Modeling of Power Network by ATP-Draw for Lightning Stroke Studies

J. Morales, A. Guzman

Abstract— **Protection relay algorithms play a crucial role in Electric Power System stability, where, it is clear that lightning strokes produce the mayor percentage of faults and outages of Transmission Lines (TLs) and Distribution Feeders (DFs). In this context, it is imperative develop novel protection relay algorithms. However, in order to get this aim, Electric Power Systems (EPS) network have to be simulated as real as possible, especially the lightning phenomena, and EPS elements that affect their behavior like direct and indirect lightning, insulator string, overhead line, soil ionization and other. However, researchers have proposed new protection relay algorithms considering common faults, which are not produced by lightning strokes, omitting this imperative phenomena for the transmission line protection relays behavior.**

Based on the above said, this paper presents the possibilities of using the Alternative Transient Program ATP-Draw for the modeling and simulation of some models to make lightning stroke studies, especially for protection relays, which are developed thought Transient Analysis of Control Systems (TACS) and MODELS language corresponding to the ATP-Draw.

Index Terms— **Back-flashover, faults, flashover, lightning stroke, modeling of lightning, outages, protection relays.**

I. INTRODUCTION

IDEALLY, an electricity supply should be invariable, presenting a perfectly sinusoidal voltage waveform. Thus, EPS are normally operating. However, for different reasons, permanent and non-permanent faults, can be produced. Thus, the EPS normal operating condition can pass of normal state to abnormal one, even it can produce outages [1].

In this context, transmission line insulation is usually either air or a high resistivity material like ceramic, polymer etc, which are usually used as mechanical support on TLs. Regarding to the causes of faults, air insulation can be short-circuited by birds, fire, accidents, and others. On the contrary, those high resistivity material usually called insulator string can be broken down especially by overvoltage due to lightning strokes, producing faults called flashovers and back-flashovers [2]. Therefore, if flashovers or back-flashover not quickly interrupted, it may cause outages, which can be very harmful from the economic and social point of view.

Regarding to lightning stroke effects on the protection relay behavior, in [3-15] it is possible to see that in different word counties this phenomena is the main cause of faults and mal-function of protection relays, which have produced unnecessary outages even blackouts. The main problem of those lightning stroke transmission line relays is based on those algorithms do not correctly classify those transient signals, identifying if a lightning stroke generates or not permanent fault (a more description is presented in [3, 16]).

In this context, in order to improve these relay mal-operations, and based on advances on digital technology, approaches based on Signal Processing Techniques like Wavelet Transform (WT), Mathematical Morphologic (MM), Artificial Neural Network (ANN), and others have been used by a number of researchers in order to develop novel protection relaying [33]. It is clear that those proposed methodologies are based on fault and lightning stroke transient signals, which are obtained thought simulations, where ATP software have been widely used in those simulations. Notwithstanding, from literature review, it is possible to see that those protection relay algorithms use simulated signals, omitting crucial elements and parameter in produce flashover and back-flashover (see Section II). For example, from these pieces of previous research, it is possible to determine that elements like the insulator string is simulated by using a voltage controlled switch. However, it is necessary simulate this element considering the voltage-time curve. The Tower Footing Resistance (TFR) usually is simulated by using only a constant resistance value, omitting their nonlinear behavior [18-27]. For example, Table I presents a summary of parameters simulated, which are used by some methodologies proposed. In Table I, it is possible to see that proposed protection relays simulate conditions of lightning specified. Notwithstanding, as is presented in Section II, it is clear that in order to simulate lightning stroke signals as real as possible, different parameters have to be simulated.

In this context, in order to develop novel lightning stroke transmission line protection relays, this paper presents the development of some models corresponding to features of lightning stroke and elements of EPS, which are developed thought TACS and MODELS language of the Alternative Transient Program [28-29]. These models are developed, resolving their characteristic equations.

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TABLE I
SUMMARY OF PARAMETERS SIMULATED FOR PREVIOUS RESEARCHES.

Researches		**Lightning Feautres**			**Lightning Type**		**TFR**		**Insulator String**	
		Ip (kA)	**Polarity**		**Direct**	**Induced**	**Without ionization**	**With ionization**	**Voltage-dependent switch**	**Voltage-time characteristic**
			Positive	**Negative**						
Literature review	ref. [27]	5, 15, 50 kA	√	X	√	X	WE	X	√	√
	ref. [34]	5, 30 kA	√	X	√	X	√ (100Ω)	X	√	X
	ref. [18]	50 kA	√	X	√	X	WE	X	√	X
	ref. [22]	3,10,15,20,30 kA	√	X	√	X	WE	X	√	√
Ip: Flash peak current amplitude										
TFR: Tower footing resistance										
WE: Without specifications										

II. FEATURES OF LIGHTNING STROKE ON TRANSMISSION LINE PROTECTION RELAYS

In order to develop novel transmission line protection relay algorithms, an acceptable simulation of lightning strokes on TLs, and basic elements of EPS, must be developed [30]. In this context, international organizations have proposed modeling guidelines for lightning representation in engineering environment [32-33]. They indicate that the most important aspects can be represented and summarized as follows:

A. Flash Current Peak Magnitude (FCPM)

The most important factor in lightning surge simulations is related to their magnitude called Flash Current Peak Magnitude (FCPM). When a lightning hits a transmission line, it injects current into the EPS. In the software ATP, the Heidler model is useful to represent that current [31].

