Mapping HV Insulators' Pollution in the Mediterranean Island of Crete

D. Pylarinos, K. Siderakis, N. Mavrikakis, E. Thalassinakis

Abstract—**The reliability of High Voltage insulators is rather important for power systems, as they are scattered throughout the network and a single insulator fault may lead to an excessive outage. The performance of outdoor insulators is strongly correlated to local operating conditions with the experienced pollution being a factor of critical importance. Therefore, pollution mapping is essential for providing improved insulator selection, installation and maintenance. The Cretan network provides a rather interesting case study as it suffers from intense marine pollution due to its coastal development and the geographical and environmental conditions. A variety of remedies have been employed over the years to cope with the problem. In this paper, service experience, pollution measurements and geographical and environmental data are considered in order to map the experienced pollution. Overall results and discussion provide a detailed insight on the pollution problem experienced in the island's network..**

***Index Terms*—high voltage, insulator, pollution, ESDD, power network, map, transmission line, marine, island, fault**

I. Introduction

The performance of outdoor insulators is an important issue for power utilities. It is strongly connected with local service conditions which include the distance from pollution sources and the experienced weather [1, 2]. Insulators are scattered throughout the network and therefore are subjected to various environmental conditions. Therefore ideal planning would have to consider all different micro-environments present throughout the network. However, this is highly impractical especially in networks that cover diverse environments and/or large areas. Therefore worst case scenarios are usually followed and previous experience and generalized data are used to assist insulator planning and management [2].

One of the main factors affecting insulators' performance is pollution. Pollutants deposited on the insulators' surface allow the flow of leakage current, which may result to dry bands formation, discharges and possibly flashover [1-2]. The term "pollution" in this case does not just refer to what it usually does (e.g. carbon emissions) but to anything that may be deposited on the insulators' surface and interfere with the insulators' performance (e.g. bird droppings). The sea is considered a primary pollution source as sea salt is carried through large distances and when diluted in water (e.g. rain, humidity etc) results to the formation of a conductive film [1, 2]. This is the reason coastal areas are considered heavily polluted. Although such general rules can be proposed (and be more or less accurate), determining the actual class of the pollution severity of a site is a more complex task as the local climate has to be strongly considered. And since detailed data are rarely available, previous experience plays a decisive role.

Another important issue is that insulators based on polymer materials more and more replace the old ceramic ones [3-5], and similar materials are also used to coat ceramic insulators [6-7]. Polymer materials provide a hydrophobic surface that does not allow the formation of a conductive film, even when water and pollutants are present [3-7]. However, their actual performance, aging and their hydrophobicity loss and recovery periods are also strongly linked to local service conditions. In any case, pollution mapping is established as an important piece of information for power utilities.

The Mediterranean island of Crete provides a rather interesting case study, as its power network is mostly coastal and is subjected to a variety of microclimates throughout the island. Further, a relatively high voltage level is used (150 kV), the network is isolated and the island's economy is largely based on tourism which means that a potential blackout during the summer (when the problem peaks) has an important impact on various levels. For all these reasons, the Greek Public Power Corporation (PPC) and the Hellenic Electricity Distribution Network Operator (HEDNO) have employed several remedies to cope with the pollution problem over the years. The latest research step aims to define diagnostic techniques for polymer insulators installed in the grid. This means that such insulators have to be removed and tested in the lab as well as in the recently constructed TALOS High Voltage Test Station [8]. However, in order to make an optimal selection and to assess correctly the insulators' status and its correlation with the experienced pollution, a pollution map of the island should be defined.

In this paper, the various steps towards defining a pollution map for Crete are presented. Measurements conducted throughout the island as well as previous network experience and specially designed measurements in TALOS [8] are considered. Although this map may be updated in the future as new data keeps coming in, it is however a first and important step towards defining some key principles

This work was supported by the POLYDIAGNO research project ((project code 11SYN-7-1503), a project implemented through the Operational Program ''Competitiveness and Entrepreneurship'', Action "Cooperation 2011", co-financed by the European Union and Greek national funds.

