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Lightning Stroke Flashover Detection Algorithm Based on Mother Function

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Abstract

Electric Power supply is a crucial topic for economic and social development. Power outages statistics show that discharges atmospherics are imperative phenomena to produce those outages. In this context, it is necessary to correctly detect when overhead line insulators are faulted. In this paper, an algorithm to detect if a lightning stroke generates or not permanent fault on insulator strings is proposed. On top of that, lightning stroke simulations developed by using the Alternative Transients Program, are used. Based on these insights, a novel approach is designed that depends on mother functions analysis corresponding to the given variance-covariance matrix. Signals registered at the insulator string are projected on corresponding axes by the means of Principal Component Analysis. By exploiting these new axes, it is possible to determine a flashover characteristic zone useful to an insulation design. The proposed methodology for flashover detection extends the existing approaches for the analysis and study of lightning performance on transmission lines.

Keywords: Mother Function, Outages, Lightning Sensitivity Analysis.

Introduction

When a lightning hits on transmission lines (TL) or distribution feeders (DF), this generates overvoltages, which are considered as the major cause of flashover on insulators [1]. However, the flashover occurrence depends if these overvoltages are higher than Basic Insulator Level (BIL) of insulators.

TL insulators, characterized by its length and isolation level can be affected by lightning strokes (LS). TLs are usually shielded, i.e. they are built with grounding wire-guard, which avoid that lightning hit directly on TLs [2].

LS affects considerably the overhead lines performance. Still, due to their unpredictable behavior and considering their increasing intensity and frequency worldwide caused by global warming, they gain more significance and become a focus of scientific research. In this context, the development of alternatives methods in order to detect if a lightning stroke generates or no permanent flashover on insulator strings could help to facilitate the analysis and study of these phenomena and their impact on electric power systems (EPS) like insulator coordination (sensitivity studies) [3-4].

Regarding to the flashover detection algorithm, transient signals corresponding to LS and registered in insulator strings are employed to extract a functional relationship that can be used to determine flashover occurrences. This function is determined through the analysis of news orthogonal bases, which are determined by the means of Principal Component Analysis (PCA). Hence, by using only these mother functions (eigenvectors), it is possible to determine when a flashover is produced, even with different data window sizes.

As regards the format of this research, it is organized as follows: In Section II, the flashover detection algorithm is presented. Section III presents some results and its flowchart. Finally, section IV presents the main conclusions of this work.

Flashover detection algorithm

In order to determine a function useful to detect the flashover occurrences, it is necessary to analyze correlations between insulator string transient signals. On this context, Principal Component Analysis (PCA) is applied to explain the variance-covariance structure through original variables linear combinations [5]. Thus, a far superior approach is to use the mother functions or eigenvectors corresponding to the variance-covariance matrix, which determine automatically if a LS generates or nor permanent flashover.

Based on the above said, it is necessary to determine the principal components and by using a visual representation of these components, it is possible to determine a mother function that best to detect when a flashover is presented. Therefore, if a database is organized in *m* observations and *p* variables, the procedure to calculate those principal components is as follows:

If a *p*-dimensional vector represents the signal transient registered in the insulator string, the variance-covariance matrix **R** is calculated by:

$$R = \frac{\sum_{i=1}^{m}(Q_i - \overline{Q})(Q_i - \overline{Q})}{(m-1)} \qquad (1)$$

Where, *m* represents the signals number, **Q** is the normalized data matrix under study and $\overline{Q}$ corresponds to their mean vector. Later on, from this matrix **R**, their eigenvalues and eigenvectors denoted by υ and γ are used in order to calculate the principal components as follows:

$$Y = Q \quad \gamma \qquad (2)$$

By using the eigenvectors, a new set of uncorrelated signals called principal components and denoted by **Y** are calculated through a linear combination.

