Recording and Managing Field Leakage Current Waveforms in Crete

Installation, Measurement, Software Development and Signal Processing

D. Pylarinos, K. Siderakis, E. Thalassinakis, I. Vitellas, E. Pyrgioti

Abstract-- Leakage current (LC) monitoring is commonly used to monitor and investigate the performance of insulators and the experienced electrical activity. Waveform shape has been well correlated with surface activity and conditions. Field measurements are most suitable since they offer an exact view of activity under field conditions. The Greek Public Power Corporation (PPC) has issued a large project to battle marine pollution in the island of Crete, which is rather severe due to coastal development. Polymer insulators and coatings have been widely employed. Specially designed LC measuring systems have been installed in HV Substations. In addition, an insulator test station has been constructed. In this paper, the obtained experience in field LC monitoring is investigated focused on monitoring and managing LC waveforms. A review of the installation, measurements, developed software and signal processing techniques and results are presented.

Index Terms-- **data processing, Fourier transforms, insulators, leakage current, measurement, neural networks, noise, software, substations, wavelet transforms.**

I. Introduction

Leakage current (LC) monitoring is a widely employed tool, used to monitor and investigate surface activity and condition of high voltage insulators. The technique can be applied on all insulator types and materials and therefore leakage current measurements are often employed in lab and field testing in order to investigate and compare the performance of different insulators. Surface activity is strongly influenced by local conditions (environmental, weather, pollution etc.) with pollution, especially marine and industrial, playing an important role [1].

Polymer materials are commonly used to suppress surface activity, due to their hydrophobic properties [2]-[5]. The Greek Public Power Corporation (PPC) experiences significant pollution problems in the island of Crete due to the network's coastal development and has employed several techniques to cope with the problem [3]. In case of lines a wide application of composite SIR insulators has been issued. In case of substations, PPC employed the use of RTV SIR coatings in order to cover ceramic insulators that could not be replaced [3]. Coated insulators portray hydrophobic behaviour but their performance through aging and their overall life expectancy are issues that require investigation [3].

In order to monitor the insulators' performance, PPC installed specially designed commercially available LC monitoring systems in two HV substations in 2001. In addition, PPC recently issued the construction of an Open Air Insulator Test Station to further test insulators. In this paper, the obtained experienced from field leakage current monitoring through the years is investigated, focused on leakage current waveforms.

II. Measuring System

In order to perform leakage current measurements, a collection ring is appropriately installed at the bottom side of each monitored insulator and the current is driven through a Hall sensor. The acquired from the sensor data are then transmitted to a commercially available Data Acquisition System (DAS). Sampling is performed continuously and simultaneously for all monitored insulators, at a rate of 2 kHz and resolution of 12bit. Extraction of data is done through connection of the DAS with a computer. PPC purchased and installed two identical systems with each one being able to monitor nine insulators. The monitored insulators are 150 kV porcelain, SIR and porcelain covered with RTV SIR coating post insulators. Pictures of the copper ring, hall sensor and DAS during field operation in are shown in Fig. 1.

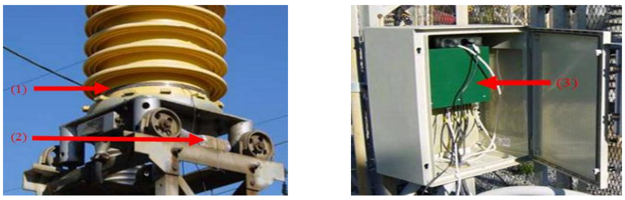

Fig. 1. The measuring system: 1.collection ring 2.Hall sensor 3. the DAS

III. Measuring Sites

Initially one device was installed in Heraklion II substation and one in Linoperamata substation. Later both devices were installed in the Linoperamata substation. With the construction of the Open Air Insulator Test Station, the devices were re-

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located in the Test Station.

A. *Heraklion II Substation*

Heraklion II Substation is located to the east of the city of Heraklion as shown in Fig. 2. Its distance from the coast is about 2 km and is located between the center and the industrial area of the city. Heraklion II suffers mainly from industrial pollution. Measurements in Heraklion II were conducted on porcelain and RTV SIR coated porcelain post insulators.