D. Pylarinos is a consultant for the Hellenic Electricity Distribution Network Operator S.A., Greece (dpylarinos@yahoo.com)

K. Siderakis is a Lecturer at the Technological Educational Institute of Crete (k.siderakis@gmail.com)

N. Mavrikakis is a PhD candidate at the Aristotle University of Thessaloniki, Greece (mavrikakisnikos@gmail.com)

E. Thalassinakis is the assistant director of the Islands Network Operations Department, Hellenic Electricity Distribution Network Operator S.A., Greece (E.Thalassinakis@deddie.gr)

regarding the pollution profile of the island's network.

II. Pollution Measurements

Three are the basic measurements proposed to assess a Site's Pollution Severity (SPS) class: the Equivalent Salt Deposit Density (ESDD), the Non-Soluble Deposit Density (NSDD) and the Directional Dust Deposit Gauge (DDDG) [2]. ESDD relies on collecting and diluting the pollution deposited on the surface of off-line insulators in certain intervals and measuring the conductivity and temperature of the solution in order to define the equivalent amount of salt in mg per cm^2. ESDD is a low cost technique that considers the insulator's profile and can be conducted on site. Therefore, it has been used in different locations throughout the island and also lately in TALOS.

To acquire the NSDD measurement the ESDD solution has to be filtered and the filter has then to be dried and weighted to calculate the weight of non-soluble deposits. NSDD is especially needed when non-soluble deposits are present (e.g. sand) but requires special equipment (a drying oven, a dessicator, a laboratory weighing scale) and is therefore costly and can not be conducted on site. Such measurements were only recently initiated in Crete, using the recently refurbished Chemistry Lab of HEDNO in Iraklion, Crete.

The DDDG measurement relies on the installation of special kits of cylindrical design that collect pollution from four directions (East, West, South, North). DDDG is an easily implemented procedure which is considered as an easy alternative for large area mapping but has the disadvantage of not considering the insulator's profile which is strongly related to the amount of deposits that actually stays on the insulator's surface and also to the cleaning effect of rain. DDDG kits are commercially available [9] but can also be fabricated using plastic tubes (e.g. [10]). Such kits have not been installed in Crete yet, but are to be fabricated and installed in the near future.

III. Set-Up

A. ESDD measurements

To acquire the ESDD measurement strings of insulators were hanged from the metal structure of towers as shown in Figure 1. These dead strings were hanged from a lower height in order to be easily and safely accessible by the crew. Measurements were conducted on site using a conductivity meter as shown in Figure 2. Solutions of standard conductivity were employed in order to verify the measurements and to calibrate the conductivity meter beforehand, as shown in Figure 3.

Fig. 1. Dummy insulator strings hanged from the metal structure of 150kV towers

Fig. 2. Measuring ESDD on site

Fig. 3. Calibration and accuracy verification using a solution of standard conductivity

B. NSDD measurements

NSDD measurements initiated rather recently as they required special equipment and could not be performed on site. The recently refurbished Chemistry Lab of HEDNO in Iraklion, provided the necessary means to perform NSDD measurements. Solutions were carried to the HEDNO Chemistry Lab using labelled bottles as shown in Figure 4. GF/A grade filters (1.6 µm) were used for filtering [2], however a water vacuum pump proved to be necessary in order for filtering to be performed, also shown in Figure 4. A drying oven and a desiccator were also used to dry filters and then allow them to cool off without absorbing moisture, and a precision scale was used to weigh filters before and after drying, as shown in Figure 5.

Fig. 4 Labelled bottles with solutions, filtering and filtering assisted with a water vacuum pump

Fig. 5. Drying oven, desiccator and precision scale

C. TALOS High Voltage Test Station

TALOS is a High Voltage Test Station constructed by HEDNO in Iraklion, Crete [8]. Its location is right next to the coast in order to be subjected to maximum pollution as shown in Figure 6. TALOS is equipped with three different bays as shown in the 3D model of Figure 7. One bay is for 150kV post insulators, another for 150kV suspension insulators and the third for both post and suspension 21kV insulators. Further, TALOS is also equipped with a specially designed arch, where different insulators are hanged offline in order to perform comparative measurements. A photo from the arch and a zoom in on the insulators is shown in Figure 8.