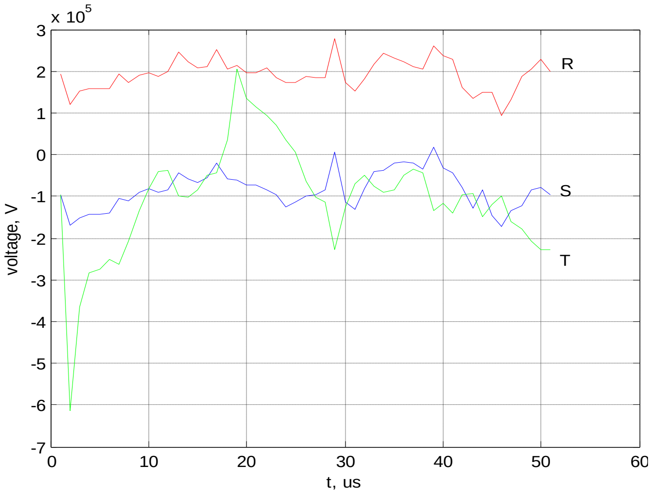
Based on the previous process, some signals corresponding to LSs that generate or not permanent flashover, are projected on new coordinates, and by analyzing this projection, representative mother functions or eigenvectors are extracted.

Proposed algorithm application

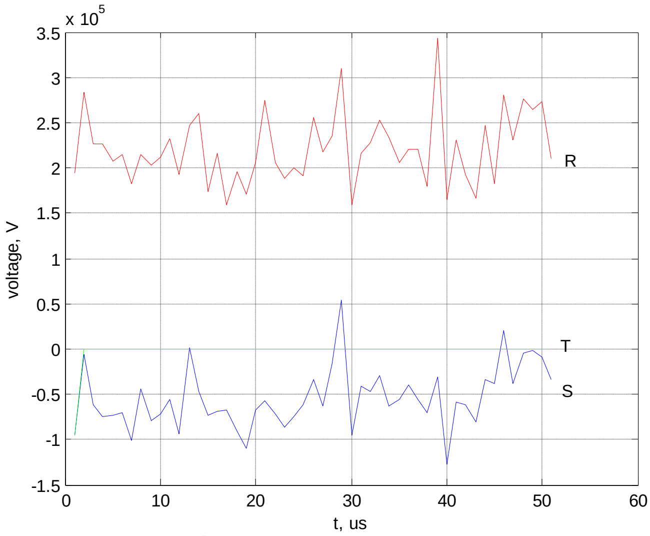
The EPS used consist of 6 buses, 5 single transmission lines, 2 transformers and 6 generators [6]. The TL is simulated using the frequency dependent model Jmarti [7]. By using the ATP software [8], different lightning stroke cases are simulated. These simulations are developed varying the flash peak current magnitude (*FPCM*), polarity, point of impact, time constants, data window size and others [9]. The lightning hits on phase conductors, guard wire and towers, and the transient signals are measured on the insulators.

Fig. 1 shows the voltages that the insulators are subjected corresponding a different cases. Fig. 1.a shows the three phases voltage curves on the insulators for a flash peak current magnitude *FPCM*=4000A, negative polarity, tower footing resistance (*TFR*=50Ω), time constants τ=1.2E-5s, *Tf*=5E-6s. Fig. 1.b shows the three phases voltage curves on the insulators for a *FPCM*=9000A, negative polarity, tower footing resistance (*TFR*=50Ω), time constants τ=1.2E-5s, *Tf*=5E-6s.

From Fig. 1.a, it is possible to see that the voltages on the insulators do not produce flashover, and from Fig. 1.b, it is clear that the flashover occurs in the insulator corresponding to the phase *T*. In this work, these characteristics of the voltage behavior are used to analyze the flashover performance, some signals that generate or not permanent flashovers are used in the training process. It is necessary to note that for the training process, only signals corresponding to the insulator localized in the transmission line middle vane, were considered.



