Determination of the Insulation Condition in Synchronous Generators: Industrial Methods and Case Study

D. Verginadis, *Member*, *IEEE*, J. Antonino-Daviu, *Senior Member*, *IEEE*, A. Karlis, *Senior Member*, *IEEE*, M. G. Danikas

***Abstract*— Electrical Machines, and especially Synchronous Generators (SG), take a significant position in Power Generation plants and in Industry Production Lines and their unscheduled outages may have very negative repercussions. One of the main reasons for their failure relies on the degradation of their stator and rotor insulation systems. Although there are several industrial methods that are commonly used for diagnosing the health of such parts, some critical aspects remain unsolved. This paper reviews the different diagnostic methods and techniques that are most commonly used in practice to determine the condition of these two insulation systems in SG, emphasizing their respective drawbacks and analyzing their variants. Consequently, a case study on a SG operating in a Power Plant in Greece which illustrates the application of all these methods is presented.**

***Index Terms*—electrical machines, diagnostic techniques, synchronous generator, electrical insulation, fault detection, stator insulation system, rotor insulation system**

I. INTRODUCTION

ELECTRICAL Machines (EM) have a considerable value in generating electricity, in energy production and in industry, as well. Synchronous Generators (SG) play a significant role in the power generation system.

On the other hand, they are subjected to maintenance protocols that are much more exhaustive than those employed in most of the rotating electrical machines operating in industry, even the largest ones [1] – [6].

SG must be reliable and they must have low maintenance requirements and long life span. One of the most vital systems for the proper operation of SG is the insulation, which must have a long and proper lifetime. Large SG have form wound stators [7] – [11]. The structure of their stator winding insulation system is more complex than in random wound stators, as shown in Fig. 1. The three main insulation levels of stator winding insulation are [6]:

- Ground wall insulation
- Insulation between turns /strands
- Semi-conductive coating

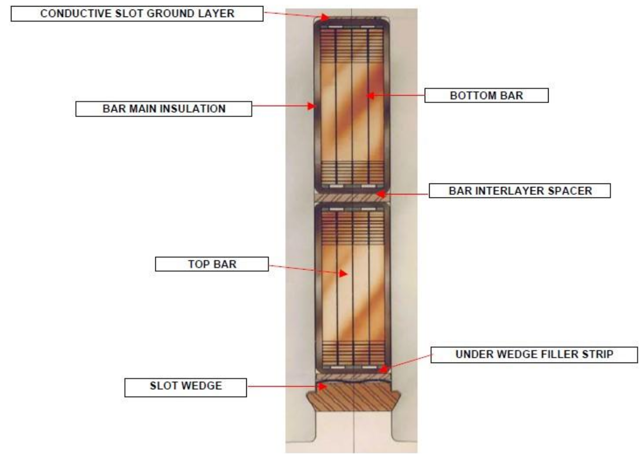


Fig. 1. Structure of stator winding insulation in wound form stators.

On the other hand, the rotor insulation of SG is based on two main parts [6] – [7]:

- Turn to turn insulation
- Slot (ground) insulation

The insulation aging in SG is usually the result of constant or transient stresses acting in combination. These stresses, which are especially relevant due to the high rated levels at which these machines operate [6], [12] – [14], can be classified onto Thermal, Electrical, Ambient and Mechanical (TEAM) stresses, which can influence the overall system causing delaminations and cracks on the insulation material or even electrical breakdown. Most of the times, when there is a deterioration of the insulation system, two or more stresses or factors are responsible for that. Multiple stresses accelerate the failure and can lead to a more significant problem in the SG.

On the other hand, the rotor insulation system is subjected to different stresses from the stator winding insulation. Usually, the rotor insulation is relatively thinner than the stator insulation. The faults of rotor turn insulation are less frequent compare to those of the stator windings, probably due to the lower magnitude of the field winding currents. According to [15], the percentage of stator faults is 60%, which is quite

Part of this research was funded by “GENERALITAT VALENCIANA, Conselleria de Educación, Investigación, Cultura y Deporte, grant number AICO/2019/224”.

D. Verginadis, A. Karlis, M.G. Danikas are with the Department of Electrical and Computer Engineering, Democritus University of Thrace, Xanthi, 67100 Greece (e-mails: dvergina@ee.duth.gr, akarlis@ee.duth.gr, mdanikas@ee.duth.gr).

J. Antonino-Daviu is with the Instituto Tecnologico de la Energia, Universitat Politècnica de València, Camino de Vera s/n, 46022, Valencia, SPAIN (e-mail: joanda@die.upv.es).

lower compared to rotor faults (13%). The main stresses on the rotor insulation are temperature and centrifugal forces. As the DC current passes through the rotor winding copper conductors, creates considerable losses, leading to copper heating [6], [16] – [17].

This paper reviews the main methods applied in the field concerning the determination of the insulation health in SG and describes a case study corresponding to large SG operating in a power generation plant in Greece. The paper includes a short discussion on the pending issues in this area as well as on the future research trends.

II. Diagnostic Techniques For Insulation Monitoring Of Electrical Machines

In most industrial processes, the determination of the insulation condition relies on off-line tests that are carried out with certain periodicity and are designed to measure certain parameters in order to characterize the insulation health. The main tests are [9], [11], [18] – [23]:

1) Insulation Resistance (IR) Test (Std. IEEE 43-2000, modified by Std. IEEE 43-2013 – IR_{1min} = 100 for most ac windings built after 1970 and IR_{1min} = 5 for most EM with random-wound stator coils and form-wound coils rated below 1 kV and dc armatures [24])
2) Measurement of Polarization Index (PI) / Dielectric Absorption (DA) (same standards – minimum PI = 1.5 for thermal class A (105) and minimum PI = 2.0 for class B (130) and above)
3) Capacitance (C) Test
4) Dissipation Factor (DF) Test (IEC 60034-27-3 – DF can be between 0.0 and 1.0)
5) Power Factor (PF) Test (Std. IEEE 286-2000 – PF can be between 0.0 and 1.0)
6) Impedance Test on rotor winding (Std. IEEE 112-2004)
7) Recurrent Surge Oscilloscope (RSO) Test (Std. IEEE 6-2016)
8) HiPot tests (Step Voltage) (Std. IEEE 95-1977, update by Std. IEEE 95-2002 – Initial voltage up to 30 or less o the maximum test voltage
9) Partial Discharges (PD) Tests (IEC 60034-27), which can be carried out in both off-line and on-line mode

In addition to the aforementioned diagnostic tests, visual inspections of the machine are often carried out, using special instruments, such as the borescope, which is an optical device consisting of a rigid or flexible tube with an eyepiece or display on one end, an objective camera on the other, linked together by an optical or electrical system in between. A visual inspection of parts of the SG is usually a powerful tool for assessing the winding condition and for determining the root of problems. For stator inspection, this type of inspection is used for the detection of spread of PD on bars or mechanical erosion and it is performed through core ventilation channels from inside the cooler chambers. Concerning the rotor inspection, this is performed under both retaining rings and through the ventilation slots flowing into air chambers, in order to detect the condition of insulation between turns and ground insulation between retaining rings and end-windings [6].