Fig. 6. The location of TALOS High Voltage Test Station

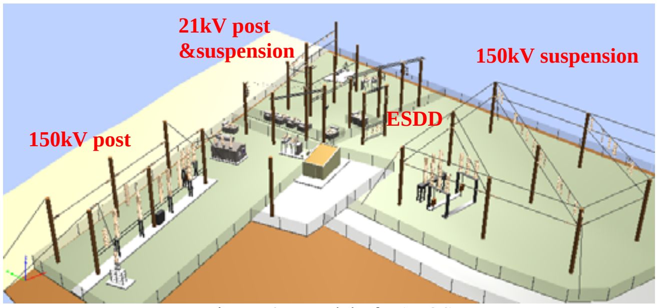

Fig. 7. 3D model of TALOS

Fig. 8. The ESDD arch and the five insulators in the low position

D. CAD calculation of surface area

To calculate the ESDD values, one has to include the surface area of each insulator. However, this value is rarely (if ever) provided by the manufacturer. Therefore, Computer Aided Design (CAD) was employed to construct 3D models for each insulator in order to calculate surface areas, as shown in Figure 9.

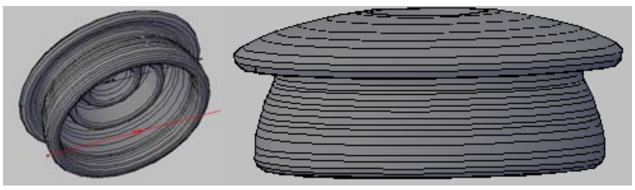

Fig. 9. CAD 3D modeling of insulators to calculate the surface area

IV. Environmental & Network Data

A. Island's morphology, location and climate

Crete is located in the Mediterranean Sea, at the Southern end of Europe as shown in Figure 10. The island has a rather elongated shape (it is 260 km long and 15-60 km wide) and has a coastline of 1046 km, mostly rocky. Three large mountain formations cover the center part of the island from east to west. The development of the island is mostly coastal with the four largest cities (Iraklion, Rethimnon, Chania, Ierapetra, Agios Nikolaos with a descending order) being located next to the coast.

Fig. 10. The island of Crete

The main characteristic of the Cretan climate is long periods of dry and then wet weather. The dry period usually lasts from April to October. Although the overall amount of rainfall is significant, most occurs only between November and March. Strong winds mainly of north-northwest direction are also present and reach their peak during the summer. These winds combined with the rocky coasts result to increased salt deposition on insulators. Further, towards the end of August increased precipitation (and relative humidity) is observed [11-13]. Therefore, pollution builds up during the dry period and increased risk is observed when wetting occurs afterwards. It should be noted that a significantly diverse behavior is observed between the eastern and the western part of the island. Strongest winds are recorded on the east side of the island whereas the west part receives almost twice the rainfall compared to the east [11-13].

B. Network Experience

The route of all major TLs of the power system of Crete (each dot is a 150 kV tower) is shown in Figure 11. Some minor TLs used to connect different S/S in Iraklion are not considered here and double circuits are considered as a single route.

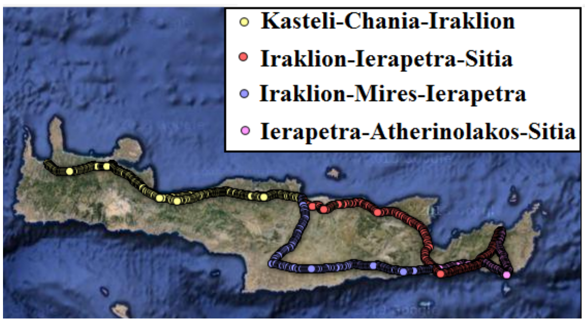

Fig. 11. The route of the major TLs of the Cretan power system

As shown in Figure 11, the TLs routes are mainly coastal which exaggerates the pollution problem. However, frequent rains on the western side of the island resulted to no pollution problems experienced there. The problem was always focused on the eastern side. It is indicative that from 1978 to 1993, 216 faults took place at the 276 km of the TLs of eastern Crete and just 1 fault (not pollution related) at the 132 km of the TLs of western Crete, although extensive cleaning activities were performed at the eastern side (and not at the west) [14].

