

Monitoring Leakage Current Waveforms in the Field

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Abstract— The performance of outdoor insulation is correlated to the interaction of the environment with the material surface. The main problem concerning outdoor insulation, which leads to a number of flashovers worldwide, is the pollution phenomenon, which is rather intense in areas located near the sea. As the pollution phenomenon evolves, electrical activity is observed on the insulators' surface. Leakage current monitoring is commonly employed in order to investigate surface activity. In this paper, a review of the obtained experienced in field leakage current waveform monitoring is presented. The measuring site is the 150kV Transmission Substation of Linoperamata, located in Crete. Typical waveform shapes and their correlation to surface activity and conditions are illustrated. World experience is taken under consideration and comparisons are made. In addition, since most of the literature refers to laboratory condition, recorded data is also investigated in order to identify not mentioned before field related issues

Index Terms— field; insulator; leakage current; noise; waveform; monitoring; RTV;

I. INTRODUCTION

The performance of outdoor insulation is strongly correlated to the interaction of the environment with the material surface. The main problem concerning outdoor insulation, which leads to a number of flashovers worldwide, is the pollution phenomenon, which is rather intense in areas located near the sea. At such sites, porcelain insulators have to be washed regularly to avoid flashover which is an expensive and time-consuming process. Composite insulators, employing silicone rubber (SIR), are used as an alternative to ceramic insulators. When existing porcelain insulation can not be replaced (due to financial or other reasons) with composite, then polymer coatings are employed. In the case of the 150kV Transmission Substation of Linoperamata located in Heraklion, right next to the sea coast, a large project that started in 1996 issued the application of Room Temperature Vulcanized Silicone Rubber (RTV SIR) coating on HV insulators. Gradually 100% of the substation's porcelain insulators were coated [1].

Leakage current (LC) measurements are widely employed in order to monitor surface activity and thus monitor pollution and insulator performance. The main advantage of this method is that it can be applied on all insulator types, under real field conditions with the installations live. However,

research worldwide is mostly done, for obvious reasons, in the laboratory with the use of artificial pollution methods. In the lab, insulators can be stressed under various applied voltages and pollution severities, until flashover occurs. Such experiments provide several conclusions for the surface activity and the resulting LC towards the flashover, knowledge that can be used in order to offer an alarm tool to be used on field LC measurements. However, conclusions regarding the insulators' performance do not safely correlate with field performance since performance on the field, especially in the case of polymer insulators, is highly connected with local conditions. Field measurements are most suitable for determining LC criteria and are certainly required in order to use those criteria to monitor insulators on the field

In this paper, a review of the obtained experienced in field leakage current waveform monitoring is presented and correlated with world experience. Typical waveforms and their correlation to surface activity and condition are illustrated. In addition, since most of the literature refers to laboratory condition, recorded data is also investigated in order to identify not mentioned before field related issues.

II. SHAPE OF LEAKAGE CURRENT WAVEFORMS

Researchers have recorded several types of LC waveforms that correspond to different stages of activity. At the very initial stages current is capacitive and sinusoid [4,10,17] but has extremely low amplitude which is why this stage tends to be neglected. The basic discrete stages of activity consists of resistive sinusoid waveforms due to the presence of a conductive film on the insulator surface [4,6,7,15-17,20], distorted sinusoid waveforms as an intermediate stage [4,6,7,10,11,16-18] and dry band arcing that causes a time lag of current onset [1,3,5-7,9,11-13,15,16,19,20,21]. Similar waveforms have been recorded in the case of tracking tests [2,7,14]. Pulses due to local discharges are often superposed on waveforms at the maximum absolute value of half cycles [3,11,12,15,16,17]. Furthermore different types of activity can coexist in the same waveform on different cycles [5-9,17]. The behavior of discharges such as occurrence, elongation and extinction varies with wet conditions of contamination and applied stress. Furthermore different various pollutants present on insulator surface can lead to different distortions [18]. Duration and extend of each phenomenon can be used to categorize waveforms [3,6-8,11,16]. Even assigning each half cycle to different activity has been proposed [15].