B. *Linoperamata Substation*

Linoperamata Substation is located west of the city of Heraklion, right next to the sea coast as illustrated in Fig. 2. The Substation suffers from intense marine pollution. Porcelain insulators needed to be washed two and sometimes three times during each summer in order to avoid flashovers [3]. In 1998 PPC started the application of RTV SIR coatings and today, 100% of the ceramic insulators installed in Linoperamata Substation is covered with RTV SIR coating. During the first period of monitoring, using a dial-up connection or entering the high voltage site with a laptop was required in order to extract data from the DAS. A number of problems emerged because of this, since entering the site was prohibited during rain, remote extraction was rather slow and the installed MODEM experienced various problems due to its installation in the field. To partially overcome the problems and enhance security, an underground cable was used to connect one of the devices with a PC that was stationed indoors. Further, the MODEM was connected to the PC and could offer fault-free remote access from any point, using specialized communication software. Various insulators were monitored in the Linoperamata Substation. All insulators were post 150kV insulators but their material varied (porcelain, composite, RTV SIR coated porcelain). An illustration of the connection of the DAS with the indoor PC and the two different sets that have been monitored from this DAS during its operation are portrayed in Fig. 3.

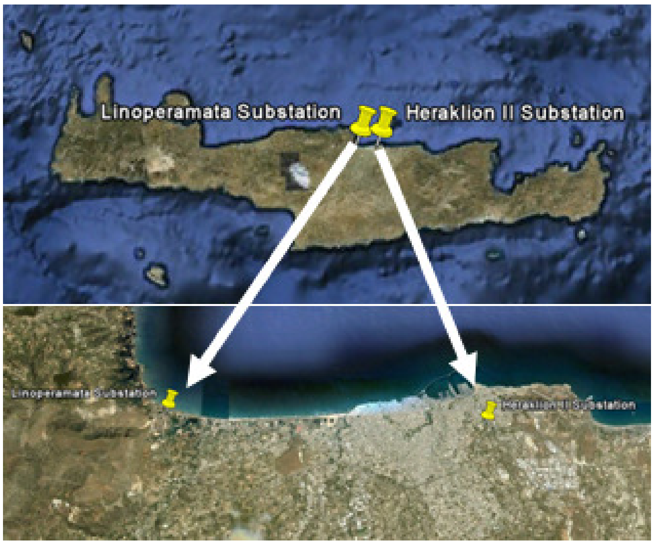
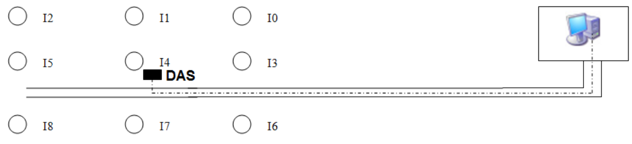


Fig. 2. Location of Linoperamata & Heraklion II substations



Channel	Insulator
0	SIR
1	SIR
2	SIR
3	Porcelain RTV SIR coated
4	Porcelain RTV SIR coated
5	Porcelain RTV SIR coated
6	Porcelain RTV SIR coated
7	Porcelain RTV SIR coated
8	Porcelain RTV SIR coated

A

Channel	Insulator
0	SIR
1	SIR
2	SIR
3	Porcelain RTV SIR coated (old)
4	Porcelain RTV SIR coated & washed with high pressure water
5	Porcelain RTV SIR coated & washed with high pressure water & recoated
6	Porcelain RTV SIR coated (old)
7	Porcelain RTV SIR coated & washed with high pressure water
8	Porcelain RTV coated (new)

B

Fig. 3. A schematic representation of the underground connection of a DAS with a PC and two different insulator sets that had been monitored from this DAS

C. *High Voltage Open Air Insulators Test Station*

The High Voltage Open Air Insulators Test Station is constructed in the area of the Linoperamata Substation, in the closest possible distance from the coast, as shown in Fig. 4. In the Test Station, post and suspension insulators (150kV and 20 kV) will be tested. The available devices will be employed in the substation in addition to other measuring devices.