(a) *FPCM* =4000A



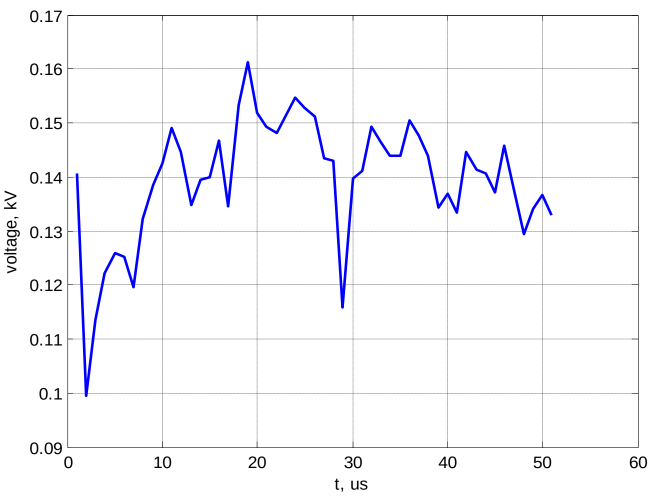
(b) *FPCM* =9000A

Fig.1. Insulator voltage at surge point for a) *FPCM* =4000A, b) *FPCM* =9000A.

The training signals through mother functions or eigenvectors corresponding to the variance-covariance matrix are decomposed. See section 2. For instance, the measured signals in the insulators are discrete time signals of 50 points i.e. the signals are represented as row vectors 1x50 with 1us among points. By using those signals, their variance-covariance matrix of size 50x50 is calculated dividing by (m-1) each element. See Eqn. (1).

Later on, by using Eqn. (2), that eigenvectors matrix of size 50x50 is calculated, which is used to calculate new signals corresponding to insulator overvoltages. These new signals replace the original signals. Fig. 2 shows the first two eigenvectors.

For example, by using the first two eigenvector, the original signals are projected on a new two-dimensional space. The procedure is repeated using other eigenvectors. The aim of the previous process is to determine which eigenvector clearly identified the flashover occurrence. Table 1 presents different features of lightning strokes.



(a) First mother function

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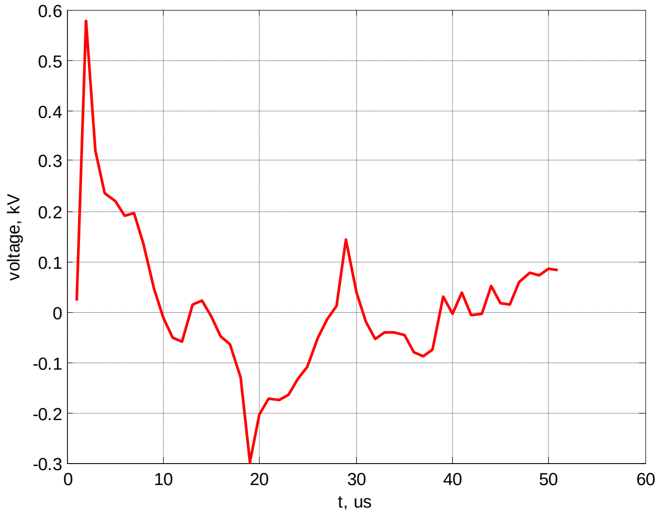


(b) Second mother function

Fig.2: First two eigenvectors (a) first eigenvector, (b) second eigenvector.

In this Table, the symbol √ represents the flashover occurrence, and *X* represents that the flashover is not produced. This Table is determined through a manual process i.e. the insulator voltage is measured and if this value to exceed the basic insulator level, a flashover is produced. In this context, some signals corresponding to Table 1 are evaluated through the detection algorithm.

Principal Components of some training signals are calculated. In Table 2, blue color values correspond to insulators on which the flashover is produced.

