ASSESSMENT OF THE ELECTRIC HYDRO GENERATOR STATOR INSULATION CONDITION BY MEANS OF ON-LINE PARTIAL DISCHARGE MEASUREMENT

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Abstract - The paper presents the principle of the measurement method, the quantities characterizing the partial discharges and the criteria utilized for the evaluation of the insulation condition. Further, the results of the measurements of several hydro generators and the variation with time of the quantities that characterize the partial discharges, Qmax magnitude and the normalized quantity NQN, over a period of about 10 years are presented. A synthetic presentation of the conclusions of the insulation condition annual evaluation and of the decisions that have been taken relating to the hydro generator maintenance has been made. The paper ends with several considerations on the method and evaluation criteria efficiency

Keywords: partial discharges, hydrogenerators, measurement, magnitude, normalized quantity

1. GENERALITIES

In general, partial discharges (PD) are small non-disruptive electrical discharges that occur in the micro cavities existing in the insulation. The discharges are partial due to the fact that in series with the micro cavity where the discharges occur there is also an area with solid insulation.

The pulses of partial discharge are very rapid phenomena that last only for a few nanoseconds. The insulations, especially the stratified ones, cannot be considered as perfectly homogenous. There are always small size micro cavities filled with gas resulting from the different contractions of the insulation constituents or even from the technological execution process itself. The occurrence of such micro cavities and cracks is favored by the intermittent action of the thermal and mechanical stresses to which the insulation is subjected during operation, as well as to the action of the pollutant factors (moisture, dust, oil) from the insulation operational environment.

In the conditions of an electrical field, these micro cavities get ionized and, when the voltage between two opposed surfaces attains the disruptive gradient of the gases contained in the micro cavity, partial discharges (ionizations) occur.

The occurrence and development of internal PDs has a negative impact on the insulation, leading to the formation of micro cavities that increase with time, forming channels when several such cavities unite, and finally resulting in craters; thus, the insulation is weakened and breakthroughs that ruin the insulation may occur.

The PD are measured as voltage pulses; that is why, during the positive alternation of the voltage wave form a discharge or a partial short circuit lead to a negative pulse oriented downwards. These pulses are called negative polarity PD and occur during the first quarter of the period, during period of increase in the amplitude of positive alternation of the voltage applied to the cavity. During the third quarter of the period a partial short circuit leads to the occurrence of a positive impulse, oriented upwards. These pulses are called positive polarity PD s and occur during the increase in the negative alternation amplitude.

2. METHOD OF MEASUREMENT

The on – line measurement can be carried out only on generators previously fitted with couplers. The method consists in previously mounting several couplers on the terminals or even the stator bus bars, taking out the wires to a terminal block, exterior, and the measurement of the PD during generator operation by means of an analyzer connected to the respective connection terminals. The couplers are usually insulator type capacitors, having a capacity of about 80-100 pF and operating voltages of 25-30 kV.

According to the type of the generator and of the stator winding, two coupler mounting systems are used:
- The differential mounting (PDA) with a coupler on each current path of each phase, at about 1 m from the connection point of the current paths;
- The directional mounting (BUS) with two couplers at each phase outlet, at about 2 m one against the other and 1 m from the terminal outlet of the machine .

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The coupler that is the nearest to the winding is called machine coupler, and the other one is called system coupler.

These systems enable the elimination of the electric noise occurring inside and in the proximity of the machine that interferes with the partial discharges from the machine. It is possible to discriminate the partial discharges by comparing the signals from the two associated couplers, situated on two current paths of a phase (for the differential system), or to the outlet of the same phase (for the directional system) and considering the time difference of nanoseconds with which they get to the analyzer due to the electrical distance between the associated couplers. The partial discharges originate in the stator winding as compared to the noise signals that come from the outside the winding.

The couplers are connected to the terminal box, to which the measurement system made up of a partial discharge analyzer and a laptop with specialized software is connected

Measurement system calculates and displays the following quantities and diagrams (fig. 1):

- The maximum magnitude (peak) of partial discharge, noted with the symbol ±Qmax, which is the magnitude corresponding to a repetition rate (P_w) of 10 pulses per second and window (negative and positive), expressed in mV:
-

$$Q_{max} = \max\,[M = f(P_w)] \qquad (1)$$
$$P_{win} \geq 10 \text{ p/sw}, \;\; w \in (0\text{-}N)$$

where:

P_w - number of pulses per second and magnitude window (p/sw)

M - magnitude of partial discharge (mV)

- The normalized quantity (also named "total activity") of PD, noted by ±NQN that is a relative quantity, equal to the ratio between the area under the curve of the number of pulses versus the amplitude (from the 2D diagram) and the area of the normal range of 10000 pulses per second at 800 mV (negative and positive);

$$NQN = \sum_{w=0}^{N} A_w = \frac{M}{N}\sum_{w=0}^{N}\frac{p_w - p_{w+1}}{2} \qquad (2)$$

$$p_w = \log_{10}(P_w) \qquad P_w \in (0,1,2\,....N) \qquad (3)$$

$$NQN = \frac{M}{NG}\left[\frac{\log_{10}(P_0)}{2} + \sum_{w=1}^{N-1}\log_{10}(P_w) + \frac{\log_{10}(P_N)}{2}\right] \qquad (4)$$

where:

A_w – surface under the curve $M=f(P_w)$ for each window

N - number of magnitude windows,

p_w - logarithm of the pulse counts

G - gain of the partial discharge detector (arithmetic, not decibels)

- The bi-dimensional diagrams 2D: the number of pulses per second and window (the rate of pulses) versus the amplitudes that define the windows;

- The tri-dimensional diagrams 3D: the pulse rate versus the phase angle of the sinusoidal voltage at which they occur and the magnitude of the window;