Fig. 4. A view of the Linoperamata Substation

A schematic representation of the part of the test station which is already active and a picture taken during the construction are illustrated in Fig. 5.

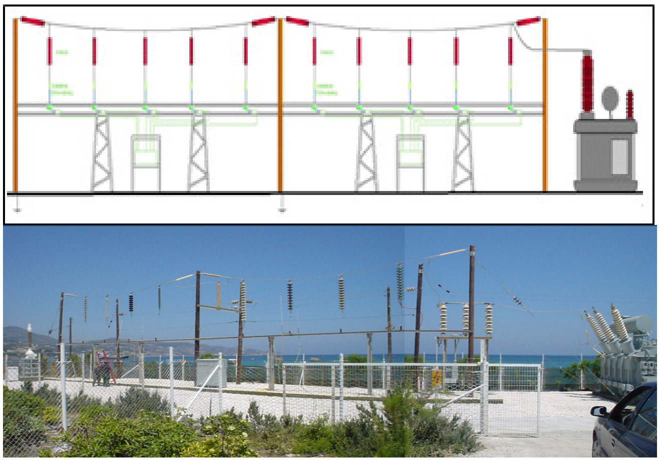


Fig. 5. A schematic representation and a picture from part of the test station

IV. Custom Made Software

The system and the provided software offered a large variety of functions related to statistical amounts that led research to significant results [3], [5]. However, its design was not oriented towards waveform monitoring. It only allowed intermittently recording of waveforms and only a one by one viewing of recorded waveforms. It also provided the ability to extract the measured waveforms to various CSV files. As the amount of recorded waveforms increased over the years of monitoring, developing custom made software in order to further investigate leakage current waveforms became a necessity.

The software's goals were to perform these basic functions:

1. conversion of multiple CSV files, to a single MAT file representative of each insulator, that would allow further processing. All CSV files corresponding to different insulators should be converted sequentially with no user action required after the initial settings.
2. navigation through LC waveforms, contained in a MAT file, in groups of waveforms of a user-defined number.
3. automate the extraction of the various groups of waveforms to different image files with user-defined names and dpi analysis
4. offer a user-friendly Graphical User Interface (GUI) which would allow ease of use even by non-specialized personnel.
5. stand-alone capability of files and ease of execution desirably by providing EXE files.

The custom-made software was developed using MATLAB. More information about the software can be found in [6]. To achieve the first goal, "Leakage Current Waveform File Converter" was developed. To achieve goals 2 and 3, "Leakage Current Waveform Viewer" was developed. Both softwares are equipped with a user-friendly GUI as shown in Fig. 6 and are provided in stand-alone executable formats (EXE). A significant save of space and a much more compact data appearance was achieved file-wise as shown in Table I.

TABLE I. Results Of Using Leakage Current Waveform File Converter

OLCA DEVICE	1	2	Sum
Number of CSV files	225	252	477
Size of CSV files	350.6 MB	2.57 GB	2.92 GB
Number of MAT files	9	9	18
Size of MAT files	3.85 MB	28.9 MB	32.75 MB
Total number of waveforms	8487	67377	75864

Further processing of recorded leakage current waveforms allowed the employment of advanced signal analysis techniques. As managing and manipulating of recorded waveforms was made possible, the significant impact of field related noise emerged. In order to evaluate noise, the nature of surface activity and world literature were taken into account.