III. VALUES USUALLY EXTRACTED FROM LC WAVEFORMS

Different approaches have been made by several researchers in order to extract a value from LC waveforms that would be

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representative of surface activity. Ugur et al [2] employed FFT on LC waveforms and calculated 60 components (from 20 to 1200 kHz) which were fed to a properly trained Neural Network that identified four types of waveforms. They also calculated the number of oscillations near each top in order to identify tracking. Sato et al [3] used the Auto Regressive method to calculate the Power Spectra. Fernando and Gubanski [4] recorded the time variation of LC and the frequency content, especially the 3rd and 5th harmonic content. Amarth et al [5,9] used level crossing analysis and introduced the mean crossing rate and time spent above high thresholds as performance measures. Suda [6,16] used the peak LC value and calculated the power spectra and especially the odd-order harmonic's component. Jeong-Ho Kim et al [7] measured peak and average values on both positive and negative cycles, cumulative charge, odd-order harmonic's content and also the number of LC pulses that exceed certain thresholds. Devendranath et al [8] measured peak value, number of peaks entering different ranges, cumulative charge, average value of LC and maxima of peak values. Lopes et al [10] used the average LC value in order to correlate it with PD measurements. Ayman H. El-Hag et al [11] calculated the average fundamental component, the 3rd 5th and 7th harmonic component and noted that large LC peak currents were recorded whether dry band occurred or not. Masahisa Otsubo et al [12] calculated frequency content, differential value and averaged differential value and used them to calculate total cumulative charge, conductive cumulative charge, charge due to dry band arcing and charge due to partial discharge. Subba Reddy and Nagabhushana [13] calculated voltage and current peaks and instantaneous voltage and current values per half cycle. Sarathi and Chandrasekar [14] employed STD_MRA analysis in order to extract patterns from LC waveforms. Kumagai and Yoshimura [15] calculated the onset time, the distortion level and the cumulative charge. Metwally et al [17] measured the V-I curves and characteristics. Waluyo et al [18] measured LC waveforms and their frequency and power spectrum. Ayman H. El-Hag et al [20] used prior measurements of LC such as initial value and slope for the first half hour of stress in order to predict its value at the end of the early aging period, using a Neural Network. They used an absolute value of the derivative of the LC to determine the early aging period. Du et al [21] used recurrent plot analysis and wavelet analysis to extract graphical patterns from LC waveforms.

However, it is not yet possible to define an extracted value that can be fully representative of the waveform shape and/or surface activity. In addition, research has been targeted on waveforms that are portraying actual electrical activity, and the impact of field noise has not yet been evaluated.

IV. EXPERIMENTAL SET UP

The measurement of leakage current is possible by inserting in the LC path a collection ring and a Hall. The Hall sensor is selected because it provides the easiest installation, the necessary bandwidth, remarkably low impedance and galvanic isolation of the electronic system from the HV side. The acquired data are transmitted to a central data acquisition system (DAS); sampling is performed continuously and simultaneously for all insulators, at a rate of 2 kHz and resolution of 12bit. The waveform portraying

the highest LC peak value in a user-defined time window is recorded. Each waveform recorded has duration of 480ms. The measuring system is shown in Fig. 1. The waveforms investigated and presented in this paper are recorded on 150kV porcelain, composite and RTV SIR coated post insulators.

