Insulators' pollution problem: Experience from the coastal transmission system of Crete

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Abstract—**Pollution of insulators is one of the most significant problems that can affect the reliability of power systems. Several practices have been employed to improve the insulation performance under polluted conditions such as extending the creepage distance, using specially designed profiles, washing of insulators and using hydrophobic materials to manufacture insulators or to coat their surfaces. Depending on the pollution type and severity as well as the local climatic conditions at the site of installation, different maintenance procedures against pollution should be employed. In this study, the insulators' pollution problem in the transmission system of Crete is described based on a statistical analysis of the insulators' faults since 1969. Also, the practices employed against insulators' pollution as well as their effectiveness are presented. Among them, the most efficient practice has been evinced the use of polymeric coatings and composite insulators. However, after about 2 decades of their large scale installation, without any faults, their performance becomes questionable due to the ageing of the polymeric materials. In order to prevent the risk of the in-service insulators failures, a fruitful collaboration of power network operator with local academia and research institutes has led to the investigation of new diagnostic procedures aiming at the assessment of the condition of field-aged insulators. To this end, the use of laser-induced breakdown spectroscopy (LIBS) technique is proposed for the remote and real-time diagnosis of the condition of in-service composite insulators.**

Index Terms—**Pollution problem, transmission system, Crete, composite insulators, maintenance practices, LIBS**

I. Introduction

The performance of insulators used in transmission and distribution systems is a key factor for their reliability. Pollution accumulation on insulators' surfaces can significantly deteriorate their performance, resulting in failures and long term electricity interruptions of the power systems. The pollution problem in the case of insulators is associated to the formation of a conductive layer on the surface due to the pollution, when the deposited air-borne pollutants become wet; this, under certain conditions, can finally lead to flashover of insulators.

To suppress the problem, several pollution maintenance practices can be employed such as the extension of the creepage distance, the use of specially designed profiles, the washing of insulators and the employment of hydrophobic materials either to manufacture the insulators or to coat their surfaces [1]. The required remedies against pollution problem in power systems are not similar for all cases, depended highly on the site of installation, the respective weather and climatic conditions. The aim of an effective maintenance procedure against pollution is to ensure high reliability of power system in the lowest possible maintenance cost.

In this study, a brief description of the insulators' pollution problem in the transmission system of Crete is presented, based on the experience gained since 1969. The climatic conditions of the island as well as the installation of the transmission system near the coastlines favour the insulators' pollution process [2]. The pollution problem is analysed based on the recorded insulators' faults in the coastal transmission system. Also, the maintenance practices employed [3]–[5], as well as their effectiveness are presented. The collaboration of power network operator with the local academia and research institutes [6] decisively contributes to better organize the maintenance procedure through the implementation of new techniques, associated with the evaluation of performance of insulators in-service.

II. Experience From The Coastal Power System of Crete

A. Power system of Crete

The power system on the island of Crete is the largest completely isolated power system in Greece, with steadily increasing power demand. The total installed power capacity of the system is 1126.2 MW; the 842 MW are produced by the 3 fuel power stations located in Linoperamata, Atherinolakos and Chania (Fig. 1), while, the rest comes from the renewable generation sources. Specifically, 184 MW are produced by wind farms and 94.2 MW by photovoltaic solar power stations, both distributed throughout the island. It must be noted that the penetration of renewable generation sources to power system of Crete is the highest in Greece.

The transmission system, elongated throughout the island,

Fig. 1. Power system of Crete [7]

comprises of 580 km of 150 kV overhead transmission lines, which are supported by more than 9600 insulators on more than 1600 towers. In addition, there are 18 outdoor and 2 indoor substations of 150 kV /20 kV (50 Hz). The transmission system is deployed along the island's coastline, as consequence of the social and the financial development of these places. There are 64 power transformers of 150 kV in service, with a total installed power capacity of 2600 MVA.

It must be noted that the transmission system of the island was initially at 66 kV (50 Hz), in the 1960's, connecting the 2 largest cities of Crete, Iraklion and Chania respectively. The first transmission lines of 150 kV were installed from 1976 to 1979. Today, the transmission system is completely upgraded to 150 kV.