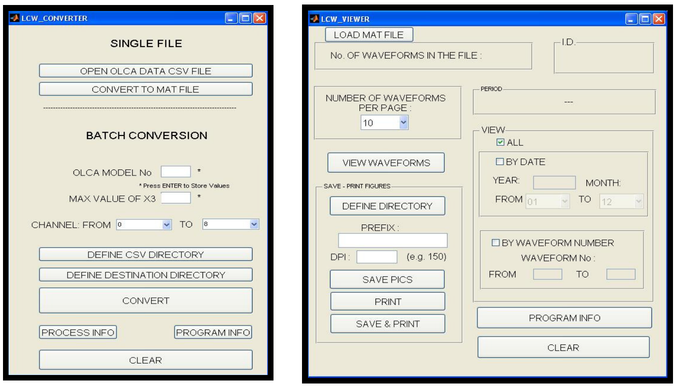


Fig. 6. The GUI of the two custom made softwares

V. Surface Activity & Leakage Current

As surface activity advances, the leakage current waveform reflects its progress. The basic stages of activity [4, 7] are described as follows: leakage current initially has a pure sinusoid form and small amplitude. As activity advances, its shape becomes distorted. The flow of leakage current heats and dries up the surface. Drying is always non-uniform and dry areas of higher resistance are formed, called dry bands. The voltage distribution along the insulator is altered and increased stress is observed along the dry bands. Dry band arcs appear which, under favorable conditions, may propagate and ultimately lead to a complete flashover of the insulator. The presence of the arc in the current path is indicated from the on-set time delay of LC waveform in every half-cycle, which causes a knee-like shape. This delay is attributed to the larger voltage required for the air break-down. Typical waveform shapes are illustrated in Fig. 7.

VI. Field Noise

Three different types of noise have been identified after the examination of the recorded waveforms: typical noise, dysfunction generated noise and single point noise. Typical noise consists of a random amount of minor peaks of random but low amplitude, as shown in Fig. 8A and Fig. 8B. Single point noise describes the recording of a single point far from the rest of the waveform. Such single points are found superimposed on all types of waveforms even those portraying typical noise (Fig. 8C) and their time allocation is random, since they do not follow the current trend (Fig. 8D and Fig. 8E). Temporary dysfunctions lead to chaotic shaped waveforms as the ones shown in Fig. 9.

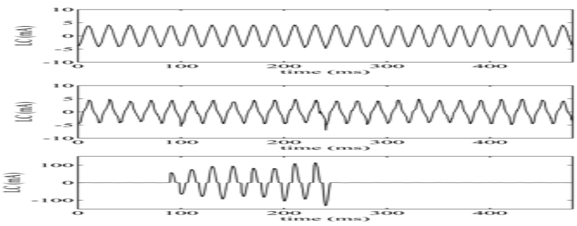


Fig. 7. Typical LC Waveform Shapes: sinuoid, distorted sinuosoid and knee-like shape (arc)

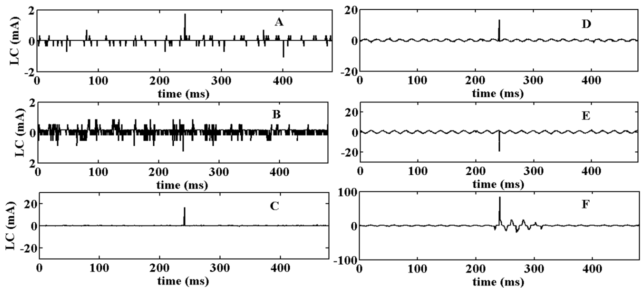


Fig. 8. A-B Typical noise, C-F single point noise

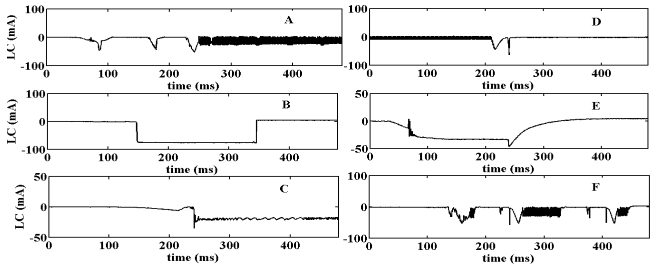


Fig. 9. A-F. Dysfunction generated noise

A large amount of waveforms generated by dysfunctions has been recorded. Their origin cannot be strictly defined, since the monitored insulators in Linoperamata substation are part of the grid and any crucial event happening on the grid could lead to a temporary chaotic LC measurement. It should also be noted that sensor faults occasionally occurred during field monitoring. Faulty sensors were replaced shortly after their damage. However, dysfunction generated waveforms were recorded also on channels that didn't suffer from a sensor fault and during normal conditions periods. It was not unusual for normal waveforms to be recorded right after the recording of a dysfunction generated waveform. Dysfunction generated waveforms could be attributed to several electrical events (switching etc) and should be expected in long term field monitoring, especially in grid integrated sites.