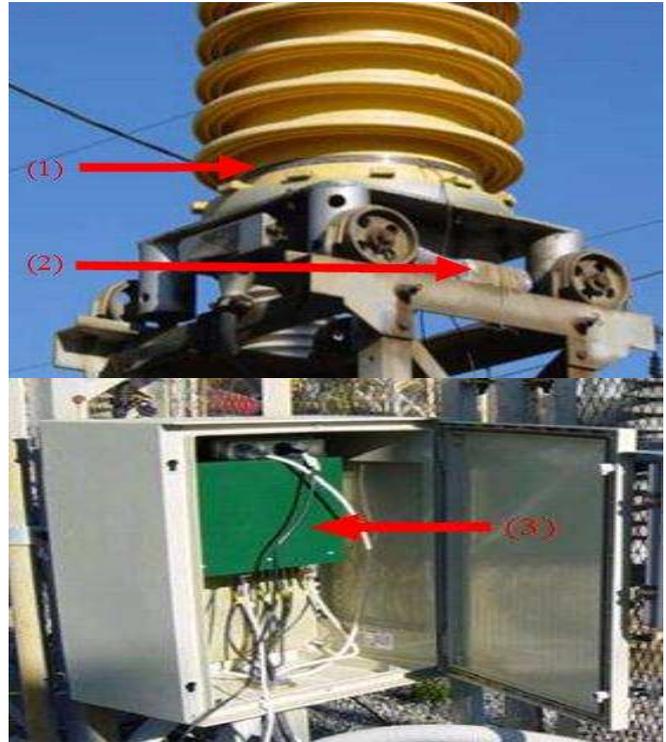


Fig. 1. The measuring system: 1.collection ring 2.Hall sensor 3. the DAS

V. REVIEW OF FIELD LC WAVEFORMS

A. Sinusoid Waveforms

Most of the sinusoid waveforms recorded, portrayed small amplitude as the one shown in Fig. 2A. However the amplitude range varies due to its dependence on the electric resistance of the conductive film on the insulator's surface. Furthermore the film's conductivity can change gradually or instantaneously which will reflect to recorded waveforms as the ones shown in Fig. 2B and Fig. 2C. This is probably the first time that this fact has been recorded and needs to be considered, especially when differential values of current are calculated in order to detect arcing as in [12].

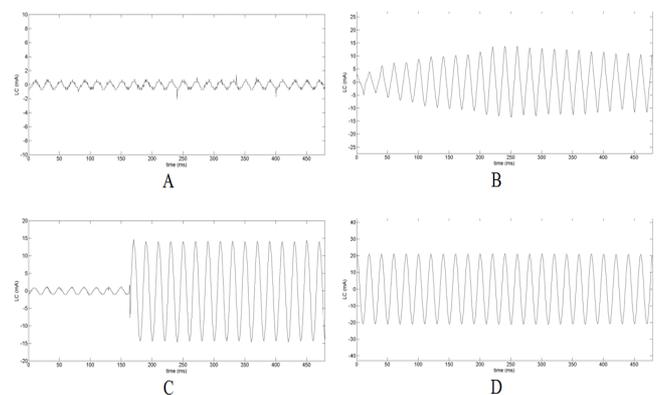


Fig. 2. A: sinusoid waveform, B: sinusoid waveform portraying a gradual conductivity increase, C: sinusoid waveform portraying a rapid conductivity increase D : the recorded sinusoid waveform with the largest amplitude

Finally it has to be mentioned that sinusoid waveforms of amplitude much higher than usually reported [3,4,5,6,9,11,15,16,20] are recorded, due to the heavy pollution and the high voltage stress applied. Waveforms with amplitude that even reaches 20mA as the one shown in Fig. 2D have been recorded. Sinusoid waveforms of similar large amplitude have also been recorded under similar conditions [11,17].

B. Distorted Sinusoid Waveforms

A large variety of distorted sinusoid waveforms have been recorded as shown in Fig. 3A-3D.

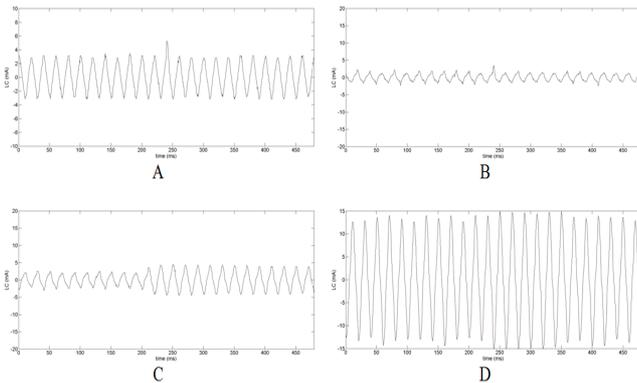


Fig. 3. A-B: distorted sinusoids, C: distorted sinusoid portraying a gradual conductivity increase, D : distorted sinusoid portraying large amplitude

No distinct correlation could be established between waveform amplitude and type of distortion. It should be noted that the presence of different pollutants on the insulator surface has been reported to cause different type of distortions [18]. Rapid transition from different distortion types and amplitudes has been recorded, as shown in Fig. 3C. Distorted waveforms of exceptional large amplitude have also been recorded as the one shown in Fig. 3D.

C. Dry band arcing and corona discharges

Two main types of waveforms have been recorded. The first type is intense dry band arcing that is sustained for more than one cycle, giving a symmetrical shape to the waveform as shown in Fig. 4A-4F.