TABLE.1. Features of Some Lightning Strokes

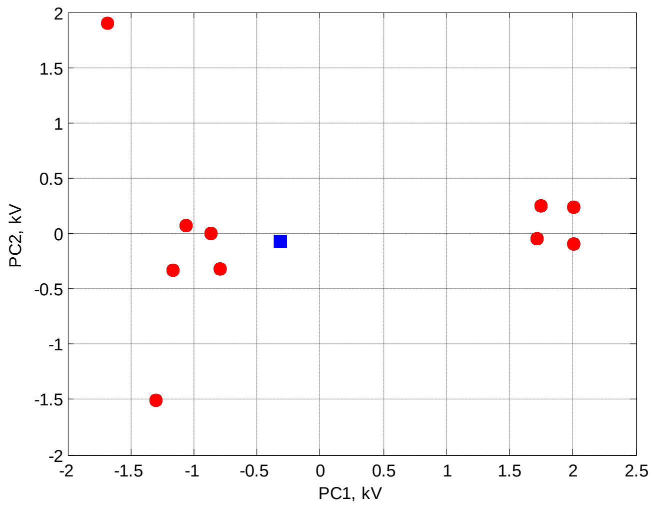
Lightning Features				Flashover			TL stretch	time constants τ, tf.	data window µs
Ip (kA)	Polarity		TFR	R	S	T			
	+	-							
4		√	50	X	X	X	13	1.2E-5s/5E-6s	50
9		√	50	X	X	√	13	1.2E-5s/5E-6s	50
6	√		50	X	X	X	13	1.2E-5s/5E-6s	50
10	√		50	X	X	√	13	1.2E-5s/5E-6s	50
TFR: Tower footing resistance									

TABLE.2. Insulator Voltages on PCs

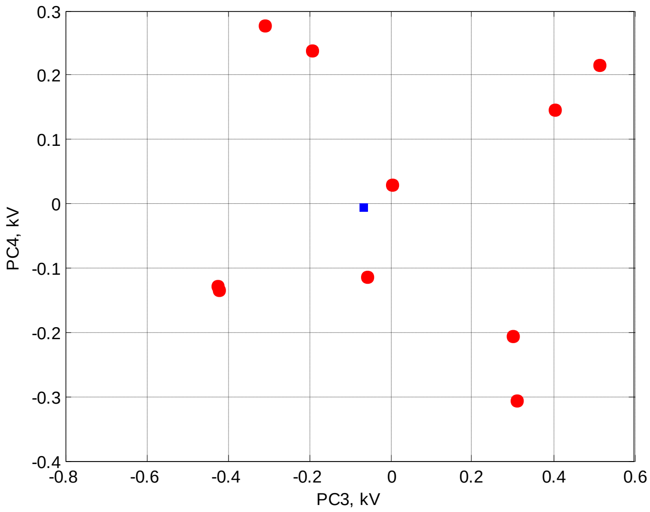
Signals Projected									
PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**	**PC9**	**PC10**
1,721	-0,04	-0,42	-0,14	0,011	-0,07	0,073	-0,03	0,053	0,008
-1,3	-1,51	0,004	0,029	-0,22	-0,03	0,036	-0,01	-0,02	0,005
-0,31	-0,08	-0,07	-0,01	0,022	0,026	0,008	0,097	0,01	-0,003
-1,69	1,899	-0,06	-0,11	-0,13	-0,02	0,019	-0,01	-0,02	0,003
-0,31	-0,08	-0,07	-0,01	0,022	0,026	0,008	0,097	0,01	-0,003

As regards the projections, Fig. 3.a shows some signals of Table 2 projected by using the first two eigenvectors. Fig. 3.b presents the lightning performance through the third and fourth eigenvector.

In Fig. 3.a, it is possible to see that the flashover occurrence represented by blue color is clearly distinguished of other signal through the first eigenvector. Thus, by using two threshold values denoted by *thmin* =-0.5 and *thmax* = +0.5, sensibility analysis can be developed. Therefore, if the value of the first principal component is inside these threshold values, the flashover occurrence, is detected.