A. *Standard Off-Line Tests*

The IR/PI [12], [17], [24] – [25] test is the most widely used method for checking the possible problems in windings from pollution and the contamination. For stator measurements, the test is done right at the machine terminals, one phase at a time, with cables and transformers disconnected. A high voltage DC supply and a sensitive ammeter are required for IR/PI test. For rotor windings, the test is carried out at the slip rings.

IR measures the resistance of the electrical insulation between the copper conductor and the core of the stator or the rotor. The minimum recommended values for IR at 1 min at 40°C are defined in the Std. IEEE 43-2000. Periodic trending on the IR over time is valuable to inform about the possible degradation of the ground wall insulation. As the machine operates over the years, the value of IR decreases.

PI is defined as the ratio between the IR measured after the voltage has been applied for 10 minutes (R_{10}) and the IR measured after just 1 minute (R_1) [26]. The PI is a measure of the importance of the absorption or polarization component of the total current. PI is valuable to determine the level of moisture, contamination, cleanness and dryness in the insulation and the imminent collapse of the winding insulation (due to fragilization). PI decreases as the machine ages, because of the higher pollution penetration into the windings.

The Capacitance (C), the Dissipation Factor (DF) and the Power Factor (PF) provide an indication of the dielectric losses within an insulation system. These measurements are conducted to identify if there are variations in C, DF and PF over time, which indicate partial discharges or insulation degradation [27]. DF tip-up method can be used to indicate the abrasion in the slot, while C and DF cannot indicate it.

Phase-to-phase, three-phase or phase-to-ground measurements can be performed for checking the C [28].

The DF is measured with a balanced bridge-type instrument, where a resistive-capacitive network is varied to give the same voltage and phase angle (tan delta) as measured across the stator winding. The DF is calculated from the R and C elements in the bridge that give the null voltage. DF variations with voltage occur as a result of contamination, aging delaminated insulation and partial discharges and that is why it is a good indicator of the insulation health. The DF tip-up depends on the waveform of the applied voltage, as well [29] – [31].

The PF is measured by accurately measuring the Voltage applied between the copper and the core of a winding and detecting the resulting current. Also, it is necessary to measure the power to the winding with a wattmeter.

Recurrent Surge Oscilloscope (RSO) test [32] – [34] is suitable for detecting interturn shorts, ground faults when rotor is at standstill or while the SG are being rotated. When a rotor winding is healthy, there is a symmetrical waveform at each one of the slip rings, otherwise the two signals are different. More specifically, a low voltage high frequency surge wave is injected at each one of the slip rings. The two signals are then compared to determine if the same waveform is observed at each slip ring. If the waves are identical then no short circuits are present. Variations in the pattern of the two waveforms would indicate shorts to be present. Impedance measurement [34] on rotor windings is a test suitable for detecting the condition of turn-to-turn insulation, which can be influenced by humidity or by other stresses, thermal or mechanical.

Finally, HiPot tests have caused a certain controversy, since they are considered as destructive by many users, because they are usually pass/fail tests. In the step-voltage HiPot tests, the applied test voltage is increased in a series of steps until reaching the maximum value defined by the Standard. They are aimed to evaluate the electrical rigidity of the insulation and to detect possible structural damages. They are basically intended to prove that the ground wall insulation system can withstand a high-applied voltage without exhibiting an extraordinarily high leakage current [6].

B. PD Tests

PD monitoring is one of the most powerful methods to determine the insulation condition. PD are electrical discharges inside high-voltage insulation system. PD are both a symptom and they can be a mechanism of aging for the electrical insulation. PD usually occur as a result of various defects as well as when the electric stress exceeds the electrical breakdown strength of the air in voids, cavities or spaces in the insulation. PD in rotating machines cause recognizable patterns, the analysis of which can specify the roots which cause the PD, such as contamination, voids or deterioration of insulation system [35] – [38].

Basically, the standard PD test (IEC 60034-27) consists of installing a set of coupling capacitors at the motor terminals and monitor the high frequency currents that flow through them. It can be done in an online or offline mode [39] – [43]:

The off-line PD measurement can be performed relatively quickly under defined conditions. There is less influence of the noise and better localization of insulation problems. Disconnection from the power system and absence of electromagnetic disturbances generated during operation permit useful measurements to be carried out with relatively simple apparatus. Also, it enables to determine PD inception and extinction PD voltage. But, voltage stresses in the winding and mechanical/dynamic stress relationships are not representative of operating conditions. The machine does not operate under real conditions and an external power supply is necessary. Finally, the fact that the machine is taken out of service has economic outages, as a consequence. On the other hand, on-line PD testing allows trending and the machine operates under real conditions, as it is not necessary to take the machine out of service. Furthermore, for this method, a separate power supply is not necessary. But this method has disadvantages, as well. First of all, there is higher influence of noise compared to off-line PD testing. Also, the installation of sensors is required and the detection of specific failures is not a possibility. Only the detection of generalized failures is possible.

Table I shows all the different, possible problems, of an EM and the suitable method to detect them.