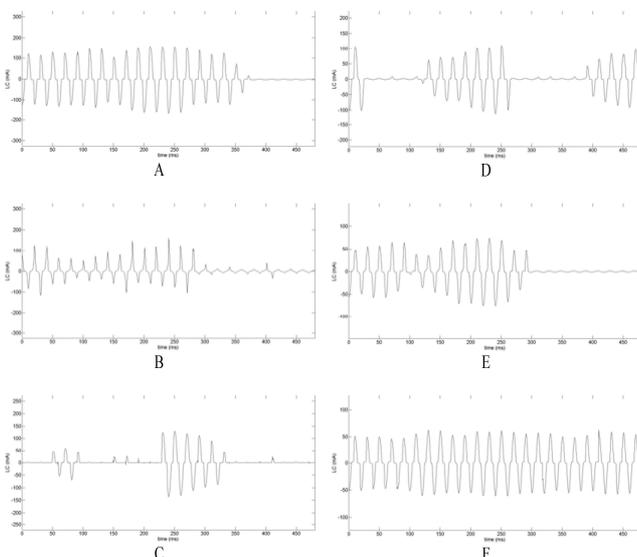


Fig. 4. Waveforms portraying intense dry band arcing

The amplitude and the duration of each arc vary. The maximum amplitude recorded on porcelain insulators was 159mA (Fig. 4A), on RTV SIR coated insulators was 139mA (Fig. 4B) and on composite insulators was 133mA (Fig. 4C). No flashover was recorded to any of the Substation's insulators and while the porcelain ones were washed, no action was taken towards the coated and composite ones. It should be mentioned that the economic profit is rather significant since the cost of one year washing (and the necessary use of Gas Turbines instead of Base Units) for the Linoperamata Substation was about the same as the cost of the RTV application, and the coating has lasted over 10 years [23].

It should be noted that arcs can be distinct (Fig. 4C and Fig. 4D) or consequent (Fig. 4E). Arcs can extinct gradually (Fig. 4A) or rapidly (Fig. 4D), and also ignite gradually (Fig. 4D) or rapidly (Fig. 4C). Finally arc duration can exceed the length of the waveform (Fig. 4F).

The second type of waveforms is more complex and involves local discharges. Water droplets on insulator surfaces elongate under electric stress and corona discharges may appear from and between the droplets causing current pulses [3-5,10-12,14,15,17,19]. Also, as the arc becomes more intense, the current is reported to be modified to a train of pulses [5,7,9,11,17]. Pollution and precipitation is an added cause for large pulses. It is reported [3] that the deposition of high-salt density fog to the contamination surface decreases the resistance rapidly resulting in the increase of LC with strong discharges. The large current provides excessive extend of dry band and prevent successive discharges from occurring. On the other hand clean fog doesn't decrease the surface resistance rapidly, resulting in the gradual development of dry bands. As a result discharges occur successively for several half waves. Further, discharges can be consequent. The duration and amplitude of each pulse varies. Pulses can be negative or positive, isolated or consequent, their amplitude can be significantly larger than the rest of the waveform or not. Furthermore, dry band arcing duration (number of half cycles) and amplitude varies. The resistance of each dry band is different and so the voltage needed to ignite arcs varies which means that arc's pulses also varies on duration. Dry band arcing and local discharges can coexist on insulator's surface and therefore be portrayed (superposed) on LC waveforms. It should be noted that arcing and/or discharges may occur on various amplitudes while a (distorted) sinusoid current is flowing on insulators surface. When the amplitude of the discharge is high, the sinusoid part seems null but when the discharge amplitude is smaller, both components becomes noticeable on LC waveforms. Distinction of the two activities cannot always be safely done from the LC waveform.

Various measurements portraying such waveforms are portrayed in Fig. 5. The large variety of forms and amplitudes should be underlined. Different types frequently coexist in the same waveform. It should also be stated that the smallest recorded discharge has amplitude of 4.95mA which is smaller than the amplitude recorded for several sinusoids and distorted sinusoids, as mentioned in paragraphs V-A and V-B. It becomes evident that the LC peak value can not be used in order to identify the type of surface activity. Further, several extracted amounts, some

described in paragraph III, can yield similar results for different waveform shapes.