B. Lightning Stroke Type

Two lightning type (direct and induced) can hit the TL. Their effect on TLs is determine directly if any atmospheric discharge generates or not flashover or back-flashover. The first lightning type correspond to direct lightning strokes, which can hit on tower structures/ground wires or they passes through the protective zone of ground wires and it hits on the phase conductor. On the contrary, induced overvoltage occurs when a lightning hits directly on ground [2]. In ATP software, this lightning stroke is simulated by implemented the Rusck equation (See Section IV.A).

C. Insulator String

This element is crucial in order to determine if the overvoltage is highest that the Basic Insulator Level (BIL), and therefore a fault is produced. The authors have determined that by using the ATP software, there are two possibilities to simulate the insulator string. Fist: It can be simulated by a voltage-dependent flashover switch omitting their voltage-time characteristic. Second: It can be simulated by a voltage-dependent flashover switch and a voltage-time characteristic. However, in this paper, the second possibility is used (See Section IV.B).

D. Tower Footing Resistance (TFR)

Another important parameter to be considered is related to the Tower Footing Resistance (TFR). It is clear that transmission tower can have either low or high TFR. In order to consider the behavior of this parameter during atmospheric discharges, this must be simulated. However, it is necessary considerer the ground ionization, which presents a nonlinear behavior of resistance ground (See Section IV.C).

E. Transmission Line Model

An adequate selection corresponding to the TL model used in the simulations, have to be developed. Thus, international organizations, recommended to use two TL models. First: untransposed distributed and concentrated parameter line model, respectively (See Section IV.D).

F. Transmission Tower (TT)

Similar to the TL model, there are two possibilities to simulate this element, the first consists of using lumped model, and the second uses distributed parameters models (See Section IV.E).

Based on the previous said, it is clear that in order to make simulation of lightning strokes, different parameter have to be simulated. Fig. 1 shows a classification of this phenomena, not only direct flash but also indirect flash, their effects on insulators, and their parameters to be considered.

Besides that, based on the literature review presented in Section I, it is clear that proposed protection relays simulate conditions of lightning specified. Table I presents a comparison among previous research, summarizing different parameters simulated of atmospheric discharges and transmission lines, which are considered by those approaches. From Table I it is possible to see that previous research considered specific values and conditions. Instead, simulation have to be developed considering those features as possible as presented in Section II.

III. FEATURES OF ATP

Originally the Alternative Transients Program called ATP was designed in order to make calculations of transient process in EPS. By using the ATP, a simulation is developed through three steps as follows. First: create and edit input files by using ATPDraw. Second: simulate electric system in the time and frequency domain by using TPBIG and third: show results of simulation by using graphical postprocessor. Regarding to the ATPDraw, it is an interactive preprocessor, which is similar central core. This preprocessor have different models that represent component of an EPS, and this also allows that users create novel models using different options like Transient Analysis of Control Systems (TACS), programming language (MODELS) and other [28-29].