TABLE I
DIAGNOSTIC METHODS

Methods	Means of Measurements	Limitations - Advantages	Computational Method	Measuring Equipment
Visual	Offline	Humidity, Thermal Deterioration, Mechanical Deterioration, Cracks, Ground Wall Insulation, Insulation Degradation, Turn-to-turn Failures	-	Borescope
IR	Offline	Humidity, Contamination, Ground Wall Insulation, Insulation Degradation	$R = \frac{V}{I}$	HV DC Supply, Ammeter
PI	Offline	Humidity, Contamination, Insulation Degradation	$PI = \frac{R_{10}}{R_1}$	Variant of IR
C	Offline	Humidity, Overheating, Dielectric Losses, Insulation Degradation	-	Capacitance Bridge
DF	Offline	Humidity, Overheating, PD, Contamination Dielectric Losses, Insulation Degradation	-	Balanced Bridge-type Instrument
PF	Offline	Humidity, Overheating, Dielectric Losses, Insulation Degradation	$PF = \frac{W}{VI}$	Voltmeter, Ammeter
RSO	Offline	Insulation Degradation, Interturn Faults, Ground Faults, Turn-to-turn Failures	-	Reflectometer
Impedance	Offline	Humidity, Thermal Deterioration, Mechanical Deterioration, Insulation Degradation, Turn-to-turn Failures	$Z = \frac{\Delta V}{I}$	AC source
PD	Offline, Online	PD, Insulation Degradation	-	Set of Coupling Capacitors, Power Supply, PD Measurement Device

III. Case Study: Application Of Industrial Methods To Determine The Insulation Condition Of A SG

Several tests were developed over the years in order to determine the insulation condition of a large SG, the information of which is shown in Table II. This SG was operating in a Power Generation Plant in Greece and it had been synchronized for the first time in 2001.

Inspections and testing of its insulation system were taking place regularly over years. More specifically, the tests performed were: visual inspection of the generator bars and of the slip rings of rotor by using a borescope, IR measurements for both stator and rotor, PI measurements for stator, C/DF measurements, Off-Line and On-Line PD Tests, Impedance measurements and RSO Test. Different tests were taken place each year depending on the SG's condition and the maintenance actions.

A. Visual Inspection

Borescope inspection was regularly performed in order to examine the condition of the stator bars and to detect the possible presence of the mechanical erosion, the deterioration of insulation surfaces, PD effects and cracks. Some suggestions for maintenance or replacement of some parts of this SG depended upon the results of this visual inspection.

Some sample pictures of different faults detected over the years via visual inspection are shown in Figs. 2 – 10. These pictures were taken by using a borescope inside the stator, show that this technology can be useful for the detection of some important insulation defects, the consequences of which can be catastrophic for the SG. Visually the degradation and ageing is getting worse, as the years pass, as well as it is possible to see erosion for mechanical activity (vibration) and erosion for electrical activity (PD).

Regarding the rotor, the field winding was also inspected by borescope under the retaining rings in order to detect the condition of insulation between turns and ground insulation and between retaining rings and end-windings. Sample pictures taken in 2009, depicting some problems in the rotor, are shown in Figs. 11 - 12. More specifically, several spacers set between the straight part of end windings were found cracked. There are no pictures for other years, as there was no problem detected for the rotor.

Electro-mechanical stressing is a problem for machine insulation. Usually, one feeds to other and usually such an insulation is under combined stressing. Different failures are shown with the use of a red circle in each picture. The insulation erosion is visible and as the years pass, the problem is getting worse.

Fig. 2. Mechanical Erosion (2009) – Slot No 08 – Ventilation Channel No 01 Top Side Out.

Fig. 3. Mechanical Erosion (2011) – Slot No 12 – Ventilation Channel No 05 Top Side Out.

Fig. 4. Mechanical Erosion (2014) – Slot No 14 – Ventilation Channel No 01 Top Side Out.

Fig. 5. Electrical Erosion (2009) – Slot No 12 – Ventilation Channel No 02 Top Side Out.

Fig. 6. Electrical Erosion (2011) – Slot No 12 – Ventilation Channel No 77 Top Side Out.

Fig. 7. Electrical Erosion (2014) – Slot No 17 – Ventilation Channel No 01 Top Side Out.

Fig. 8. Crack in Slot No 9 (2012).

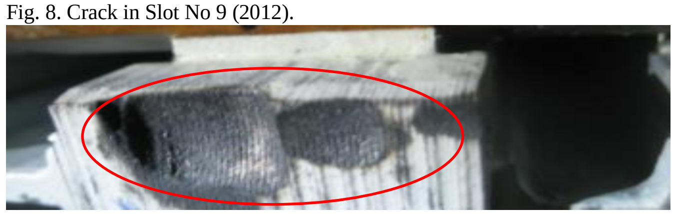


Fig. 9. Crack in Slot No 10 (2012).

Fig. 10. Degradation of stator bar insulation.

Fig. 11. Cracked Spacers Between End Windings Under Retaining Rings (2009).

Fig. 12. Cracked Spacers Between End Windings Under Retaining Rings (2009).

TABLE II
TECHNICAL DATA OF THE SG

Data	***Value***
Rated Power	202 MVA
Rated Voltage	15,75 kV
Rated Current	7405 A
Rated Frequency	50 Hz
cosφ	0,85
Poles	2
Rated Speed	3000 rpm
Rated Excitation Voltage	299 V
Rated Excitation Current	1848 A
Core Length	4620 mm
Number of Slots	60
Cooling Type	Air / Water
Winding	GVPI

B. *IR/PI Measurements*

TABLE III
IR/PI MEASUREMENTS - STATOR

Phase U	***2005***	***2009***	***2010***	***2011***	***2012***	***2014***
IR after 1 min	2400 MΩ	3300 MΩ	2860 MΩ	2466 MΩ	3300 MΩ	3220 MΩ
IR after 10 min	17500 MΩ	21200 MΩ	15100 MΩ	16800 MΩ	19140 MΩ	20200 MΩ
PI	7,3	6,42	5,28	6,81	5,8	6,27

TABLE IV
IR MEASUREMENTS - ROTOR

Rotor Winding	***2009***	***2010***	***2011***	***2012***	***2014***
IR after 1 min	1670 MΩ	8860 MΩ	20000 MΩ	14400 MΩ	16000 MΩ
IR Referred to 20 °C after 1 min	1904 MΩ	53160 MΩ	38000 MΩ	25920 MΩ	-

Different periodic offline tests were performed to measure the IR and PI parameters in order to have an idea of the ground wall insulation condition. Table III shows the results of the measurements of these parameters for the stator insulation over different years. Note the slight decrement in the IR until 2011, and the increase in 2012, but in general the measurements remain stable over time. The PI shows a very high value (>2) which denotes a clean and dry condition so the decrement in IR seems not caused by the humidity/dirtiness, which are significant factors that affect IR and PI [44].