It should be noted that pollution was overall historically responsible for a large percentage of faults that was gradually diminished as more maintenance experience was gained (e.g. from 32.5% in the 80s to 19.6% in the 90s [11]). The first HTV SIR insulators were installed in 33 150kV towers from 1993 to 1998 on a trial basis. The location of these towers is shown in Figure 12 and, as expected, refers mostly to towers located near the cost in the central and eastern part of the island.

Fig. 12. The location of the 33 150kV towers where HTV SIR insulators were first installed on a trial basis (1993-1998)

Table I shows some data regarding the current status and the year of large scale installation of HTV SIR insulators for each TL. The priority followed, hints to the lines that faced most problems (and is also related to the importance of the lines, its length etc). As shown, the first large scale installation took place at the Iraklion-Ierapetra and Ierapetra-Atherinolakos TLs in 2004. Then other TLs followed. Two of them (Iraklion-Mires and Iraklion-Chania) are still equipped with glass and suspension strings in tension towers whereas HTV SIR insulators have been installed in suspension towers. HTV SIR insulators will be installed in the tension towers of these lines in 2014-2015. The TL from Mires to Ierapetra is also expected to be fully equipped with HTV SIR insulators in 2014-2015.

TABLE I: TLS AND INSULATORS

TL	Ins. Type	Year of large scale installation of HTVs
Atherinolakos-Ierapetra	HTV SIR	2004
Iraklion-Ierapetra	HTV SIR	2004
Atherinolakos-Sitia	HTV SIR	2006
Ierapetra-Sitia	HTV SIR	2010
Iraklion-Mires	HTV SIR, Glass, Porcelain	2013
Iraklion-Chania	HTV SIR, Glass, Porcelain	2013
Mires-Ierapetra	Glass	-
Chania-Kasteli	Porcelain	-

To gain an insight on the improvement caused by the replacement of ceramic insulators with HTV SIR, a typical fault report for a certain part of the Iraklion-Ierapetra TL is shown in Figure 13. A significant decrease in the number of faults is shown after the installation of the HTV SIR insulators (2005 and forth).

Fig. 13. Faults on part of the Iraklion-Ierapetra TL

It should be noted that no pollution related faults have been recorded on HTV SIR insulators yet. However, determining the cause of a fault may be tricky, therefore a safer way is to consider the variation of the total number of faults. Thus, the overall improvement caused by the use of HTV SIR can easily be seen in Figure 14 where the faults per 100 km per year and decade are presented (1980-2010). As shown, there is a significant improvement in the 00s which is the decade where large scale installation of HTV SIR insulators took place.

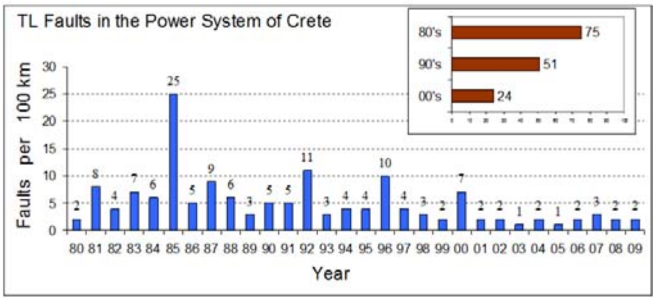

Fig. 14. Transmission Line faults (1980-2010) per 100 km

V. POLLUTION MEASUREMENTS

ESDD measurements were conducted on various locations throughout the island, as shown in Figure 15. Dead strings were hanged from the metal structure of towers and conductivity measurements were conducted on site. Further, CAD design was used to calculate the surface area of each insulator. However, monthly visits (as required by [2]) to all sites was a rather impractical plan as a large amount of man-hours would be needed by the Line crew. Therefore, it was decided that, considering the local climate, one measurement per year could provide a satisfactory approximation, provided that this measurement is conducted after the end of summer, in September-October (and thus near the end of the dry period) and before any rain falls. This way there is a large possibility to actually record a near-worst-case measurement which is the ultimate goal. Further, the procedure was repeated for three years and the largest ESDD value was considered for each location (tower) to maximize the accuracy of the approximation.