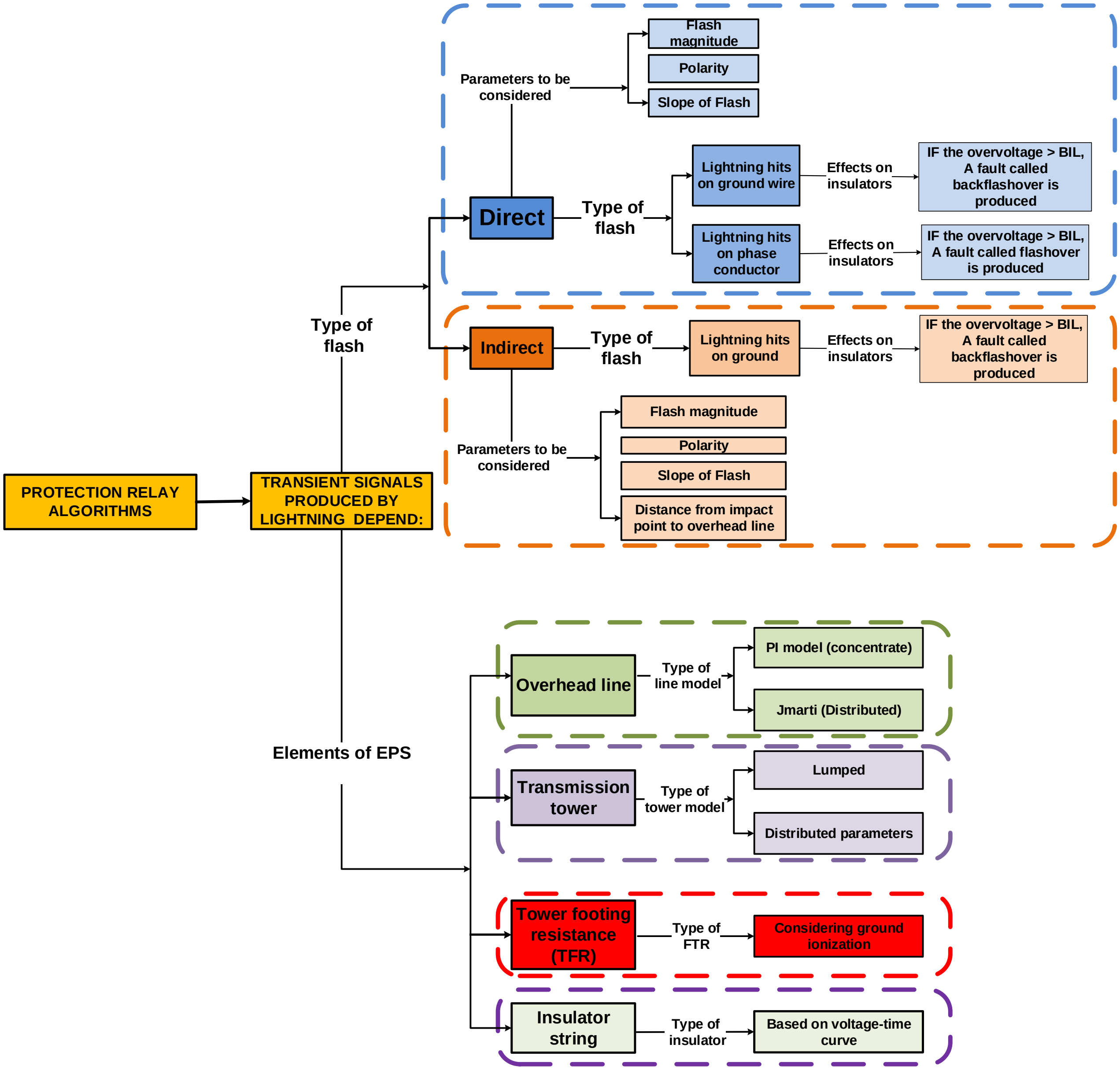


Fig. 1. Type of direct and indirect lightning.

A. TACS and MODELS

In this paper, in order to develop different models corresponding to induced lightning, ground ionization, etc. TACS and MODELS language have been main used. MODELS language is a description language of the ATP program, which provides a format focuses on description of the structure of a model, and the function of its elements.

IV. CONSTRUCTING AND RESULTS OF THE MODELS

It is clear that ATP-Draw has several models of basic elements like generator and transformer. In this context, in this paper, the authors have considered to builds models of elements different to those presented in ATP, which are presented as follows:

A. Lightning Stroke Type

In ATP, the direct lightning stroke is represented by an impulsive current source (Heidler) and a parallel resistance of 400Ω [31]. Fig. 2 shows the lightning stroke model implemented in the ATP program. In this model, parameter of lightning like magnitude, polarity and time can be adjusted.

On the other hand, regarding to the induced lightning stroke, the main aspect concerning to Rusck´s methologolgy for lightning induced overvoltages (LIOs) estimation in transmission lines, is presented. In this paper, the calculation methodology that was adopted for the LIOs simulation is the technique proposed by Rusck [35]. It is highly used and recognized by institutions wording recognition like IEEE Std 1410 or CIGRE [36-37].

The Ruck’s methodology, firstly models the return current imposed by the lighting discharge on the TL. Hence, it calculates the electric field value generated by this return current in the ground surface, and from this electric field; values of LIOs on TL are formulated.

Rusck´s theory calculates LIOs on overhead lines based on expressions for the scalar and vector potentials due to a step current in the lightning channel over a perfectly conducting earth. The Rusck configuration is shown in Fig. 3.a.

Besides that, a rectangular system of co-ordinates in space is used so that the system origin corresponds to the point where the lightning hits the surface of earth. The phase conductor is assumed to be located at distance *D* meters from the origin, having a mean height above ground of *h* meters and running along the *x* direction. See Fig 3.b. In this context, the induced voltage produced by discharge in the nearer point along the overhead line, i.e. *x=0*, can be computed as follows:

$$V_{(t)} = 2Z_o I_o h \frac{vt}{D^2+(vt)^2}\left[1+\frac{\beta vt}{\sqrt{(vt)^2+D^2(1-\beta^2)}}\right] \tag{1}$$

In this case, $V_{(t)}$ is the induced voltage (LIO) at a point where the lightning hits on the overhead line; *t* is the time in seconds; *c* is the velocity of light in free space (m/s); *I* is the return-peak current value (kA); *h* is the average height of the overhead line; Z_o is the surge impedance of discharge channel (30Ω); and *D* is closest distance between the discharge incidence point and the overhead line (m).