The insulation resistance of the rotor winding was tested by feeding the winding with 500 VDC for one minute and measuring the resistance between the winding and the rotor body in standby mode. In general terms, the values of insulation resistance show that the rotor insulation is in good condition. However, a significant increment is detected between 2009 and 2010. The reason for this may be the maintenance actions, which were recommended after the borescope inspections (see Figs. 11 - 12). These maintenance actions, which are analyzed in G, yielded higher values of IR for the ulterior years.

C. *C/DF Measurements*

Measurements of C and DF were also taken over different years. Table V provides the values of the C and DF measurements for the period 2010 - 2014. The capacitance of rotor winding to ground was also measured and the results are shown in Table VI. Note that C, both for stator and rotor windings, as well as DF remain approximately constant during this period a fact that shows that no significant increment of the dielectric losses and humidity was detected during this period. An increase in DF indicates insulation aging due to overheating or moisture [12], [45] – [46].

D. *PD Measurements*

Online PD tests, as well as offline PD tests were conducted in order to investigate the condition of the insulation system of this generator and its degradation [47].

The procedure for the acquisition of the offline PD data was the following: each phase of the generator was tested separately. The test voltage was increased in steps up to $0.6*V_n$ kV, where V_n is the SG rated voltage. At each voltage step, the PD activity was recorded and the PD measurement results were presented in three-dimensional (3D) diagrams: the diagram was the Phase resolved Phi-Q-N (Phase angle – Apparent charge – Number) chart which represents all the individual PD pulses that have occurred over the selected acquisition time-frame. 3D diagrams are very important for the better understanding of PD. Inner PD as well as slot PD are visible in Phi-Q-N patterns. Also, by a close look at the collected data, it was possible to figure out if the measured PDs are surface PD or not. The measurements of PDs were conducted with: acquisition time 20 sec, the dead time 7 μsec and 1002 periods.

Inner PD arise from voltage over stress within gas filled gaps and voids inside the main insulation system. They are surly present and typical for all resin impregnated mica tape-based insulation systems. As long as they are in the expected range, they can be regarded as no critical on all the phases. The risk factor is very low.

Slot PD arising inside slots where bars of U Phase are set. These discharges happen between insulation surfaces and slot walls due to the presence of air gap and a lack of Slot Corona Protection. Due to this situation, the electrical field of main insulation is no more well defined so the well-designed electrical field stress is no more the same and it stresses the insulation with higher voltage than nominal. The result is that the life-time of bars insulation in Phase U is shorter if compared with other phases. This type of PD is very dangerous and the risk factor, as represented below, very high.

On-line P.D. measurements at different reactive load and winding temperatures could confirm the presence of high slot PD. Online PD monitoring provides continuous information on the stator winding condition. As commented above, its main problem is that it detects general problems in the winding insulation (it is more difficult to locate the origin of the fault) and it is more affected by the electrical noise. Figs. 13 - 15 show some consequences of PD activity in different parts of the slot of the SG. On the other hand, Fig. 16 shows the evolution of the PD activity at the phase U of the generator at phase voltage (Phase Resolved Partial Discharge (PRPD) [49]). Phi-q-N diagram is the same with PRPD graphs. The visualization of the graphs reveals a certain decrement of the PD activity between 2011 and 2014, probably due to an intermediate treatment of the insulation. This seems to be coherent with the measurements of the IR commented above [48]. In 2010 and 2011 it seems that there was a predominance of positive pulses, which denotes potential problems in the insulation surface due to slot PD discharges, which is in concordance with the pictures shown in Figs. 13 – 15.

E. Impedance Measurements

Measurements have been carried out with the volt-ampere system. A variable 50 Hz alternate voltage source was used and it was applied to the slip rings. Current has been increased in step of about 1 A till a maximum of 10 A. At the maximum current the voltage did not exceed 70 V. Simultaneous readings of the current flowing into the test circuit and of the voltage at the slip rings have been made at each current step. Simultaneously, the voltage drops between each slip ring and the accessible poles connection have been performed always at each current step. The measurements shown in Table VI are the average of each value. Table VII shows the maximum and minimum value of total voltage, current and full impedance over the years. The aforementioned impedance measurements show that there is no turn-to-turn short-circuits and faults in the rotor winding of this synchronous EM.

F. RSO Test

The test is based on an oscillograph inspection of the voltage travelling wave between the slip rings along the symmetrically constructed winding field rotor. If the waveforms were different there could be a turn-to-turn fault or earth faults. But, when the waveforms are identical, as shown in Fig. 17 for three different years, the rotor winding can be considered free from turn-to-turn short-circuits and earth fault both in standby and dynamic condition. SR1/OS is the voltage of slip ring 1 and the SR2/IS the voltage of slip ring 2.

G. Maintenance Actions

All the aforementioned measurements are very helpful for the determination of the insulation condition of the SG. IR/PI measurements are very helpful in order to check the ground wall insulation as well as the existence of moisture on the winding insulation. These measurements were taken place on 2009 - 2012 and 2014 both on stator and rotor winding. C/DF/PF measurements can give significant information about insulation degradation, as well, and a first approach for the indication of PD. C/DF measurements on stator were taken place on 2010 - 2012 and 2014, while C measurements on rotor on 2009, 2011 and 2012. The most suitable test for detecting PD is the PD test (online or offline), which was taken on 2010 - 2011 and 2014. The existence of moisture, especially on turn-to-turn insulation can be verified by impedance measurement on rotor, which were taken on 2009 - 2012 and 2014. It is important to be mentioned that the measurements chosen each year, to be taken, were the suitable ones according to the SG condition. The above measurements indicate a SG in good condition. As the years pass, different maintenance actions are recommended in order the condition of the SG to get better or to stay at the same condition. After each year, cleaning of stator core and winding as well as cleaning of rotor body and the end-winding under retaining rings were made. Moreover, the stator windings resin injection was recommended and performed under wedges, in slots, between top bars and slot wall and between bottom bars and slot wall on 2005 and on 2009. The scope of this injection was to prevent mechanical vibrations that could facilitate the erosion of insulation system. This is confirmed by the measurements above. On 2009 - 2010, the installation of an online PD monitoring system was recommended in order abnormal situation or sudden changes in the behaviour of stator winding to be observed and to predict if the SG is close to possible faults and problems. On 2012, after 11 years of operation, the replacement of the stator windings was recommended, as they were in bad condition and the degradation was evolving rapidly. Also, the electrical field within the insulation was no more well defined. Therefore, on September 2012, a total rewind of stator windings was carried out. Final, on 2014, replacements of phase separators were recommended during the last year of inspection, described in this manuscript, which is a preventative method in order to assure reliable operating condition of close junctions protective caps belonging to different phases. Also, the operation of the generator at low rate of Reactive Power (MVAr) was also recommended in order to reduce the vibration of bars and the stress of main insulation. The rotor is in a better condition compared to the stator and that is why there are less recommendations for maintenance and improvement compared to recommendations for the stator.