VII. Techniques To Overcome Field Noise And Data Size Problems

Three techniques were employed to investigate the impact of noise [8], [9]: the negligible threshold, maximum and minimum point smoothing and the fundamental frequency criterion. Using the negligible threshold all waveforms that portrayed peak value smaller than a predefined threshold were identified as typical noise. Maximum and minimum point smoothing was employed to isolate and eliminate single point noise while retaining the rest of the waveform. Using this technique, the maximum and minimum value of the waveform are detected and replaced by the neighboring point with the largest absolute value. When using the Fundamental Frequency criterion, the fundamental frequency of each waveform is calculated using the Fourier Transform and if found different that the fundamental voltage frequency (50 Hz), the waveform is discarded as dysfunction originated.

VIII. Results

Investigation showed that the usually proposed negligible threshold value of 1mA was ineffective and a negligible threshold of 2.5mA was proposed [8]. When using such a threshold on the sum of the recorded waveforms the discard percentage exceeded 80% [9]. Investigation of the recorded waveforms showed that the 2.5mA threshold was less than half of the smallest recorded discharge which is illustrated in Fig. 10.

Further, by using Wavelet Multiresolution Analysis (MRA) [10], [11] it was possible to decompose the signal in components of various frequency bands as shown in Table II. By computing the standard deviation of the details lost in every decomposition level, it was then possible to introduce the S_R ratio [8], which could be used similarly to the SNR ratio although neither the exact actual signal nor noise was known. The ratio S_R is given by equation S_R=D1/Dmax , where the standard deviation of the details of level k is denoted as D_k and Dmax is the maximum of all D_k. Using the S_R ratio it was found that relatively clear waveforms were rare under the 2.5mA threshold (less than 3.5% of the discarded waveforms in case of non-ceramic insulators) [8].

Investigation over the threshold showed that single point noise and dysfunction generated noise had a significant impact on all amplitude ranges. Further, each technique is supplementary to the others and combined use of all three discards over 90% of the sum of the recorded waveforms [9]. It should be noted that the majority of the monitored insulators are non-ceramic and only a small number of porcelain insulators are monitored in order to be used as control elements, and that fact has an impact on the percentage of recorded noise, since activity is rarer on non-ceramic insulators.

IX. Automating The Classification Of Field Leakage Current Waveforms

An attempt was made to design an artificial intelligence system that could classify field leakage current waveforms. A small data set of 500 waveforms was employed. MRA was also employed. More details can be found in [11]. A schematic representation of the procedure is shown in Fig. 11. The measured waveform was decomposed in 6 levels using wavelet MRA. The standard deviation of the details in each level was computed and that resulted to a six point vector. The vector was normalized and the normalized six-point vector was used as a fingerprint pattern. The pattern was fed to a properly trained neural network that performed the classification.

TABLE II. Frequency Bands For Different Mra Levels

Decomposition Level	*Approximation*	*Details*
1	0~500 (Hz)	500~1000 (Hz)
2	0~250 (Hz)	250~500 (Hz)
3	0~125 (Hz)	125~250 (Hz)
4	0~62.5 (Hz)	62.5~125 (Hz)
5	0~31.25 (Hz)	31.25~62.5 (Hz)
6	0~15.625 (Hz)	15.625~31.25 (Hz)