On the other hand, the induced voltage in the line could be considered as the injecting of current source, such as:

$$I_{(t)} = \frac{4Z_o I_o h}{Z}\frac{vt}{D^2+(vt)^2}\left[1+\frac{\beta vt}{\sqrt{(vt)^2+D^2(1-\beta^2)}}\right] \tag{2}$$

Where, I_t is the current which goes through the overhead line, and *Z* is the surge impedance of the line.

Based on the Rusck´s theory, in this section, a computational model of LIOs on TLs is implemented in ATP-Draw environment specifically using MODELS language. The mechanism corresponding to LIOs is programed in the 94 type model, which in this paper is called *Induced Voltage*. Fig. 4 shows the MODEL code and their parameters, respectively.

In order to verify the MODEL behavior, by using the MODEL *Induced Voltage*, LIOs at different distances from the strike point are evaluated. The injected current sources are connected to the TL as is shown in Fig. 5. Where the TL and different positions of impact point on the earth surface are considered.

Regarding the LIOs simulated, it is composed with lightning strokes with a range value from 3kA to 31,1 kA. Where Ip=31,1kA is the peak typical value of the return stroke current. On the other hand, three values of distance from lightning impact point on earth surface to the overhead line D=100m, D=150m, D=200m, were simulated in this paper. For instance, Fig. 6 shows the waveform obtained for lightning stroke currents of 10kA, with a minimum distance from the TL to lightning strike of 100m.

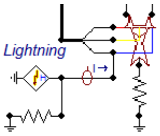
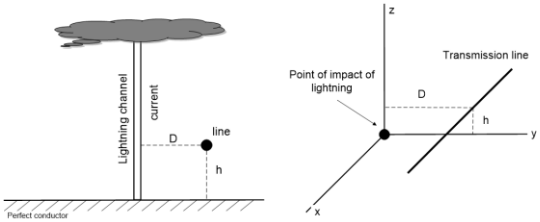
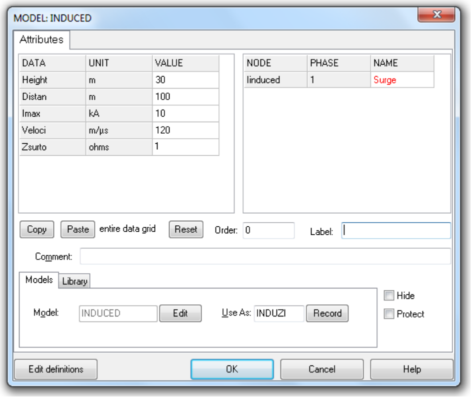


Fig. 2. Direct lightning stroke model.



(a) (b)

Fig. 3. Geometry of Rusck Model.



DATA	UNIT	VALUE
Height	m	30
Distan	m	100
Imax	kA	10
Veloci	m/µs	120
Zsurto	ohms	1

NODE	PHASE	NAME
Iinduced	1	Surge

entire data grid

Order: 0

Label:

Comment:

Model: INDUCED

Use As: INDUZI

☐ Hide

☐ Protect

(a) Induced Voltage MODEL parameters.

```
MODEL INDUCED
OUTPUT
    Iinduced
TA
    Height {dflt:30.} -- Height of Conductors [m]
    Distan {dflt:100.} -- Shorter distance between the line and the discharge [m]
     Imax {dflt:10.} -- Flash peak current magnitude [kA]
     Veloci {dflt:120.} -- Current wave velocity [m/µs]
     Zsurto {dflt:1.} -- Characterisitc impedance of line [ohms]
VAR
    beta
    A
    B
    C
    D
    Vinduced
    Iinduced
    T1
INIT
    A := 0
    B := 0
    C := 0
    D := 0
    beta := 0
    Vinduced:=0
    Iinduced:=0
    T1:=1
ENDINIT
EXEC
    T1:=t*1000000
    beta := Veloci/300
    A:=2*30*Imax*Height*beta*Veloci*T1
    B:= (Distan*Distan)+((beta*Veloci*T1)*(beta*Veloci*T1))
    C:= beta*beta*Veloci*T1
    D:= (beta*beta*Veloci*Veloci*T1*T1)+(Distan*Distan*(1-(beta*beta)))
    Vinduced := (A/B)*(1+(C/(SQRT(D))))
    Iinduced:=Vinduced
ENDEXEC
ENDMODEL
```

(b) MODEL code.

Fig. 4. MODEL Induced Voltage.

B. Insulator string

In this paper, insulators are simulated by a voltage-dependent flashover switch and based on the voltage-time characteristic. Fig. 7 shows the volt-time curve of a string. Thus, the dielectric strength of an insulator string as a function of time to flashover for a lightning impulse voltage wave is:

$$V_f = 400 * L + \frac{710 * L}{t^{0.75}} \tag{3}$$

Where, V_f = flashover voltage in kV, t = time to flashover in µs, and L = length of the insulator string in meters.

In this context, the flashover mechanism corresponding to insulators can be represented by the volt-time curve, which in this paper is implemented using MODELS language. Thus, in the next model called *Flashover*, the volt-time curve is implemented, being calculated in the INIT section. See Fig. 8 and Fig. 9, respectively.