TABLE V
C/DF MEASUREMENTS – STATOR

Phase U	*2010*	*2011*	*2012*	*2014*
DF	7,80%	7,50%	7,40%	8,30%
C	0.490 μF	0,483 μF	0,490 μF	0,476 μF

TABLE VI
C MEASUREMENTS - ROTOR

Rotor Winding	*2009*	*2011*	*2012*
C to Ground	1.07 μF	0.97 μF	1.00 μF

Fig. 13. Traces of slot PD (2009) – Slot No 18 – Ventilation Channel No 03 Top Side Out.

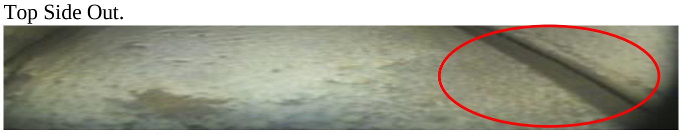
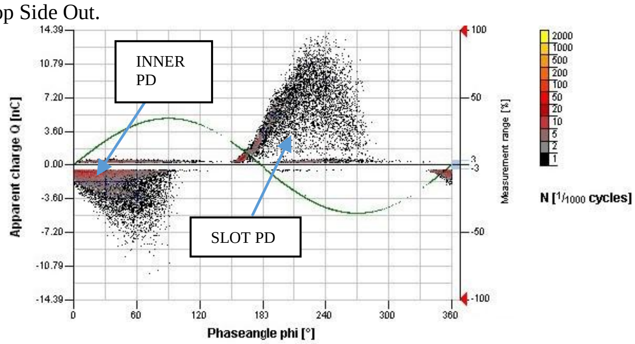
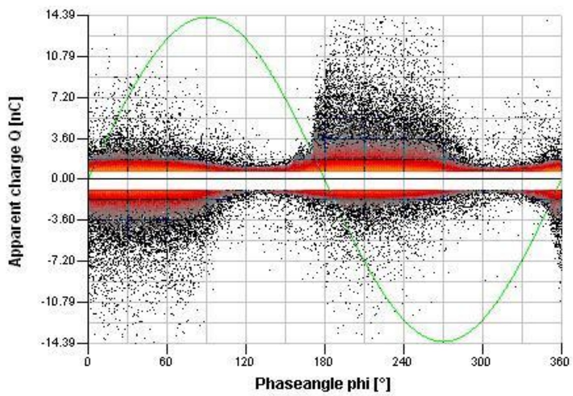


Fig. 14. Traces of slot PD (2011) – Slot No 12 – Ventilation Channel No 791 Top Side Out.

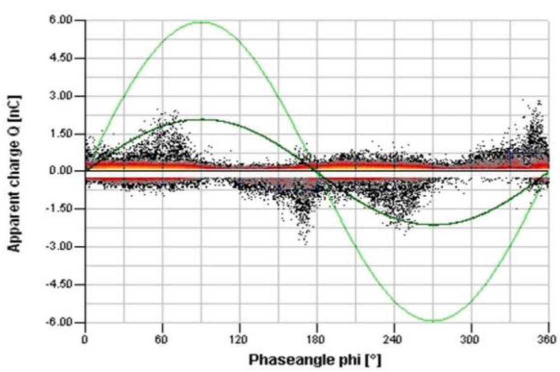
Fig. 15. Traces of slot PD (2014) – Slot No 15 – Ventilation Channel No 47 Top Side Out.



(a)



(b)



(c)

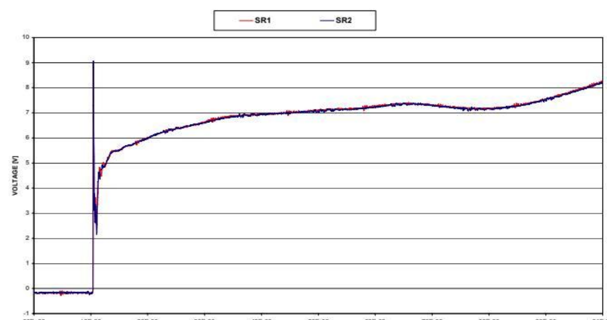
Fig. 16. PD activity in phase U of the stator in: (a) 2010, (b) 2011 and (c) 2014. Note the different y-axis scales between (a)-(b) and (c).

TABLE VII
IMPEDANCE MEASUREMENTS - ROTOR

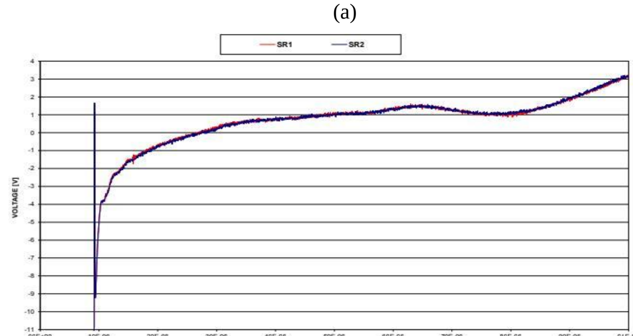
Rotor Winding	*2009*	*2010*	*2011*	*2012*	*2014*
Total Voltage	40.61 V	33.60 V	31.34 V	31.44 V	31.85 V
Current	7.10 A	5.56 A	5.57 A	5.53 A	5.56 A
Full Impedance	5.72 Ω	6.10 Ω	5.59 Ω	5.66 Ω	5.70 Ω