An added issue was the correlation of measurements conducted on fog profile insulators (as the one shown in Figure 1) with SPS classes that are linked with ESDD values measured on disc profile insulators [2]. It has been proposed [15] that a correlation factor of 0.8 ± 0.3 should be applied to correlate the measurements on different profiles. However, this provides a rather large span. Therefore, comparative measurements were performed for a three months period in TALOS High Voltage Test Station using the arch described in paragraph III-C of this paper. Although more measurements should be conducted, the first results give a correlation factor slightly larger than the upper limit proposed in [15], and this factor is used in this paper. NSDD measurements were conducted on the insulators installed in TALOS, however further research is required before any results can be published.

In order to classify a Site's Pollution Severity (SPS) to the three basic classes (light, medium, heavy), slightly different ranges of ESDD measurements have been proposed by IEC [2], IEEE [16] and CIGRE [17]. The IEC values are given through an ESDD-NSDD diagram and have relatively large cross-areas, therefore the more specific IEEE and CIGRE values shown in Table II provide an easier (although may less accurate) solution. The CIGRE limits have been applied in this paper and the final results are shown in Figure 15.

Table II. SPS and ESDD values

SPS	ESDD value (mg/cm2) (IEEE) [16]	ESDD value (mg/cm2) (CIGRE) [17]
light	<0.06	<0.06
medium	0.06-0.10	0.06-0.12
heavy	>0.10	>0.12

Fig. 15. SPS classes throughout the island based on ESDD measurements

Most selected towers belong to eastern coastal lines and especially the Iraklion-Ierapetra TL due to the significance of the line and the experienced pollution problems (before the installation of HTV SIRs). Further, multiple towers were selected near the larger cities as these were areas also exposed to other pollution types (industrial, domestic etc). As shown in Figure 15, the proximity to pollution sources, mainly the coast and large cities, is a key factor for the experienced pollution. Further, the figure underlines the fact that environmental factors such as rainfall patterns and wind direction should also be considered when determining an SPS class. Heavy pollution has been recorded next to all big coastal cities (Iraklion, Rethimnon, Agios Nikolaos and Ierapetra), but not near Chania even though Chania is larger than Agios Nikolaos and Ierapetra. This verifies the different conditions experienced on the west part of the island as described earlier in this paper. Further, it is shown that milder pollution is recorded as the line moves away from the city and/or the coast. The measurements conducted on coastal towers located in the southern part of the island shows a lighter pollution image which could be attributed to the usual direction of the wind which is north-northwest [11].

VI. Future Work

Next steps include additional measurements in TALOS which will allow the definition of a correlation factor between the reference disc insulator, fog profile ceramic insulators and HTV SIRs. Further, a new weather station is to be installed in TALOS in order to have detailed weather data.

Insulators will also be occasionally removed from the network in order to perform several tests on them in TALOS and in labs that are in cooperation with HEDNO. In Figure 16, the surface of an HTV SIR removed from the network is wiped for ESDD measurements and the result of such cleaning are clearly visible in another such insulator where wiped sheds appear different compared to the others.

Fig. 16. ESDD measurements on HTV SIR insulators removed from the network

Further, DDDG kits are to be manufactured using low cost materials (pipes) and to be installed in TALOS and if possible in several other areas throughout the island. Even though the installation of HTV SIR will be almost complete in most TLs by next year, a detailed mapping of the pollution throughout the island will give important data that may be used to assist future research goals set, such as the diagnosis of the condition of polymeric insulators.

VII. Conclusion

Assessing pollution is an important procedure for power utilities as it can assist in insulator planning and maintenance. Crete provides an interesting case study due to certain characteristics of its power network. Pollution mapping in Crete draws a peculiar picture: although the network is mostly coastal, a diverse behavior is recorded between the western and the eastern side of the island. This should be attributed to the local weather which provides different stresses to the two sides. Further, it is shown that besides the distance from the sea, an added significant factor seems to be the proximity to cities. Network experience has shown that the installation of polymer insulators has greatly improved reliability. However, further research is required in order to assess the performance and aging of these insulators. Pollution mapping will provide valuable data towards this goal.

VIII. Acknowledgment

This work was supported by the POLYDIAGNO research project (code: 11SYN-7-1503) which is a research project implemented through the Operational Program ``Competitiveness and Entrepreneurship'', Action

"Cooperation 2011" and is co-financed by the European Union (European Regional Development Fund) and Greek national funds (National Strategic Reference Framework 2007 - 2013).