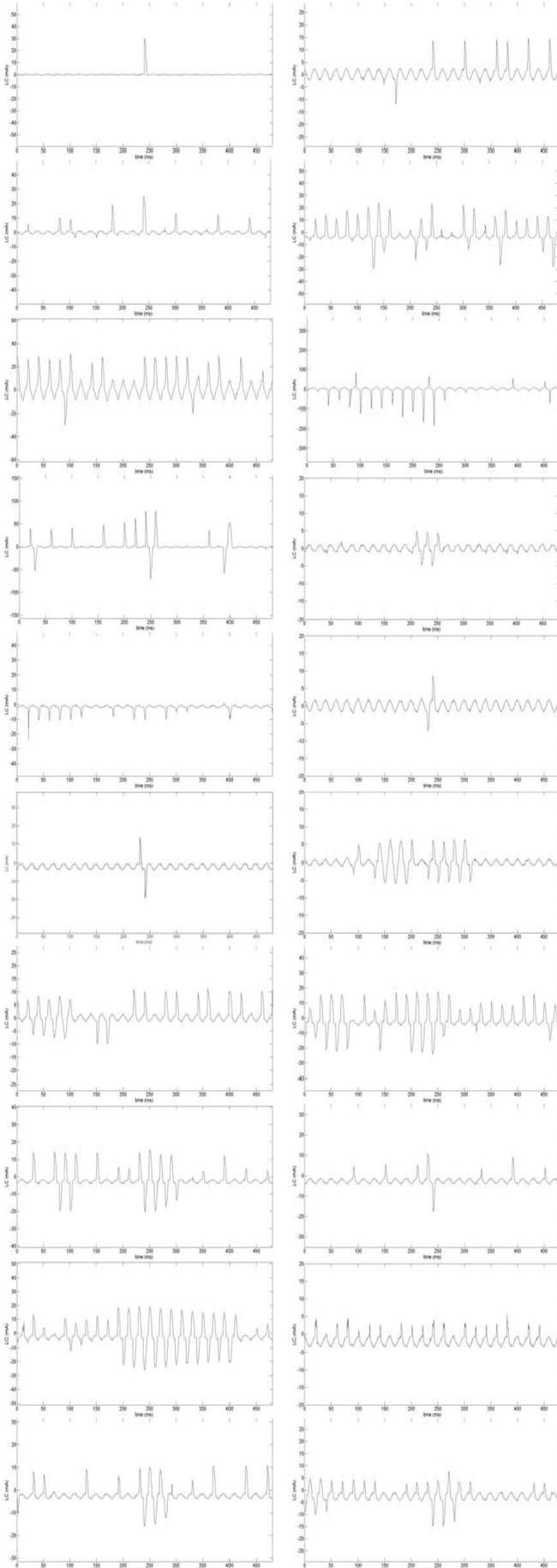


Fig. 5. Waveforms portraying dry band arcing and/or corona discharges

VI. FIELD NOISE

The noise is a factor of low impact on laboratory measurements due to the highly controllable conditions and is rarely taken under consideration. Suda [6] evaluated the frequency characteristics of background noise, while Amarth et al [5] just stated minor distortion of LC waveforms due to noise generated by radio interference and other sources. In order to cope with the noise problem in the lab, Kumagai [15] proposed a negligible threshold of 0,05mA.

It should be noted that in the case of field measurements the noise factor becomes significant. In the case of a severe marine environment, as the one in the considered test site, a negligible threshold of 1mA (significantly higher than the 0.05mA proposed for lab measurements) has been proposed by Vosloo et al [22].

The monitored insulators and the measuring system is located on the field, subjected to the weather, high voltage stress and several events happening during the operation of a HV substation (switching of heavy loads, opening and closing of switches etc). Dysfunctions are bound to happen during long term monitoring and exaggerated noise is expected to be recorded. Furthermore, since the monitored insulators are part of the grid, access to the measuring system is limited and sensor or cable faults can not be immediately addressed. Examination of the recorded waveforms made possible the identification of three different types of noise: Typical Noise, Dysfunction Generated Noise and Single Point Noise.

A. Typical Noise Waveforms

Typical noise (noise which is always present) consists of random amount of minor peaks of also random but low amplitude, as shown in Fig. 6.