C. Tower Footing Resistance (TFR)

TFR is a crucial parameter in lightning strokes studies. Their performance is variable with the time, thus their value is not constant. Therefore, it is necessary to visualize the impedance change when a lightning hits TLs. This section presents a model implemented using Transient Analysis of Control Systems (TACS)-MODELS to determine the impedance value considering their non-linear performance. Taking the impedance value equation and considering the current value, the TFR value is estimated during contingency simulation. The model considers a threshold current value for ground ionization phenomena initiation.

On the other hand, following a lightning stroke to TL, high currents flow into the ground through the TFR, producing the soil ionization. The impedance value corresponding to the transmission tower base varies depending on soil resistivity, flash peak current magnitude which flows on the TT base, and other. The TFR can be calculated as follows [38]:

$$R = \frac{R_0}{\sqrt{1 + \frac{I}{I_0}}} \tag{4}$$

Where R_o represents the TFR at low current, I represents the surge current into ground, I_0 represents the current which initiate the soil ionization which is calculated as follows:

$$I_0 = \frac{1}{2\pi}\left(\frac{E_0 \rho_0}{R_{0^2}}\right) \tag{5}$$

Usually the I_0 valor for ionization gradient by using 300kV/m is 52.5kA. From Eq. 4 it is possible to see that TFR values have a non-linear performance. Later on, that equation is implemented by using TACS-MODELS.

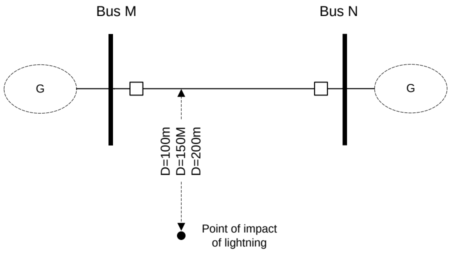


Fig. 5. Position of the point of impact of lightning on the earth surface.

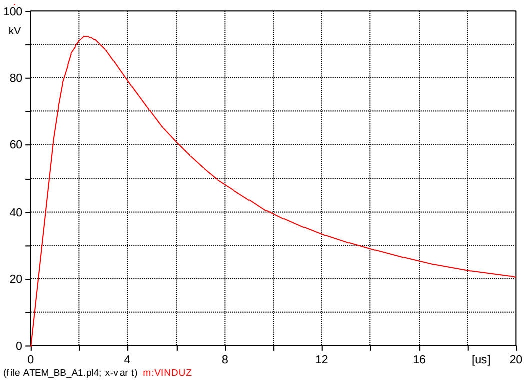


Fig. 6. LIOs with distance 100m from the TL to lightning impact point.

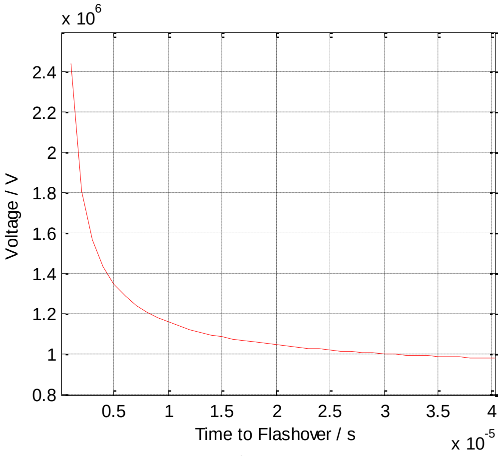
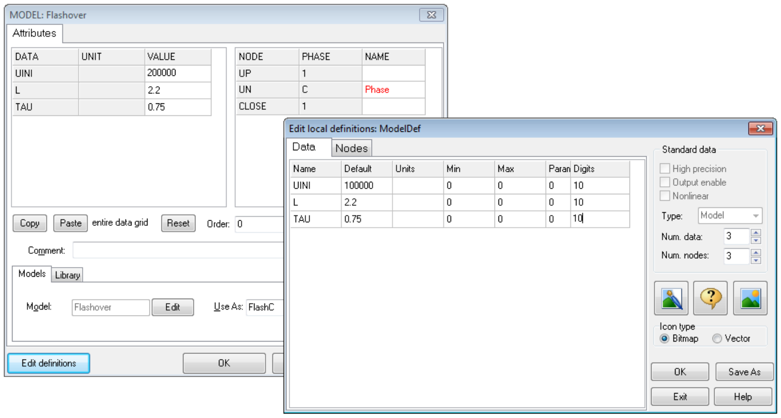


Fig. 7. Volt-time characteristic of porcelain insulator under lightning impulse

In this paper, at every step size Δt=1µs, the MODEL calculates the current resistance value, which is reflected by TACS in order to be considered into of the TT. Hence, the circuit shown in Fig. 10 can be connected to tower base.

In this context, a *.mod* file model named VARESIS, using Eq. 5 estimates the current resistance value. On the other hand, from Fig. 11 it is clear that data are adjusted by using the *.sup* file. It should be noted that the surge current into ground *I* is not specified due to this value is automatically measured by the VARESIST model, and the resistance value *R* is then calculated continuously.