B. Insulators pollution problem – Statistical analysis

The short distance of the transmission system from the coastlines, as evident from Fig 1, together with the island's climatic conditions, can be considered as the main causes for the severe insulators' pollution problem [2]. It has to be mentioned that the great majority of the pollution faults was recorded in the eastern part of the island. The first pollution problems, attributed to the burning of the wooden poles, were recorded in the early 60's, during the operation of the 66 kV transmission line. In the 60's and 70's, the transmission system was suffering from frequent and long lasting electricity interruptions, caused by the severe insulators pollution problem. Similarly, 32.5% of the total faults recorded for the transmission system in the 1980's and the respective 19.6% in the 1990's were caused by pollution [2]. However, during the last two decades, the pollution faults have been significantly reduced, mainly due to the use of hydrophobic polymeric insulating materials (coatings and composite insulators).

The insulators' pollution problem can be analysed using the data of the pollution power outages since 1969. Fig. 2(a) presents the total number of faults in transmission lines caused by pollution per month, the respective faults per hour shown in Fig. 2(b), for the period 1969 to 2002 [2]. It is demonstrated that the great majority of pollution faults occurred, mainly from September to October during the night or early in the morning (Fig. 2(a) and 2(b)). The strong marine winds in dry period (summer months) are able to transfer great amount of sea borne pollutants, spraying the insulators installed close to the coastlines. Following, the prolonged dry summer period without rainfalls, favours the large concentration of pollutants on insulators' surfaces.

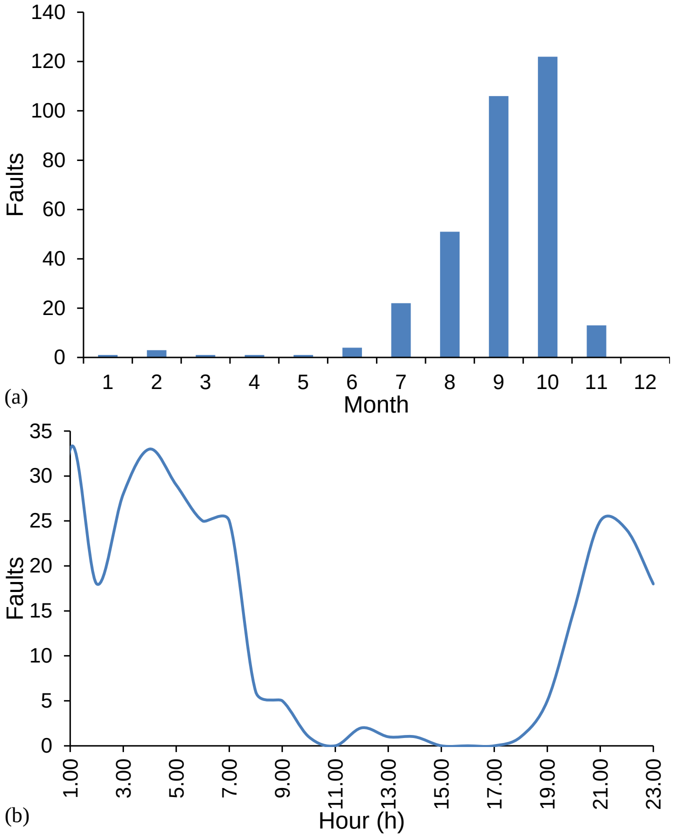

Fig. 2. Number of pollution faults (a) per month and (b) per hour from1969 to 2002 [8]

Immediately after the end of the dry period, a wet period of high humidity, especially in the morning and during the night, follows. Then, the accumulated pollutants, high in salinity due to sea salt pollutants, are diluted. A high conductive layer is formed on the insulators' surface, which under certain conditions can lead to flashover. For the other months of the year, pollution faults occur rarely, since the natural cleaning effect of the winter rainfall period follows. Finally, the greater number of the pollution faults in the eastern side of the transmission system is directly attributed to the stronger summer winds towards this direction as well as the lower frequency of rainfalls.

C. Maintenance procedure against pollution

The maintenance practices, described in this study, were mainly employed for the ceramic insulators already installed in the overhead high voltage transmission lines and outdoor substations on the island. Fig. 3 shows the number of total faults per 100 km of the 150 kV transmission lines and the number of the workpower from 1980 to 2015. Although the required number of workpower is considerably reduced, the system reliability is increased and maintained in a desired level for more than 15 years (2000 – 2016), which is a result of the effective maintenance procedure. The maintenance practices which have been applied since 1978, are described below.