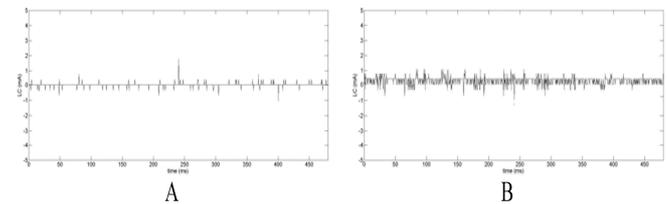


Fig. 6. Typical Noise of low (A) and higher (B) intensity

It should be noted that the field LC measurement system is targeted towards recording significant surface activity. Therefore, its range of accuracy includes measurements of relatively high amplitude (over 0.5~1mA). Further, the system is designed to function unattended for long periods of time, since it is situated in an open air 150kV HV substation, monitoring insulators that are live and part of the grid. In order to cope with the memory problem, and due to the digitization process, sinusoids of very low amplitude (lower than 0.1752mA) are portrayed as squares, as shown in Fig. 7.

On the other hand, typical noise consists of spikes that exhibit amplitude in the area of 0.35mA. That means that measurements in the typical noise area are usually incoherent and, further, that supplemental devices have to be used in order to investigate extremely low activity. This is the reason why corona discharges of low amplitude and capacitive sinusoid current can not be investigated with the available system. The effect of typical noise and the inability to investigate extremely small sinusoids are portrayed in Fig. 8.

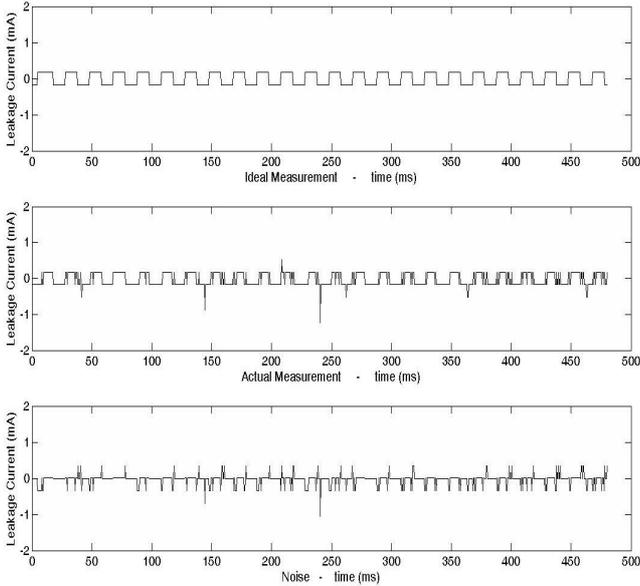


Fig. 8. A LC measurement of extremely low amplitude. The actual measurement, the extracted noise and the ideal (noise-free) measurement

B. Dysfunction Generated Noise

A large amount of waveforms generated by dysfunctions has been recorded and some typical waveforms are shown in Fig. 7.

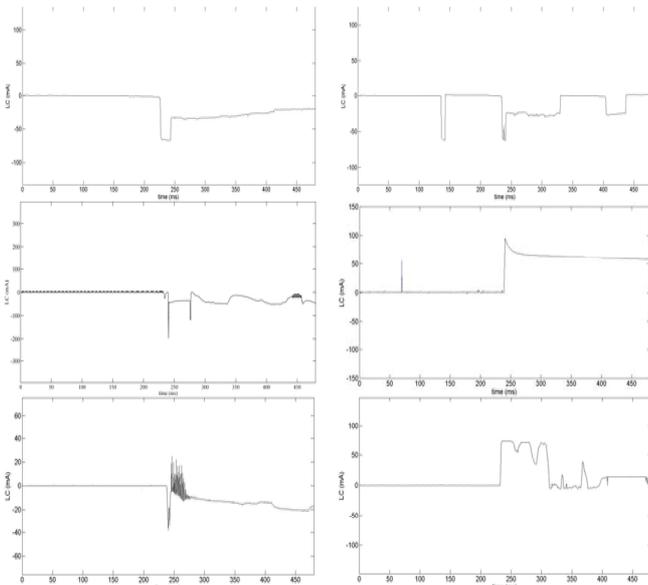


Fig. 7. Dysfunction Generated Noise

Their origin cannot be strictly defined, since monitored insulators are part of the grid and any crucial event happening on the grid could lead temporarily to a chaotic LC measurement as the ones shown in Fig. 7. It should be noted that two sensor faults originated a number of dysfunction generated waveforms. The sensors were replaced shortly after their damage. However, dysfunction generated waveforms have been recorded on all channels, even those that didn't suffer from a sensor fault, and during different time periods. Usually, shortly after the recording of a dysfunction generated waveform, normal waveforms are recorded, frequently at the very next time window. That means that dysfunction generated waveforms should be expected to be recorded in a grid integrated HV test site,

even if the measurement apparatus is fault free. It is evident that such waveforms can lead to erroneous results for any value extracted from the waveform, regardless the method used.