(a) First and second PCs.



(b) Third and fourth PCs.

Fig.3: Insulator voltage projected (a) 1 and 2PCs, (b) 3 and 4 PCs.

By using the first eigenvector, the flashover detection algorithm is tested using insulator overvoltages, which are different to those signals used in the training process. This evaluation is developed through an *on-line* projection of new signals, which is developed through a convolution between the test new signal and the first mother function or eigenvector. Signals with different data window sizes are tested. However, the only requirement is that the signal must be adjusted to a 1x50 size, which can be done through interpolation or aliasing, respectively. This requirement is necessary due to that the first eigenvector size is of 1x50, respectively.

Table 3 presents some insulator overvoltages located in different point along the TL, which correspond to different flash peak current magnitudes, polarity, tower footing resistances, lightning front times and different data window sizes.
In this Table it is possible to see that the signal corresponding to *FPCM*=70kA, polarity (-), *FTR*=50Ω, phase(*R*), and the signal corresponding to *FPCM* =9.8kA, polarity (-), FTR=200Ω, phase (*T*), they produce flashover on the insulators (green color in Table 3). On the other hand, In Fig. 4, these signals projected on the first two PCs. For example, the flashover occurrence on the phase *R* corresponding to the FTR=70kA, is correctly detected.
As regards the phase *S*, it is possible to see in Fig. 4 that the flashover is not produced. This result is achieved even employing a data window of 1ms. On the contrary, from Table 3, it is possible to see that the first principal component calculated values are inside or outside of the threshold values, depending of the case. Corresponding to the first principal component, in Table 3 it is possible to see that these values converge to the correct values, depending if they generate or not permanent flashover.
On the other hand, the methodology is tested with different data window sizes. For example, two overvoltage signals measured on the insulators with data windows of 50us (black color) and 1ms (green color) are shown in Fig. 5, which correspond as follows:
First: 7.5kA, phase R, data window=50us.
Second: 70kA, phase S, data window=1ms.

From Fig. 5 and Table 3, it is clear that the detection algorithm have an acceptable performance even with different data window sizes. Thus, only adjusting the data window to size of 50 points, it is possible to analyze the insulator voltage. Fig. 6 shows the flashover detection algorithm flowchart.

TABLE.3. First Principal Component Values of Testing Lightning

Lightning Features				Phase	Flashover	TL stretch	time constants τ, tf.	data window us	First PC value
Ip (kA)	Polarity (+)	Polarity (-)	TFR						
7.5	√		50	R	χ	2	2.2E-5s/2E-6s	50	1,694
				S	χ				1,753
				T	χ				1,979
5.5		√	200	R	χ	2	2.2E-5s/2E-6s	50	-1,124
				S	χ				-1,12
				T	χ				-0,853
9.8		√	200	R	χ	2	1.2E-5s/5E-6s	50	-1,588
				S	χ				-1,352
				T	√				-0,313
70		√	50	R	√	13	1.2E-5s/5E-6s	1ms	-0,253
				S	χ				-1,465
				T	χ				-2,042

TFR: Tower footing resistance

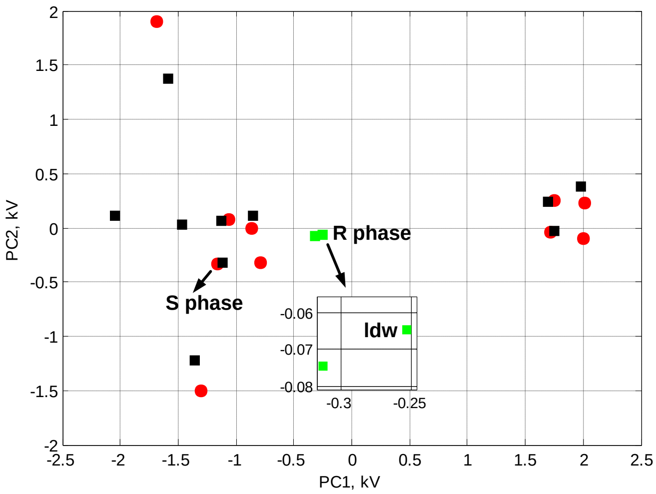


Fig.4: Insulator voltage projected on the first and second PCs.