The first method, applied in 1978, was insulators' washing with sponges and bucket [4]. However, a lot of workpower

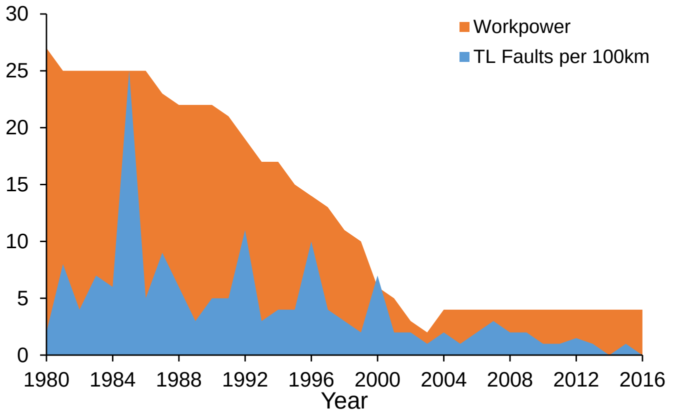

Fig. 3. Transmission line faults from 1980 to 2016 per 100 km

as wells as long-lasting electricity interruptions of the transmission system were required during the washing procedure. The sponge washing was last performed in 1981 [4], [9]. For the next 3 years, from 1982 to 1985, the insulators' washing stopped. This decision was finally resulted to a sharply increase of insulators pollution failures in 1985 [2], [4], [9]. After that, it was clear that the maintenance practices had to be performed on a periodical basis to ensure the reliability of power system.

In 1985, the sponges were replaced with high pressure water for the washing of the insulators. This practice was known as dead-washing, because the supply of the transmission system was interrupted during the washing procedure [4]. About ten years later, in 1995, live-line washing was additionally employed for the transmission lines, by using high pressure water from helicopter. This method was fast and there was no need for taking the lines out of service. Washing of insulators was usually performed in Crete twice a year (in August and in September). The experience showed that the effectiveness of washing methods was strongly related to weather conditions at the time applied. Furthermore, these methods had high financial cost, considering the financial losses from the required power interruptions during the cleaning procedure.

In an effort to reduce the pollution faults by increasing the insulators' creepage distance, ceramic cap and pin insulators designed for 400 kV were used in 150 kV lines. However, more than half of those insulators were damaged by flashover and were replaced with 150 kV insulators from 1985 to 1994. In the same period, less than 1% of the 150 kV insulators, installed at the same line, had to be replaced [9]. Thus, it was clear that the creepage distance of the insulators was not the only parameter that had to be considered.

In 1998, RTV silicone rubber coatings were applied on ceramic insulators in Linoperamata's substation and since then, RTV SIR coating applications were rapidly increased, especially in the case of outdoor substations. The total amount of RTV SIR coating materials, applied in the following ten years, was about 7000 kg. The pollution faults of insulators have been significantly reduced since then. However, one decade later, the RTV coatings in service were observed to peel off from the ceramic insulators surface, thus, reapplication was required.

The first small scale installations of composite insulators were performed in 1979, 1993 and 2000. In the first installation of 1979, 300 Teflon insulators were used in a transmission line; however, after 4 years in service, Teflon insulators damaged from brittle fracture and were replaced. In 1993 and 2000, composite insulators were mainly installed for investigation purposes in some lines throughout the island. In 2004, a large scale replacement of ceramic with composite insulators took place in the eastern side of transmission network, where the pollution problem was more severe. Since then, the number of composite insulators in the transmission lines has been rapidly increased throughout the transmission system. It is noteworthy, that in 2000, only 3% of the installed insulators were of composite type, this number approaching 78% in 2016. Composite insulators' flashover due to pollution has not been yet recorded. However, the performance of composite insulators after a long term exposure in service stresses becomes questionable; it is known that the polymeric materials are susceptible to ageing, caused by environmental, electrical and mechanical stresses [10]. Thus, evaluation of the performance of in-service composite insulators, aiming to optimize the maintenance actions, is necessary to ensure high reliability levels of the power system. To this direction, academia and research institutes of Crete, in collaboration with the power network operator, have undertaken the challenges, to face the overcoming challenges to assess and differentiate morphological and/or structural characteristics of the composite insulators', which are associated with ageing.

III. Diagnostic Techniques

The collaboration of the power network operator with the local academia and research institutes [6] efficiently contributes in the condition assessment of field-aged composite insulators [11]–[18]. Based on the pollution severity measurements and the age of composite insulators in service, a small number of them were removed from the transmission lines in 2014, in the framework of the preventive maintenance program. Evaluation was performed through surface morphology and material characterization, wettability classification as well as through electrical tests.