DATA	UNIT	VALUE
UINI		200000
L		2.2
TAU		0.75

NODE	PHASE	NAME
UP	1	
UN	C	Phase
CLOSE	1	

Order: 0

Comment:

Model: Flashover

Use As: FlashC

Name	Default	Units	Min	Max	Paran	Digits
UINI	100000		0	0	0	10
L	2.2		0	0	0	10
TAU	0.75		0	0	0	10

☐ High precision
☐ Output enable
☐ Nonlinear

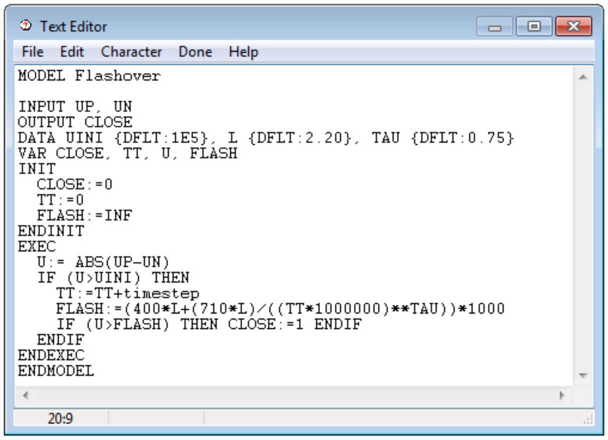
Type: Model

Num. data: 3

Num. nodes: 3

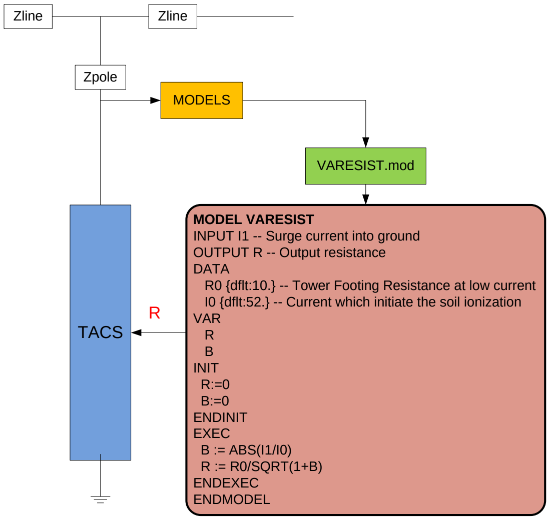
Icon type: ● Bitmap ○ Vector

Fig. 8. MODEL parameters.



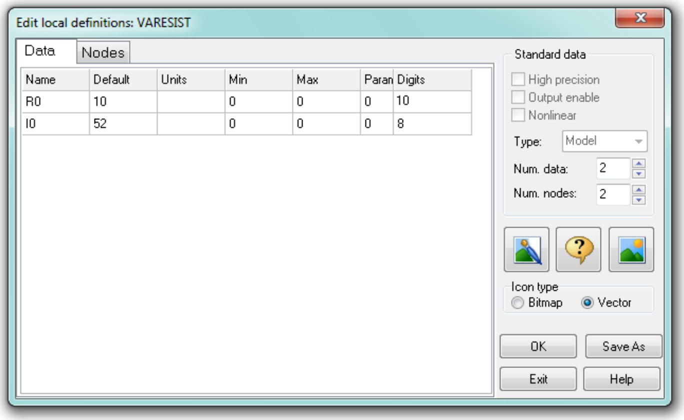
```
MODEL Flashover

INPUT UP, UN
OUTPUT CLOSE
DATA UINI {DFLT:1E5}, L {DFLT:2.20}, TAU {DFLT:0.75}
VAR CLOSE, TT, U, FLASH
INIT
  CLOSE:=0
  TT:=0
  FLASH:=INF
ENDINIT
EXEC
  U:= ABS(UP-UN)
  IF (U>UINI) THEN
    TT:=TT+timestep
    FLASH:=(400*L+(710*L)/((TT*1000000)**TAU))*1000
    IF (U>FLASH) THEN CLOSE:=1 ENDIF
  ENDIF
ENDEXEC
ENDMODEL
```

Fig. 9. MODEL code.



```
MODEL VARESIST
INPUT I1 -- Surge current into ground
OUTPUT R -- Output resistance
DATA
   R0 {dflt:10.} -- Tower Footing Resistance at low current
   I0 {dflt:52.} -- Current which initiate the soil ionization
VAR
   R
   B
INIT
  R:=0
  B:=0
ENDINIT
EXEC
  B := ABS(I1/I0)
  R := R0/SQRT(1+B)
ENDEXEC
ENDMODEL
```

Fig. 10. Single Line Diagram for the resistance estimation.



Name	Default	Units	Min	Max	Paran	Digits
R0	10		0	0	0	10
I0	52		0	0	0	8

☐ High precision
☐ Output enable
☐ Nonlinear

Type: Model

Num. data: 2

Num. nodes: 2

Icon type: ○ Bitmap ● Vector

Fig. 11. Representation of the .sup file.