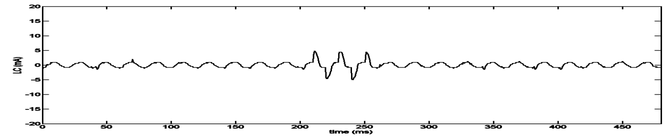


Fig. 10. The smallest recorded discharge

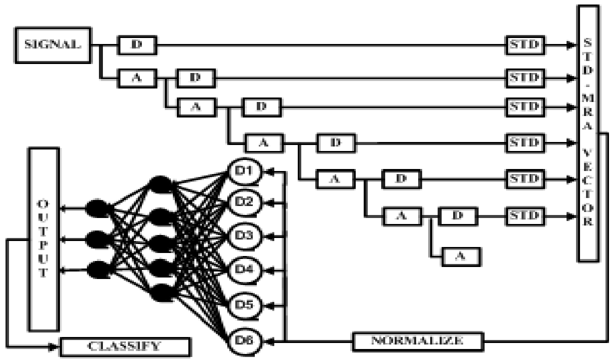


Fig. 11. A schematic representation of the pattern recognition system

Three basic types of waveforms were used in this study (sinusoid, small arc, extended arc). An arc was considered extended when it spanned through the whole waveform. A typical waveform and its corresponding pattern for each type are shown in Fig. 12.

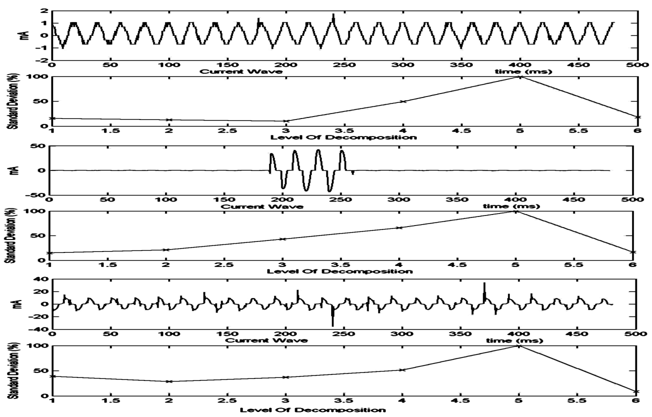


Fig. 12. The three waveform types and their corresponding pattern.

The selection and the design of the neural network was done considering attributes described in [12]-[14] related to simplicity, speed and efficiency. The multilayer Feed Forward network with back propagation learning algorithm was chosen as the network topology. One hidden layer is sufficient in order to identify categories that are not linearly separated but are located in the same area. A 6-5-3 network was employed, with the first layer (input layer) being the 6 point vector. The neural network must identify 3 categories; therefore three output neurons are sufficient. In order to minimize the risk of “trapping” the algorithm around a local minimum, the number of neurons per layer should decrease from the input layer to the output layer. Hence, five neurons were selected for the hidden layer. Each waveform type is correlated to a three-element output vector easily separable from the others. Type A to [1 0 0]’,Type B to [0 1 0]’ and Type C to [0 0 1]’.

The hyperbolic tangent function is chosen for the hidden layer for its speed and efficiency. The Log-Sigmoid function is chosen for the output layer in order to compress the outputs into the [0, 1] domain. The learning algorithm used is the Levenberg-Marquardt due to its speed in the case of medium-sized networks. The train set consists of 4 Type A waveforms, 3 Type B waveforms and 6 Type C. Only 40 waveforms, out of 500, were not discarded as noise in this data set. From the remaining 40, 16 were used as a training set. The system portrayed 100% success and managed to identify correctly all 40 waveforms. It should be noticed that the investigated data set contained only noise and waveforms that could clearly be identified as one of the types shown in Fig. 12. However, further investigation of activity portraying waveforms showed that this is hardly the case in field leakage current waveforms and that a variety of complex waveforms is recorded, and that further categorization is needed.

X. Complexity Of Field Waveforms

Investigation of activity portraying waveforms showed a large variety of shapes, duration and magnitude [4], [16]. Conductivity changes (sudden or gradual) which can be linked with wetting and pollution conditions are pictured in sudden or gradual amplitude changes of the recorded waveforms. In addition, pulses are often superimposed on waveforms’ crest. Orientation, amplitude and frequency of pulses’ appearance vary. Further, although the amplitude of the recorded waveforms generally increases as activity advances, it became evident that an amplitude criterion can not be employed for categorization. For example, in the range of 0~20mA, sinusoids, distorted sinusoids and discharges have been recorded. Further, transition from one activity type to another can be rapid and not always straightforward which can be attributed to the constant changes of the insulators’ surface under field conditions.