The surface morphological characterization was based on visual inspection according to field inspection guides and scanning electron microscopy (SEM) images. Discoloration was observed throughout the insulators' polymeric housing surface (Fig. 5(a)), and it was differed in intensity depending mainly on the polymeric material type [18]. Also, corrosion of metal end fittings was detected (Fig. 5(b)) to be more pronounced for the insulators installed close to coastlines, indicating that the sea-borne pollution contributes to the oxidation process of the insulators' metal parts. Finally, SEM images revealed surface cracking (Fig. 5(c)) on EPDM housings, which are the most discoloured ones [18].

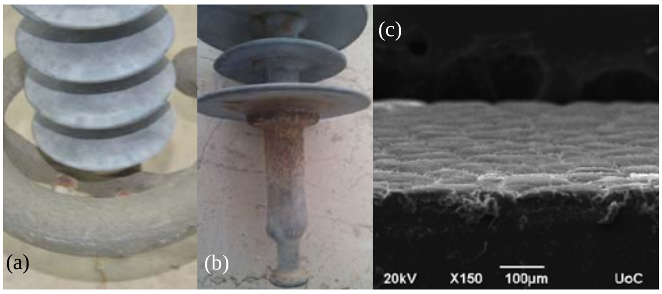

Fig. 5. Discoloration of housing (a), corrosion of metal fittings (b) and cracking of housing surface (c)

Wettability classification of the polymeric housings' surfaces of field-aged composite insulators was performed by using the spray method and the contact angle method according to IEC 62073 [19]. Also, the dynamics of the hydrophobicity, associated with hydrophobicity transfer mechanism, were evaluated [20]. Specifically, the field-aged EPDM housings were characterized as hydrophilic (Fig. 6(a)) before washing the accumulated surface natural pollution layer; however, after washing, they were hydrophobic [18]. On the other hand, the naturally polluted field-aged SIR housings were hydrophobic both before (Fig. 6(b)) and after washing. This behaviour, associated with the hydrophobicity transfer mechanism, was better demonstrated in [20]. It was found that the required hydrophobicity transfer time for the field-aged SIR housing was similar to the new (Fig. 6(c)). However, the surface hydrophobicity of the artificially polluted field-aged EPDM housing was lost (Fig. 6(c)).

Surface material degradation of field-aged polymeric housings was investigated though EDX analysis and FTIR ATR spectroscopy. The results revealed oxidation of the rubber component of the housing material surface in a much higher degree for the case of EPDM than that of SIR [18]. FTIR results (Fig. 7) confirmed the structural changes of the polymeric housings' surfaces, showing scission of the rubber bonds (2 and 4 in Fig.7c), formation of hydroxyl groups (3 in Fig.7c) and dehydration of the filler (1 in Fig.7), which were more pronounced in the case of the EPDM insulators [18].

The electrical performance of field-aged insulators was tested by the inclined plane test (IPT) according to IEC 60587 [19] and by real time leakage current measurements in TALOS outdoor high voltage test station. The results of the inclined plane test showed higher mass loss for the field-aged EPDM than that of the SIR insulators, although the higher amount of ATH filler comprised [18]. However, both EPDM and SIR insulators successfully passed the IPT. Moreover, the measurements performed at TALOS high voltage test station showed higher values of leakage currents for the field-aged EPDM than SIR insulators, especially, under wet conditions, despite the fact that the insulators, investigated, had similar creepage distances.