For example, Fig. 12 shows the TFR waveform using a flash current of 150kA, Δt =1µs and simulation total time = 300µs. In this situation is possible to see the TFR non-linear variation. A more detailed description of some examples is presented in [39].

D. Transmission Line Model

It is well known that the Jmarti and Pi models of ATP, are usually used in order to make simulation of faults. However, in order to analyze and discussed how influence the overhead line model under effects of transients caused for atmospheric discharges. In this section, an analysis of induced lightning stroke when they hit on the ground to 100m distance from the overhead line, is presented. Thus, various simulations and subsequent analysis at various points on the overhead line with Jmarti and Pi models is performed.

Regarding to the Jmarti model, Fig. 13 shows the behavior of voltage corresponding to each phase after that an induced lightning hits the ground. This figure shows different waveforms and a variation on their maximum peaks, corresponding to the three phases. This behavior is due to the overvoltage reflection produced by the induced lightning stroke to 100 m of the overhead line. On the other hand, the maximum voltages values are produced in different time values.

On the other hand, as regards to the Pi model, Fig. 14 shows the overvoltages produced by the induced lightning stroke. In this figure it is possible to see that not only a variation among waveforms but also overvoltage reflections, are not produced. Besides that, the three phase take their maximum value in a time of 42,5µs, which is longer that the time take by the Jmarti model.

The authors have considered timely to make the analysis by using both TL models, because it could generates voltages different those the reality, which will lead to mal-operation of devices like protection relays and others.

E. Transmission Tower

Similar to the previous case, TT are considered crucial parameters in order to develop new protection relay algorithms. Therefore, TT must be correctly selected and simulated in order to consider reflected voltage waveforms from cross arms. In this context, this section presents a comparative study corresponding to the TT simulation using two existing models in ATP. The first uses lumped model, and the second uses distributed parameters models characterized by their impedance and travel time. Therefore, overvoltage signals and waveforms registered by insulator strings that exist in each phase using different lightning features, are discussed.

It is necessary to note that the EPS simulated corresponds to a three-phase 220kV radial system, which contains two loads; the transmission line is composed of six spans, whose length among spans is 400m. The tower height is 32m and wood cross-arms of 8.5 m, respectively.

Regarding to lightning currents, values of 20kA, 50kA, 100kA, 150kA and 200kA, considering positive and negative polarity, are simulated. As regards to the tower design, two ground wires are localized at the top of the tower. The lightning impact point is directly on the ground wire. On the contrary, lumped and distributed parameter tower models, are simulated according to Fig. 15 and Fig. 16, respectively. Then, the lightning hits on the ground wire, and by using those two tower models, overvoltage values on their insulators are determined.

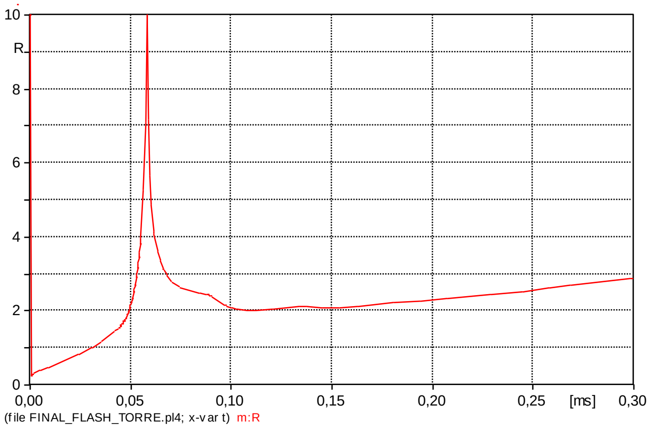


Fig. 12. Resistance value with Ip=150kA, simulation time=300µs.

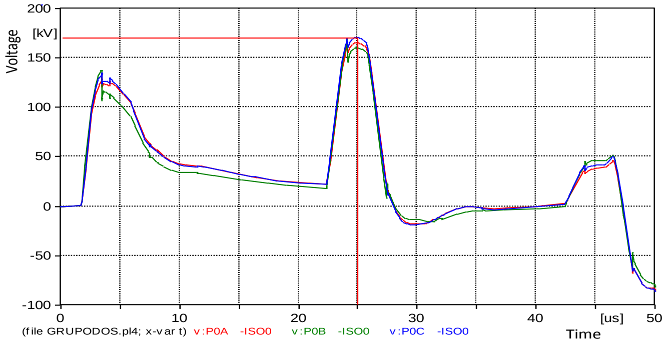


Fig. 13. Three phase voltage by using Jmarti model.