Therefore, research is currently focusing on further investigation and classification of field leakage current waveforms using new additional identification criteria [16]. It has been proposed that that the duration of the activity should be used to further categorize waveforms [17]. An additional criterion should be applied to discriminate between e.g. a heavily distorted half-cycle and a discharge portraying half-cycle [16]. Several other techniques and classifiers (e.g. genetic algorithms, Euclidian classifiers) are currently tested in order to provide a more accurate categorization.

Some complex field waveforms are portrayed in Fig. 13. More waveforms can be found in [16].

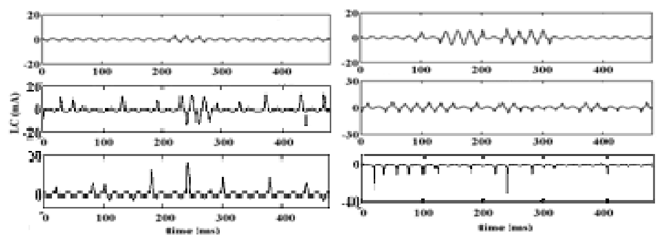


Fig. 13. Examples of complex field leakage current waveforms

XI. Conclusions

Performing leakage current measurements is a well established tool to monitor the performance of insulators. The Greek Public Power Corporation (PPC) has been monitoring leakage current for more than 9 years on post insulators installed in high voltage substations of the Cretan Network. The Cretan Network suffers from severe marine pollution due to coastal development. To cope with the problem, the use of polymer insulators and coatings has been employed. Further, an Open Air Test Station is being constructed, with a part being already operational, to further test post and suspension insulators. Leakage current measurements are mostly performed on composite insulators and porcelain insulators coated with RTV SIR. Measurements on porcelain insulators are also conducted in order to be used as control. A brief review of the obtained experience on recording and managing leakage current waveforms during various stages has been presented in this paper. Installation sites, measurements, developed software and signal processing techniques that have been employed are presented together with results concerning field noise, waveform shapes and pattern extraction and recognition. Results presented in this paper are currently further employed by PPC to enhance research on field leakage current monitoring.

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XIII. Biographies

Dionisios Pylarinos was born in Athens in 1981. He received a Diploma degree in Electrical and Computer Engineering from the University of Patras in 2007. Presently he is with the High Voltage Laboratory of the Department of Electrical and Computer Engineering at the University of Patras. He has worked as a scientific consultant for PPC. His research interests include outdoor insulation, electrical discharges, signal processing and pattern recognition.

Kiriakos Siderakis was born in Heraklion in 1976. He received a Diploma degree in Electrical and Computer Engineering in 2000 and the Ph.D. degree in 2006 from the University of Patras. Presently, he is an Application Professor at the Department of Electrical Engineering, at the Technological Educational Institute of Crete. His research interests include outdoor insulation, electrical discharges, high voltage measurements and high voltage equipment diagnostics and reliability.

Emmanuel Thalassinakis received the Diploma in Electrical and Mechanical Engineering and also the Ph.D. degree from the National Technical University of Athens. After working for the Ministry of the Environment, in 1991 he joined the Public Power Corporation (P.P.C.) where he is now Assistant Director of the Islands Network Operations Department.

Isidoros Vitellas was born in 1954 in Greece. He has a diploma in Electrical Engineering and the Ph.D. degree in the same field. He is currently Director of the Islands Network Operations Department in P.P.C. (Public Power Corporation) Athens, Greece.

Eleftheria Pyrgioti was born in 1958 in Greece. She received her Diploma degree in Electrical Engineering from Patras University in 1981 and the Ph.D. degree from the same University in 1991. She is an assistant professor at the department of Electrical and Computer Engineering at the University of Patras. Her research activity is directed to high voltage, lightning protection, insulation coordination and distributed generation.