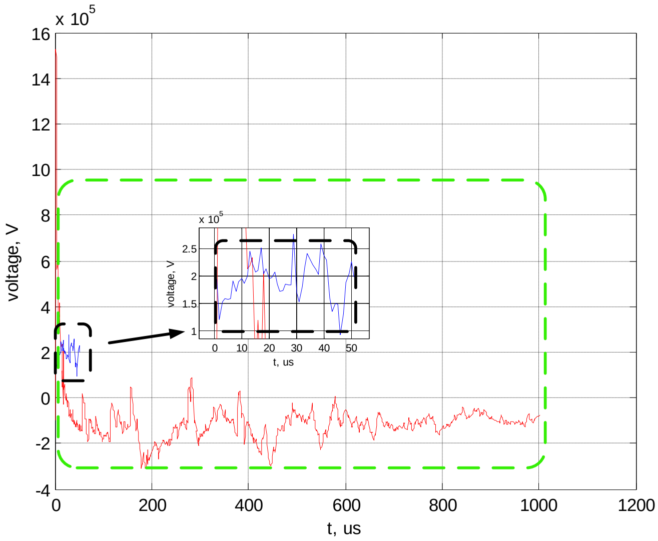


Fig.5: Insulator voltage based on the window size.

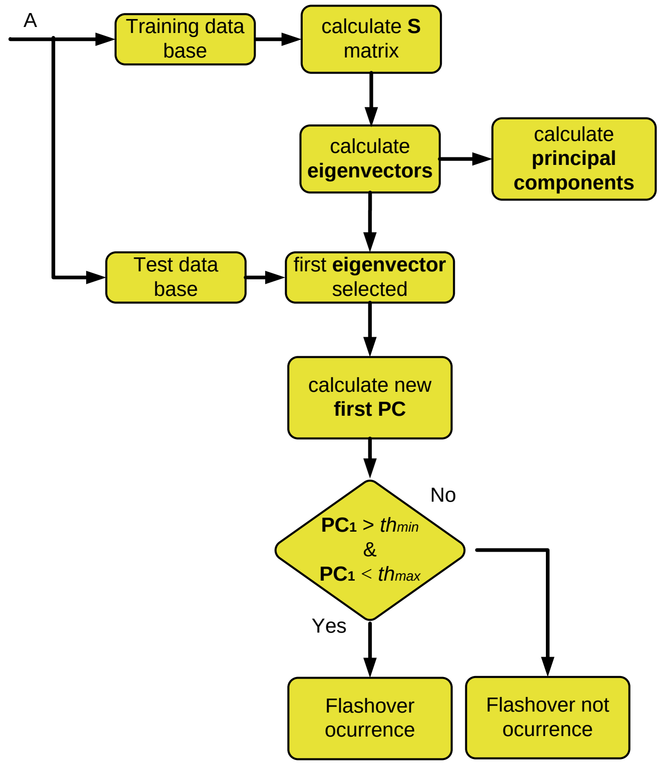


Fig.6: Flowchart

Conclusion and contributions

In this work, a function corresponding to an eigenvector is extracted. This eigenvector is used in order to determine if on other insulators, a flashover is produced. Therefore, an automatic process can be developed.

The detection algorithm performance is tested with different features of lightning stroke; even their performance is immune to different data window size, which can be adapted to the algorithm using interpolation or aliasing.

Due to the potential of the detection algorithm, this work can be employed to analyze other elements, where specific conditions must be considered.

Acknowledgments

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