TABLE VIII
IMPEDANCE MEASUREMENTS (MIN – MAX) - ROTOR

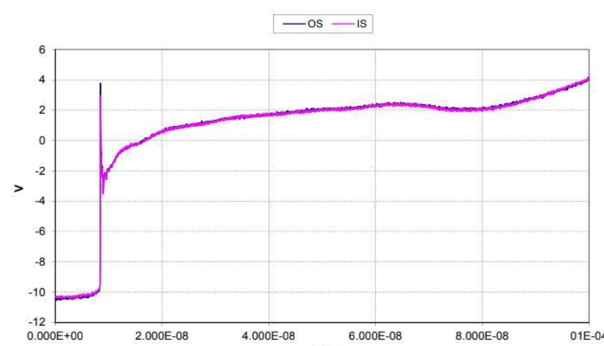
Rotor Winding	*2009*	*2010*	*2011*	*2012*	*2014*
Total Voltage	6.24V - 57.82 V	7.50V - 60.20 V	6.08V - 57.67 V	6.02V - 56.76 V	6.53V - 58.17 V
Current	1.11A - 10.00 A	1.17A - 9.99A	1.12A - 10.09 A	1.08A - 9.87A	1.16A - 10.06 A
Full Impedance	5.62Ω - 5.78Ω	6.37Ω - 6.02Ω	5.41Ω - 5.72Ω	5.57Ω - 5.75Ω	5.63Ω - 5.78Ω



(a)



(b)



(c)

Fig. 17. RSO Test in: (a) 2010, (b) 2012 and (c) 2014.

IV. Conclusions

SG are the most critical assets of power plants and their unscheduled outages may have very negative repercussions for the whole power generation system., Therefore, it must be assured that their different components and, more specifically, the insulation system of both rotor and stator maintain their respective properties (low dielectric losses, high dielectric strength, good structural integrity (i.e. no defects, voids or damages).

As shown in the paper, the visual inspection via borescope cameras is always an interesting option to detect insulation problems in stator or rotor (erosion, defects due to impacts, cracks). However, it is only able to detect evident problems, whereas it is not always suitable to find incipient failures or internal problems.

With regards to off line tests, PD tests, IR/PI and C/DF/PF measurements, Surge tests, Impedance measurements and RSO Test are excellent options to measure different insulation properties (insulating resistance, humidity/dirtiness, dielectric losses, turn shorts, etc.). However, their development implies the disconnection of the unit as well as equipment of certain complexity. This makes their application sporadic which complicates the continuous monitoring of the insulation condition. Moreover, most of them have their own constraints and are mainly focused on the ground wall insulation condition.

In this context, PD tests reveal as a powerful source for the determination of the insulation condition. While offline tests may be ideal to locate the exact point where a potential damage starts, the online PD tests are suitable to perform a continuous monitoring of the insulation condition. In the PD tests carried out in the field SG, the analysis of the PD data over the years enables, not only to detect the presence of early insulation problems, but also to discern where the fault is originated (in this case, due to slot PD). These facts confer this technique with a great potential for the diagnosis of this delicate part of the machine.

Taking into consideration all the aforementioned, the conclusion that can be extracted is that a good diagnosis on both stator and rotor can lead to a minimization of shutdown time, maintenance time and consequently financial losses. Last but not least a combination of all diagnostic methods that were described above leads to a better and more realistic and more complete estimation of the condition of both stator and rotor insulation systems of the SG [50] – [54].

It is true that many advances have been lived over recent years concerning the determination of the insulation condition. On the other hand, several issues are still pending. One of the most significant issues is the development of a reliable online method that enables to determine the degradation level of the insulation at each time. It would be very useful for the industry if an immune method to the surrounding noise could be developed in order to yield results, that can be interpreted by non-expert users or that can be automatically processed by intelligent algorithms. Some promising methods based on broadband insulation spectroscopy have been recently proposed in [55]. Moreover, there are specific tests for some parts of the machine (e.g. the rotor) that have not been applied in the presented case study. This shows the limitations of condition monitoring of the insulation system in the field, where not all available tests are regularly applied due to diverse causes (lack of knowledge, non-availability of necessary equipment…).

Future research could be a better correlation between laboratory data and on-line data. It may deal with permissible PD in stator insulation depending of course on the type of insulation. Furthermore, a thorough study may be carried out regarding long-term effects of small PD.

V. Acknowledgement

The authors of this paper would like to thank Mr. Pericles Stratigopoulos, Director of Komotini Power Plant, Public Power Corporation S.A. – Hellas for providing the pictures of stator and rotor and the measurements for this SG.

References

[1] J.Pyrhoonen, V. Hrabovcova, S. R. Semken, “Electrical Machines Drives Control: An Introduction”, 2016, John Wiley & Sons Ltd, UK.

[2] M. Redondo, C. A. Platero and K. N. Gyftakis, "Turn-to-turn fault protection technique for synchronous machines without additional voltage transformers," 2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Tinos, 2017, pp. 117-121.

[3] S. Afrandideh, M. E. Milasi, F. Haghjoo and S. M. A. Cruz, "Turn to Turn Fault Detection, Discrimination, and Faulty Region Identification in the Stator and Rotor Windings of Synchronous Machines Based on the Rotational Magnetic Field Distortion", in IEEE Transactions on Energy Conversion, vol. 35, no. 1, pp. 292-301, March 2020.

[4] S. J. Chapman, Electric Machinery Fundamentals, Fourth. New York: McGraw-Hill Higher Education, 2004.

[5] A. Hughes and B. Drury, Electric motors and drives: fundamentals, types and applications. Newnes, 2019.

[6] G.C. Stone, E. A. Boulter, I. Culbert, H. Dhirani, “Electrical Insulation for Rotating Machines: Design, Evaluation, Aging, Testing, and Repair”, A John Wiley & Sons, INC., 2004. Canada.

[7] R. Brütsch and M. Chapman, “Insulating systems for high voltage rotating machines and reliability considerations”, 2010 IEEE International Symposium on Electrical Insulation, San Diego, CA, 2010, pp. 1-5.

[8] Nathaniel Taylor, “Diagnostics of stator insulation by dielectric response and variable frequency partial discharge measurements”, Licentiate Thesis, KTH Royal Institute of Technology Stockholm, November 2006.

[9] A. Cimino, F. Jenau, C. Staubach, A. Mashkin and F. Pohlmann, "Analysis of fault detection in the electrical insulation system of rotating machines," 2018 International Conference on Diagnostics in Electrical Engineering (Diagnostika), Pilsen, 2018, pp. 1-4.