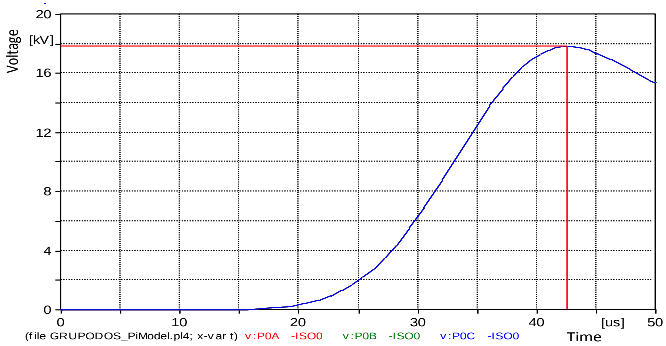


Fig. 14. Three phase voltage by using Pi model.

Regarding to the overvoltage using distributed parameters model, Fig. 17 shows the overvoltage corresponding to the phase R when a lightning of 20kA hits on the TT. The initial surge value is -180kV, approximately. Their first peak has a value of -400kV. However, their most important peak value is 820kV, approximately. Regarding to the phase S and T, their initial peak value is 0.09MV and the highest peak value is 991.5kV, and 1.0429MV, respectively. It is necessary to note that in this figure those reflected waveforms from cross arms are detected. This issue is represented in Fig. 17 by green color.

On the other hand, as regards to the lumped model, Fig. 18 shows those three phase overvoltages considering a flash current of 20kA. From this figure, it is possible to see that their

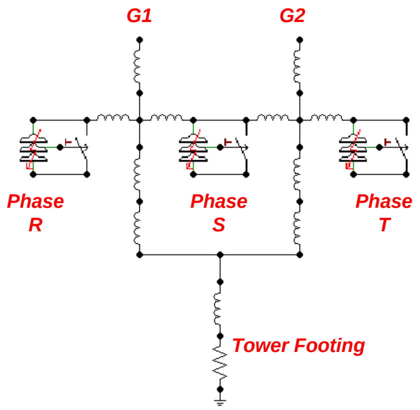


Fig. 15. Lumped Tower Model using ATP.

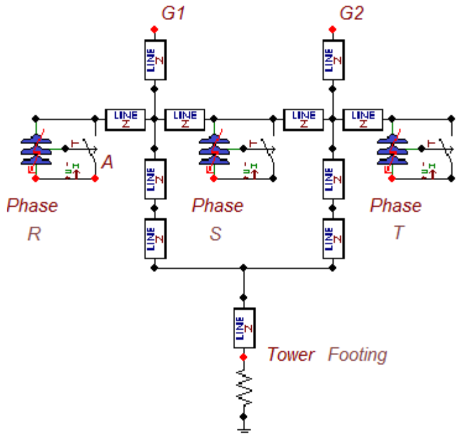


Fig. 16. Distributed Parameter Tower Model.

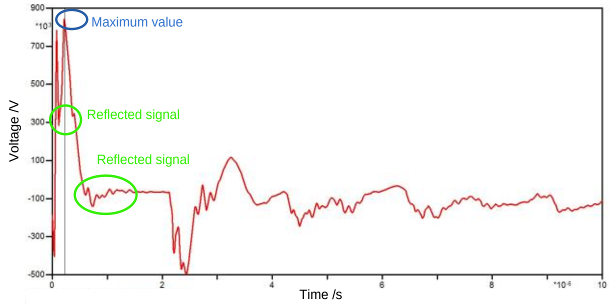


Fig. 17. Three phase overvoltage using distributed parameter with a flash current of 20KA in phase R.

waveforms are similar among them. However, the overvoltage value of phase R (0.86245MV) is different to the others two phases, S=1.042MV and T=1.0121 MV, respectively. In addition, in this figure, those reflected waveforms from cross arms are not distinguished, which in Fig. 18 are represented by black color.

V. CONCLUSIONS

Lightning strokes will give rise to the ultra-high-speed protection mal-operation. However, it is clear that observe this phenomena experimentally on EPS is hard and complicate, thus numerical simulations are used in order to develop novel transmission line protection relays. In this context, the modeling of lightning features and EPS elements can help to researchers to find solutions for problems relating to transmission line protection relays. In this paper, the advantages and helpfulness of ATP, especially TACS and MODELS language has been verified for lightning stroke transient signals simulation.

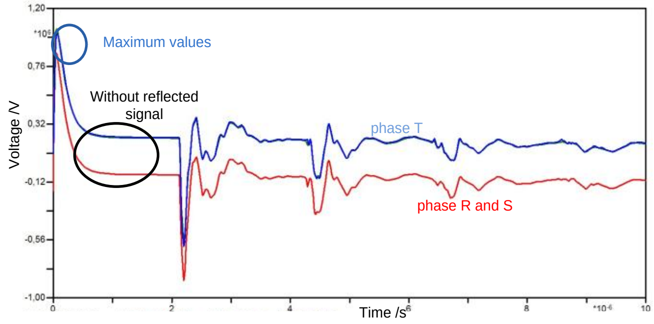


Fig. 18. Three phase overvoltage using lumped parameter with a flash current of 20KA in phase R.

Based on the results, this paper could be considered a guide for those students, teachers, researchers who are interested in protection relay environment.

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VIII. BIOGRAPHIES

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