IV. LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS)

Implementation of the aforementioned diagnostic methods

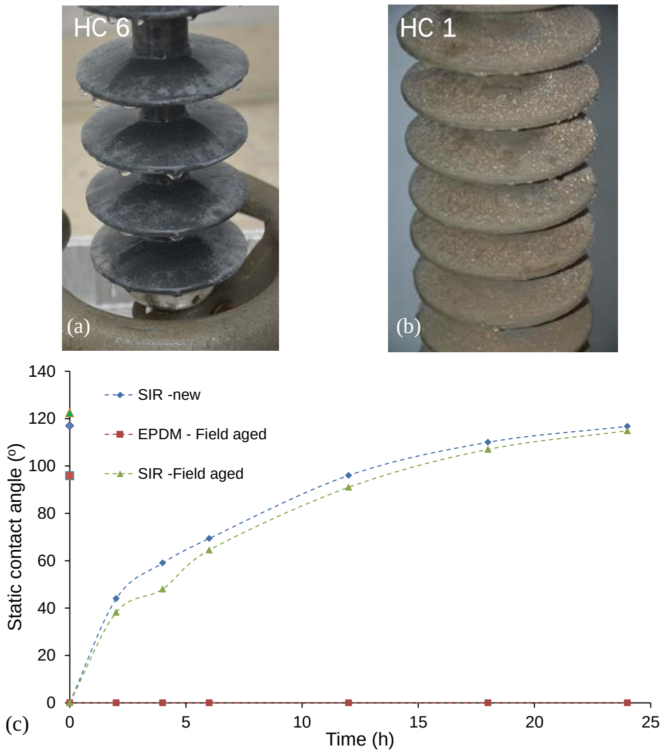

Fig. 6. Hydrophilic behaviour of a field-aged EPDM insulator (a), hydrophobic behaviour of field-aged SIR insulator (b) and hydrophobicity transfer rate for field-aged and new housing materials (c). [20]

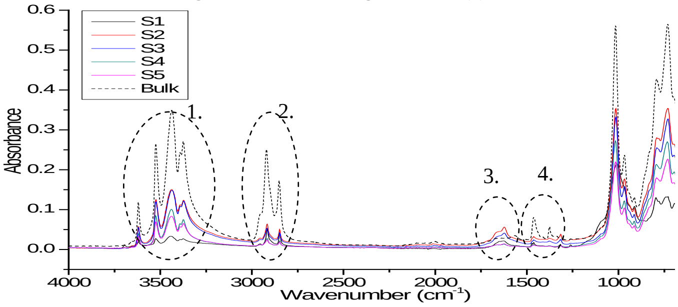

Fig. 7. FTIR spectra of surface (S1, S2, S3, S4, S5) and bulk material of the polymeric housing of field-aged EPDM insulators.

requires disconnection of the insulators from the transmission lines, sampling of the polymeric housing and laboratory examination of the samples (specimens) by experts, resulting in high financial costs for the power network operator. Hence, in order to prevent such time consuming and highly expensive maintenance procedures, it is necessary to develop a non-destructive diagnostic techniques for remote, real-time and on-site inspection of the insulators condition.

To this end, the development of a new remote and real time laser-based technique for assessing the condition of field-aged composite insulators has been investigated. Laser-induced breakdown spectroscopy (LIBS) technique [21] was found to meet the requirements, since it presents minimal or zero sample preparation, short (nearly instantaneous) measurement time, compact and easy-to-use equipment of low maintenance cost, thus, enabling its application outdoors and in remote environments.

LIBS is based on the analysis of atomic or molecular plasma emission, that follows irradiation of a material with a high intensity (above the ablation threshold [22]) laser pulse and is characteristic of its chemical composition. LIBS major advantage is that it provides rapid multi-elemental analysis of the chemical composition of the housing material, which is extremely useful for the real-time and simultaneous identification of the polymer type, the fillers composition, and even surface contamination, by monitoring its removal within the first few laser pulses.

Remote LIBS analysis of a field-aged composite insulator requires a laser source, optics to direct the laser beam onto the insulator's surface, and a plasma light collection-analysis-detection system. In this work, remote LIBS analysis was performed with the use of a telescope for plasma light collection, in conjunction with an optical fiber transmitting the light into a spectrometer.

A typical LIB spectrum of a SIR insulator is shown in Fig. 8. The major emission lines detected are those of Si, Al, Ti, Mg, Ca, Na and H. Although C atomic emission (at 247.8 nm) is hardly distinguishable, CN molecular emission band is detected at relatively high signal-to-noise ratio. CN molecule is formed in the plasma, upon the reaction of C with the atmospheric nitrogen [23] and its detection indicates that the housing material is organic in nature. Strong Si atomic emission denotes that the polymeric housing is PDMS. Also, Na may be derived from sea-borne pollution deposited on the insulator surface. The rest of the elements, detected, originate from the fillers, which are inorganic compounds such as MgO, $Al_2O_33H_2O$ (ATH), TiO_2 and $CaCO_3$. The results demonstrate that the housing material of the insulators, examined herein, is either SIR or EPDM, in agreement with ATR-FTIR spectroscopic measurements.