C. Single Point Noise

Single point noise results to a single point measurement recorded far from the rest of the waveform. Such single points are found superimposed on all types of waveforms (Fig. 8A-8D), even those portraying typical noise (Fig. 8A) and dry band arcing (Fig. 8D). It has to be noted that their time allocation is random, which means that they do not always follow the current trend as shown in Fig. 8B and Fig. 8C. Such noise generated peaks can lead to the extraction of erroneous values that are related to the LC peak value, the slope of the waveform and the differential value of the current.

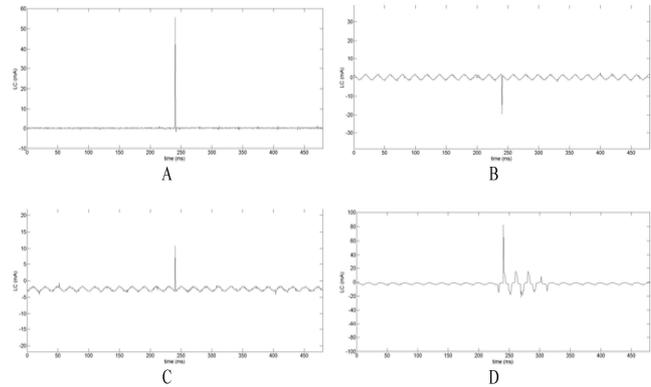


Fig. 8. Single Point Noise

VII. DISCUSSION

Field measurements are far more complex than the ones carried out in a lab. Besides the obvious issues of limited access to the measuring system, the magnitude of voltage stress (150kV) and the chaotic environmental influence, several issues emerge that are relevant with the measurement finally recorded. Three different types of noise are identified that can lead to erroneous conclusions if an extracted value, instead of the actual waveform, is taken under consideration. The need of a pre-recording stage capable of minimizing (or even totally removing) the impact of noise emerges as a necessity.

However, field measurements also revealed not previously reported issues concerning the shape of activity portraying waveforms that are recorded on the field. It should be mentioned that erroneous results can be concluded, if several methods that are effective in the lab are applied in the case of field measurements, in order to extract representative values from LC waveforms. This conclusion emphasizes the strong correlation of surface activity with local conditions and hints that the measuring system should be designed taking under consideration field conditions.

Field measurements prove highly suitable for monitoring the performance of insulators. Therefore, besides the monitoring in Linoperamata Substation, the Greek Public Power Corporation (PPC) has constructed an Open Air High Voltage Insulators Test Station. The Test Station is located right next to the coast, in the area of the Linoperamata Substation, in order to suffer from the maximum pollution possible. As research continues, different types of insulators

will be tested, in the Test Station, and stressed until flashover occurs, a possibility not available for insulators that are part of the grid.

VIII. CONCLUSION

Substation maintenance is an issue for every utility worldwide. One of the main problems, which concerns outdoor insulation, is the accumulation of contaminants on the insulation's surface. Especially in areas located near the sea due to the marine influence. In Crete, the phenomenon is rather intense due to the island's coastal development. To cope with the problem, the Greek Public Power Company (P.P.C.) issued a project that led to the extended use of composite insulators and RTV coatings on porcelain insulators.

The leakage current monitoring method is employed in order to monitor the insulations' performance during the project. A measuring system is installed at the 150kV Transmission Substation of Linoperamata which is located right next to the coast, in Herakleion, Crete. The field LC measuring system monitors several porcelain, composite and RTV SIR coated post insulators that are part of the grid, for a period over 10 years.

Field measurements are essential in order to obtain an image of the actual activity, and the insulation performance, experienced in the field. A review of the gathered experience on field leakage current waveform monitoring is presented in this paper. Several methods employed worldwide, in order to extract representative values from the LC waveform are briefly presented and field related issues correlated with such methods are mentioned.

Activity portraying waveforms are presented and correlated to basic stages of surface activity. Certain waveform characteristics that are related with the nature of field measurements are recorded and presented probably for the first time. The issue of field related noise is also investigated and three different types of noise are identified and presented.

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