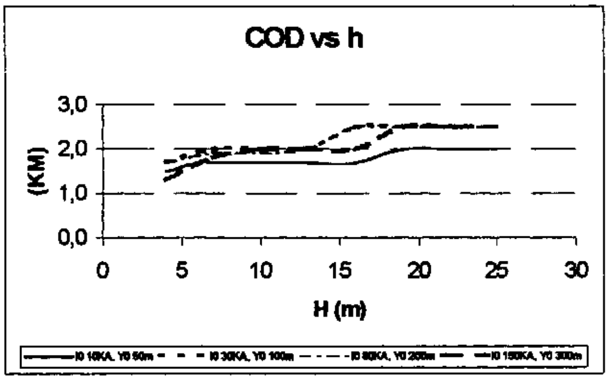


**Fig.11: Location of the COD vs. h for combinations of $I_0$-$Y_0$.**

$Y_0$

## IV. CONCLUSIONS.

The use of the computer tool developed in the present work (CHDATP) it has resulted to be very effective for the analysis of sensibility related with the induced surges represented with the pattern of Chowdhuri that was implemented in ATP [1]. Of this analysis the most important conclusions are presented next:

- The variation of $Y_0$ affect directly in the trip times of the return stroke wave as well as in the magnitude of the overvoltage in each point on the conductor, that is the reason why $Y_O$ have a big influence over the location of the COD.
- The value of $I_0$ has its greater influence in the values of maximum magnitude of the overvoltage whose present a linear behavior with respect it. Also, it does not have greater influence on the behavior of the COD.
- The effect to consider lowest values of the front times ($T_f$ between 0,5 and 2 μs) is related to putting under the system to severe increases in the injection of current by unit time, which represents a more drastic elevation of potential between the conductor and earth by unit time.
- About the representation of the phenomenon of overvoltage by indirect lightning stroke in the ATP [1], is important to consider a adequate number of nodes to make the simulation, mainly in the zone where the maximum overvoltage appear, because when more nodes are chosen greater could be the precision of the results.
- It is considered of extreme importance the fact to have made the sensitivity studies in critical situations for the selected variables given by the comfort and flexibility that tool CHDATP displays to the user, mainly about the waveform of the lightning stroke and their effect in the resulting overvoltage wave in the points where the COD are registered. In the results obtained for variations of $T_f$ and $\beta$ they make us think that the behaviors of the COD are seen very influenced by such waves. It is the way to obtain a widely profile of the behavior of the COD and the maximum overvoltage values which have been generated under specific characteristics of the conductor and the atmospheric discharge.

## V. NOMENCLATURE.

| | | |
|---|---|---|
| kV | : | Kilo volts. |
| EMTP | : | Electro Magnetic Transient Program. |
| ATP | : | Alternative Transient Program. |
| c | : | Speed of the light in the free space. |
| μs | : | microseconds. |
| ms | : | milliseconds. |
| $T_f$ | : | Front Time of the return stroke current. |
| $T_h$ | : | Time to half value of the return stroke current. |
| mts, m | : | Meters. |
| $I_0$ | : | Amplitude of the return stroke current. |
| $\beta$ | : | Ratio of return stroke velocity to velocity of the light in free space . |
| Yo | : | Perpendicular distance of the line from the strike point. |
| X | : | Distance of measurement point on the line from the point of the least distance to the strike point |
| h, hc | : | Height of the conductor and the cloud. |

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