Some preliminary, but rather promising, remote LIBS measurements, were performed on-site, at TALOS HV Test Station, at a distance of almost 10 m away from the field-aged SIR insulators (Fig. 9(a)). It should be noted that the insulators were not irradiated while being in operation, but, instead, they were detached from the transmission lines. The results demonstrate that the intensity ratio (R) of CN molecular emission band head (at 388.2 nm) over Si atomic emission (at 390.55 nm) is systematically lower in the spectra corresponding to the field-aged insulators than it is in the (reference) spectra corresponding to the new insulators ($R_{OLD} = 0.07 \pm 0.01$ and $R_{NEW} = 0.14 \pm 0.01$) (Fig. 9(b)). The reduced intensity ratio measured for the field-aged SIR insulators is attributed to the loss of CH3 groups and/or Si atoms, caused by degradation of PDMS backbone, in agreement with ATR-FTIR measurements.

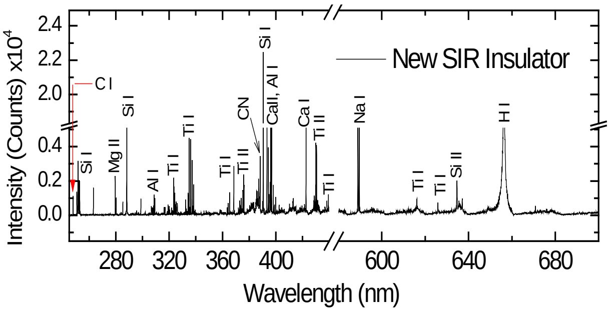

Fig. 8. LIB spectrum of a new SIR insulator (Nd:YAG laser; λ=1064 nm) The spectrum is an average of 10 single-shot spectra.

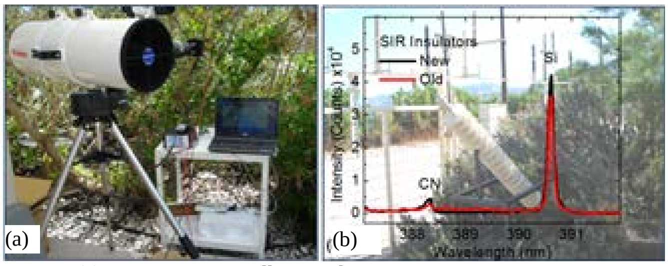

Fig. 9. (a) Remote LIBS collection-detection system at TALOS HV Test Station. (b) LIB spectra recorded upon irradiation of a new (stock) and a 21 yrs old (field-aged) insulator (Nd:YAG laser; λ=1064 nm).

The higher the difference between the ratios measured for the field-aged insulators and the new insulator, the higher the level of their degradation and the lower their quality. In principle, LIBS is demonstrated to be a reliable and field deployable technique. However, optimization of the diagnostic model requires automation of the insulator area targeting procedure with the laser through the telescope, controlling insulators stability so that the measurement is not affected by weather conditions and using high energy output lasers, which can be portable and easy to use in harsh environments.

V. CONCLUSIONS

The insulators' pollution problem was first recorded in the 66 kV transmission system of Crete in the early 60's. In the decades of 60's and 70's, the transmission system suffered from frequent and long-lasting electricity interruptions, caused by insulators' pollution flashover. This is because, the weather and the climatic conditions of the island, together with the short distance of the transmission system from the coastlines, favour the insulators' pollution and wetting processes.

In an effort to ensure high reliability level of the island's transmission system, a maintenance plan against insulators' pollution has been started since 1978 by the power network operator. The remedies against the insulators' pollution aim to prevent the formation of conductive pollution layer on the insulators' surface. Towards this direction, washing of ceramic insulators with sponges or with dead-washing or even with live-line washing, using RTV SIR coatings as well as the replacing ceramic insulators with composite ones have been attempted by the power network operator. Among the maintenance practices against insulator pollution over these years, the use of polymeric materials (RTV SIR coatings and composite insulators) can ensure high reliability level of the transmission system in the lowest maintenance cost.

However, since the performance of composite insulators exposed in-service stresses for about two decades became questionable, the power network operator faces new challenges, associated mainly with the ageing of the polymeric materials of the composite insulators. Thus, the evaluation of the condition of in-service composite insulators is necessary to optimize the maintenance actions. The collaboration of the power network operator with academia and research institutes of Crete does not only efficiently contribute to assess the condition of field-aged composite insulators, but also to introduce a new remote and real time laser based assessing method.

The results from the adopted evaluation procedure, showed that the EPDM insulators were more degraded than SIR ones. Finally, the preliminary results of remote LIBS were found to be very promising, leading in the definition of an indicator that can indicate the insulators' performance. However, more experiments are needed for the development of a reliable, real-time and remote technique for evaluating composite insulators in service.

ACKNOWLEDGEMENTS

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