IX. References

[1] CIGRE WG 33-04, TF 01, *A review of current knowledge: polluted insulators*, CIGRE, 1998

[2] IEC/TS 60815, *Selection and dimensioning of high-voltage insulators intended for use in polluted conditions*, International Electrotechnical Commission, 2008

[3] R. Hackam, Outdoor HV composite polymeric insulators, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 6, No. 5, pp. 577-585, Oct. 1999

[4] K. Papailiou, F. Schmuck, *Silicone Composite Insulators: Materials, Design, Applications*, Springer, 2012

[5] J. S. T. Looms, *Insulators for High Voltages*, IET, 1988

[6] K. Siderakis, D. Pylarinos, "Room temperature vulcanized Silicone Rubber coatings, Application in high voltage substations", in: *Concise Encyclopedia of High Performance Silicones*, John Wiley & Sons Inc, USA, 2014

[7] E. A. Cherney, R. S. Gorur, "RTV silicone rubber coatings for outdoor insulators", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 6, No. 5, pp. 605-611, Oct. 1999

[8] TALOS High Voltage Test Station, www.talos-ts.com

[9] http://www.macetech.co.za/DUSTDESC1.htm

[10] http://www.parrett.uk.com/dustgauge.htm

[11] J. Stefanakis, E. Thalassinakis, K. Siderakis, D. Agoris, E. Dialynas, "Fighting Pollution in the Cretan Transmission System. 25 Years Experience", presented at the Contamination Issues on High Voltage Installations conference, Iraklion, Crete 2001 (available at: http://talos-ts.com/files/2001_CIHVI.pdf)

[12] S. Gubanski, "Greek power company evaluates alternatives to combat pollution in transmission system on Crete", *INMR,* Vol. 10, No. 4, Page 30, 2002

[13] E. Thalassinakis, J. Stefanakis, K. Siderakis, D. Agoris, "Measures and techniques against pollution in the Cretan transmission system", presented at the 2nd IASTED European Conference on Power and Energy Systems (EuroPES), Crete, Greece, June 25-28, 2002 (available at: http://talos-ts.com/files/2002_IASTED-2.pdf)

[14] K. Siderakis, J. Stefanakis, E. Thalassinakis, D. Agoris, E. Dialynas, "Coastal Contamination of the High Voltage Insulators in the Cretan Power System", presented at the 2nd Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion, IEE Conference Med Power 2000, Herzlia, Israel, November 13-15, 2000 (available at: http://talos-ts.com/files/2000_MEDPOWER.pdf)

[15] CIGRE WG C4.303, *Outdoor insulation in polluted conditions: guidelines for selection and dimensioning*, CIGRE, 2008

[16] IEEE Std 1313.2-1999, *IEEE Guide for the Application of Insulation Coordination*, The Institute of Electrical and Electronics Engineers, 1999

[17] CIGRE WG B2.03, *Guide for the establishment of naturally insulator testing stations*, CIGRE, 2007

X. Biographies

Dionisios Pylarinos received a Diploma degree in Electrical and Computer Engineering in 2007 and the Ph.D. degree in the same field in 2012 from the University of Patras, Greece. He is a researcher/consultant for the Public Power Corporation Greece and the Hellenic Electricity Distribution Network Operator, Greece since 2008, in the field of HV insulator testing and monitoring and he is a member of the team behind TALOS High Voltage Test Station. He is a member of the Technical Chamber of Greece and of the Greek National CIGRE Committee. His research interests include outdoor insulation, electrical discharges, leakage current, signal processing and pattern recognition.

Kiriakos Siderakis was born in Iraklion 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, Greece. Presently, he is an Assistant 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. He is a member of the Greek CIGRE and of the Technical Chamber of Greece.

N. Mavrikakis was born in Heraklion of Crete, Greece, in 1986. He received the Diploma degree in electrical and computer engineering from Aristotle University of Thessaloniki, Greece, in 2009, where he is currently pursuing the Ph.D degree at the High Voltage Laboratory. His research interests include field and laboratory diagnostic techniques for evaluating the performance of high voltage insulators.

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 (PPC). He is the Assistant Director of the Islands Network Operations Department of the Hellenic Electricity Distribution Network Operator S.A., a former part of PPC.