[10] M. Sumislawska, K. N. Gyftakis, D. F. Kavanagh, M. D. McCulloch, K. J. Burnham and D. A. Howey, "The Impact of Thermal Degradation on Properties of Electrical Machine Winding Insulation Material," in IEEE Transactions on Industry Applications, vol. 52, no. 4, pp. 2951-2960, July-Aug. 2016.

[11] M. Riera-Guasp, J. A. Antonino-Daviu and G. Capolino, "Advances in Electrical Machine, Power Electronic, and Drive Condition Monitoring and Fault Detection: State of the Art," in IEEE Transactions on Industrial Electronics, vol. 62, no. 3, pp. 1746-1759, March 2015.

[12] A. Cimino, F. Jenau and C. Staubach, "Causes of cyclic mechanical aging and its detection in stator winding insulation systems," in IEEE Electrical Insulation Magazine, vol.35, no.3, pp.32-40, May-June 2019.

[13] G. Pietrini, D. Barater, F. Immovilli, A. Cavallini and G. Franceschini, "Multi-stress lifetime model of the winding insulation of electrical machines," 2017 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), Nottingham, 2017, pp. 268-274.

[14] C. Saxén, E. K. Gamstedt, R. Afshar, G. Paulsson and F. Sahlén, "A micro-computed tomography investigation of the breakdown paths in mica/epoxy machine insulation," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 25, no. 4, pp. 1553-1559, August 2018.

[15] Mostafaei, M., Faiz, J., “An overview of various faults detection methods in synchronous generators.”, IET Electr. Power Appl, vol. 15, pp. 391-404, 2021.
[16] A. Bellini, F. Filippetti, C. Tassoni, and G. A. Capolino, “Advances in diagnostic techniques for induction machines,” IEEE Trans. Ind. Electron., vol. 55, no. 12, pp. 4109–4126, 2008.
[17] M. Kiani, W. Lee, R. Kenarangui and B. Fahimi, "Detection of Rotor Faults in Synchronous Generators," 2007 IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, Cracow, 2007, pp. 266-271.
[18] G. C. Stone, "Condition monitoring and diagnostics of motor and stator windings – A review," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 20, no. 6, pp. 2073-2080, December 2013.
[19] Sang Bin Lee, Tae-June Kang, Heedong Kim, Taesik Kong and Chaewoong Lim, "Case studies of stator winding turn insulation failures in medium voltage motors," 2017 Annual Pulp, Paper and Forest Industries Technical Conference (PPFIC), Tacoma, WA, 2017, pp. 1-8.
[20] C. Zoeller, M. A. Vogelsberger, R. Fasching, W. Grubelnik and T. M. Wolbank, "Evaluation and current-response based identification of insulation degradation for high utilized electrical machines in railway application," 2015 IEEE 10th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Guarda, 2015, pp. 266-272.
[21] M. F. Cabanas et al., "Detection of stator winding insulation failures: On-line and off-line tests," 2013 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), Paris, 2013, pp. 210-219.
[22] IEEE Guide for Insulation Maintenance of Electric Machines," in IEEE Std 56-2016, vol., no., pp.1-86, 11 Nov. 2016.
[23] IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus - Electrical Machinery," in IEEE Std 62.2-2004, vol., no., pp.1-108, 8 June 2005.
[24] A. Brown, E. David and M. Essalihi, "Insulation resistance measurements for machine insulation," 2011 Electrical Insulation Conference (EIC), Annapolis, MD, 2011, pp. 261-264.
[25] H. Torkaman, F. Karimi, “Measurement variations of insulation resistance/polarization index during utilizing time in HV electrical machines – A survey”, pp. 21–29, 2015.
[26] S. A. Bhumiwat, "Insulation resistance and polarization of rotating machines," 2011 Electrical Insulation Conference (EIC), Annapolis, MD, 2011, pp. 249-253.
[27] Sang Bin Lee, K. Younsi and G. B. Kliman, "An online technique for monitoring the insulation condition of AC machine stator windings," in IEEE Transactions on Energy Conversion, vol. 20, no. 4, pp. 737-745, Dec. 2005.
[28] P. Werelius, M. Ohlen, Jialu Cheng and D. M. Robalino, "Dielectric frequency response measurements and dissipation factor temperature dependence," 2012 IEEE International Symposium on Electrical Insulation, San Juan, PR, 2012, pp. 296-300.
[29] P. J. Berry and E. S. Hamdi, "Monitoring the stator winding insulation condition of a large synchronous motor," 2016 51st International Universities Power Engineering Conference (UPEC), Coimbra, 2016, pp. 1-6.
[30] A. Grav, I. Erling, H. Sverre and N. Arne, “Review of Partial Discharge and Dielectric Loss Tests for Hydropower Generator Bars”, Proceedings of the Nordic Insulation Symposium 2017.
[31] Howard Sedding, “Dissipation Factor Acceptance Criteria for Stator Winding Insulation”, Diagnostic News, IRIS Power, 2016.
[32] I. Kerszenbaum and C. Maughan, "Utilization of Repetitive Surge Oscillograph (RSO) in the detection of rotor shorted-turns in large turbine-driven generators," 2011 Electrical Insulation Conference (EIC), Annapolis, MD, 2011, pp. 398-401.
[33] O. Imoru, L. Mokate, A. A. Jimoh and Y. Hamam, "Diagnosis of rotor inter-turn fault of electrical machine at speed using stray flux test method," AFRICON 2015, Addis Ababa, 2015, pp. 1-5.
[34] P. Kumar, V. Raghavendra Rao, “Recurrent Surge Oscillograph (RSO) for Rotor Winding Shorts Detection.” 2012.
[35] C. Malliou, A. Karlis and M. G. Danikas, "Electrical machine insulation: Partial discharges, consequences and diagnostic technique," 2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Tinos, 2017, pp. 468-474.
[36] A. Contin, "Diagnostics of insulation systems by means of partial discharges," 2015 IEEE 10th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Guarda, 2015, pp. 191-197.
[37] G. C. Montanari and A. Cavallini, "Partial discharge diagnostics: from apparatus monitoring to smart grid assessment," in IEEE Electrical Insulation Magazine, vol.29, no.3, pp.8-17, May-June 2013.
[38] G. C. Montanari, A. Cavallini, F. Ciani and A. Contin, "Accelerated aging, partial discharges and breakdown of Type II turn-to-turn insulation system of rotating machines," 2016 IEEE Electrical Insulation Conference (EIC), Montreal, QC, 2016, pp. 190-193.
[39] N. Dehlinger and G. Stone, "Surface partial discharge in hydrogenerator stator windings: Causes, symptoms, and remedies," in IEEE Electrical Insulation Magazine, vol.36, no.3, pp.7-18, May-June 2020.
[40] Wong Jee Keen Raymond, Hazlee Azil Illias, Ab Halim Abu Bakar, Hazlie Mokhlis, Partial discharge classifications: Review of recent progress, Measurement, vol. 68, 2015, pp. 164-181.
[41] Luo Y, Li Z, Wang H., “A Review of Online Partial Discharge Measurement of Large Generators”, Energies, vol. 10, no. 11, pp. 1694, 2017.
[42] G. C. Stone, "A perspective on online partial discharge monitoring for assessment of the condition of rotating machine stator winding insulation," in IEEE Electrical Insulation Magazine, vol. 28, no. 5, pp. 8-13, September-October 2012.
[43] M. Ghassemi, "Accelerated insulation aging due to fast, repetitive voltages: A review identifying challenges and future research needs," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 26, no. 5, pp. 1558-1568, Oct. 2019.
[44] R. Soltani, E. David and L. Lamarre, "Impact of humidity on dielectric response of rotating machines insulation system," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 17, no. 5, pp. 1479-1488, October 2010.
[45] S. J. Williamson, R. Wrobel, J. Yon, J. D. Booker and P. H. Mellor, "Investigation of equivalent stator-winding thermal resistance during insulation system ageing," 2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Tinos, 2017, pp. 550-556.
[46] C. Zöller, et al. “Evaluation and current-response based identification of insulation degradation for high utilized electrical machines in railway application.” 2015 IEEE 10th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), 2015, pp. 266-272.
[47] A. Ovsyannikov, S. Zhivodernikov, D. Vodennikov and A. Kokh, "Partial Discharges: Questions for Discussion," 2020 International Conference on Diagnostics in Electrical Engineering (Diagnostika), Pilsen, Czech Republic, 2020, pp. 1-6.
[48] Bo Yue, Xiaolin Chen, Yonghong Cheng, Jiancheng Song and Hengkun Xie, "Diagnosis of stator winding insulation of large generator based on partial discharge measurement" IEEE Transactions on Energy Conversion, vol.21, no.2, pp.387-395, June 2006.
[49] H. Illias, Teo Soon Yuan, A. H. A. Bakar, H. Mokhlis, G. Chen and P. L. Lewin, "Partial discharge patterns in high voltage insulation," 2012 IEEE International Conference on Power and Energy (PECon), Kota Kinabalu, 2012, pp. 750-755.
[50] M. Kande, A. Isaksson, R. Thottappillil, N. Taylor, “Rotating Electrical Machine Condition Monitoring Automation—A Review”, Machines, no 5, pp. 24. 2017.
[51] L. Frosini, "Monitoring and Diagnostics of Electrical Machines and Drives: a State of the Art," 2019 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), Athens, Greece, 2019, pp. 169-176.
[52] P. Tian, C. A. Platero and K. N. Gyftakis, "On-line Turn-to-Turn Protection Method of the Synchronous Machines Field Winding," 2019 IEEE 12th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Toulouse, France, 2019, pp. 69-74.
[53] L. Frosini, "Novel Diagnostic Techniques for Rotating Electrical Machines—A Review." Energies 13, no. 19, pp.5066, 2020.
[54] D. Verginadis, J. Antonino-Daviu, A. Karlis, M. G. Danikas, “Diagnosis of stator faults in synchronous generators: Short review and practical case”, In Proceedings of the 2020 ICEM, Gothenburg, Sweden, 23–26 August 2020.
[55] P. Neti and S. Grubic, "Online Broadband Insulation Spectroscopy of Induction Machines Using Signal Injection," in IEEE Trans. Ind. Appl., vol. 53, no. 2, pp. 1054-1062, March-April 2017.

Dimosthenis Verginadis received his M.Eng and M.Sc Degree in Electrical and Computer Engineering from the Department of Electrical and Computer Engineering, Democritus University of Thrace, Xanthi, Greece and he is currently a Ph.D. Candidate at the same Department. His fields of interest are electrical machines, insulation systems and diagnosis.

Jose A. Antonino-Daviu received the M.Sc. and Ph.D. degrees in electrical engineering, both from the Universitat Politècnica de València, Valencia, Spain, in 2000 and 2006, respectively. He has worked for IBM, involved in several international projects. He is currently a Full Professor in the Department of Electrical Engineering, Universitat Politècnica de València. He was an Invited Professor at Helsinki University of Technology, Finland, in 2005 and 2007, Michigan State University, USA, in 2010, Korea University, South Korea, in 2014, Université Claude Bernard Lyon 1, France, and Coventry University, U.K., in 2016. He is a coauthor of more than 200 papers published in technical journals and conference proceedings. He is also the coauthor of one international patent. Dr. Antonino-Daviu is an Associate Editor of the IEEE transactions on Industrial Informatics, IEEE Industrial Electronics Magazine and IEEE Journal of Emerging and Selected Topics in Industrial Electronics.

Athanasios Karlis (M'2000, SM'2012) received his Dipl.-Eng. and PhD degrees from Electrical & Computer Engineering Department of the Aristotle University of Thessaloniki, Greece (1991 and 1996 respectively). He is currently Associate Professor at the Department of Electrical & Computer Engineering, Democritus University of Thrace, Greece. His research interests are in electrical machines and drives, renewable energy sources and electrical power systems. He is also founder and Advisor of the Democritus University of Thrace IEEE IAS SBC and Chair of the IEEE IES/IAS/PELS Joint Chapter (Greece Section). He received the 2015 IEEE Outstanding Branch Chapter Advisor Award and the 2016 Outstanding IEEE IAS Student Branch Chapter Advisor Award.

Michael G. Danikas received his B.Sc. and M.Sc. degrees in Electrical and Electronic Engineering from the University of Newcastle-upon-Tyne, UK, (1980 and 1982 respectively) and his Ph.D. from the University of London, Queen Mary College, London, UK, in 1985. He is currently Professor at Democritus University of Thrace, Department of Electrical and Computer Engineering. His research interests are in partial discharges in solid dielectrics, surface discharges and flashovers on insulating surfaces, transformer oil breakdown and diagnostic techniques in high-voltage insulating systems.