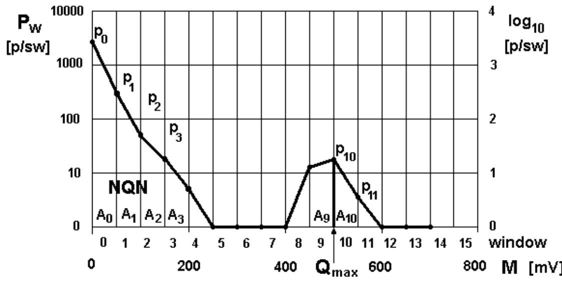

Fig. 1. Definition of the normalized quantity NQN and maximum magnitude Q_{max}

3. CRITERIA FOR THE EVALUATION OF THE STATOR WINDING CONDITION

Based on the research and experience in measurements and the analysis of events and maintenance works in the field of electrical generator insulations [4], three main and two intermediary categories of insulation conditions have been defined:

Table 1.Categories of insulation condition

Category	Condition description	Level of risk
I	Very good condition (new insulation), good, normal	operation without risks
I-II	Acceptable condition, slow , normal, small scale deteriorations	operation without risks
II	Slow, normal deteriorations	average breakdown risk
II -III	Slow, normal, average scale deteriorations with a tendency towards becoming more severe	average breakdown risk
III	Severe deteriorations	high breakdown risk

Based on the experience from the literature in the field [5,6,7], on the utilization instructions of the IRIS type analyzer [8] and on authors' experience, the limit values of the maximum magnitude and the normalized quantity have been established according to the level of the hydro generator rated voltage and the condition of insulation (table 2). Also, qualitative criteria for the assessment of the insulation condition on the basis of the 2D and 3D diagram analysis, presented in table 3, have been developed.

Table 2. Quantitative criteria

Cat.	Insulation condition	± NQN (p.u.)		± Qmax (mV)		
		<15 kV	> 15 kV	< 7 kV	10 ÷ 15 kV	> 15 kV
I	Good	<100	<250	< 60	< 170	<300
II	Slow, normal deteriorations	100-250	250-450	60-140	170 - 400	300-600
III	Severe deteriorations	>250	>450	> 140	> 400	>600

Note

The maximum amplitude Qmax indicates the level of insulation deterioration in the worst affected point in the

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winding. The normalized quantity NQN is proportional to the total extent of the overall insulation deterioration.

Table 3.Qualitative criteria

Assessed parameter	Assessment criterion	Insulation condition
1.Variation of arameters ±Qmax and ±NQN with time	increase < 25 %	Category I – Good condition
	Constant increase	Category II – Slow, normal deteriorations
	increase > 100 %	Category III – Severe deteriorations
2. Curve aspect in 2D diagrams	Polarity equality Ratio R = -Qmax / +Qmax =1 Curves overlapping / knitting p/sf = f(mV) in 2D	Volume PD in the slot area due to separation between layers (delaminations) and empty spaces (voids) in the insulation mass (thermal effect). Cat. II
	Mainly negative polarity Ratio R =-Qmax/ +Qmax > 2 Curves position ± p/sf =f(mV) in 2D	Volume PD, due to the voids between the insulation and the copper conductor (cyclic load effect) R= 1-2 cat. I, R >2 cat. II, R>> 2 cat. III
	Mainly positive polarity Ratio R=+Qmax/ -Qmax > 2 Curves position ± p/sf =f(mV) in 2D	Surface PD in the slot area between the insulation and the slot wall due to the deterioration of the conductive lacquer coating R= 1-2 cat. I, R >2 cat. II, R>> 2 cat. III
3. PD presence in the 3D diagrams, on the sinusoid	Presence of negative PD at α between 0^0 and 90^0, centered on 45^0	Volume PD due to separation (voids) between insulation and the copper conductor (cyclic load effect)
	Presence of positive PD at α between 180^0 and 270^0, centered on 225^0	Surface PD in the slot area between the insulation and the slot wall due to the deterioration of the conductive lacquer coating
4. Aspect of the 3D and 2D diagrams relating to the PD in the frontal area (ZF)	In 3D, PD occurrence at α = 15^0, 75^0, 195^0, 255^0 In 2D, curve humps ± p/fs =f(mV) at high magnitudes and low p/sf	Surface PD in the area of the frontal ends due to dust, oil, etc., pollution and / or of their consolidation weakening and/or deterioration of the conductive lacquer on the surface of the insulation
5. Extent of the PD occurrence in the 3D diagrams (p/sf and mV)	0-20 p/sf	Category I – Good condition
	20-50 p/sf	Category II – Slow deteriorations, normal
	>50 p/sf	Category III – Severe deteriorations

4. MEASUREMENTS RESULTS

Further, the results of the on-line PD measurements and analysis for the evaluation of the insulation condition of 4 hydro generators selected out of the 13 with a measurement history are presented. All these generators have mica-epoxy type stator winding insulation.

At **HG 2 HPS Mărişelu**, 75 MW, 15.75 kV (fig. 2) during the entire period 1999 – 2010 the values of ±NQN and ±Qmax on all the phases had a practically constant evolution. The ±NQN parameters surpassed the maximum reference value of 450 p.u., varying around the value of 800 for all the phases. This has indicated an expanded extent of the deterioration (category III).

The ±Qmax parameters remained within the reference range (300-600 mV) indicating a slow and normal deterioration of the insulation (category II). The zigzag aspect of the PD variation curves was due to the maintenance works, simple or more complex. The effect of these works on the stator winding resulted in a certain improvement in the PD parameters.

In the 2D diagrams (fig.3), on all the phases, for all the measurements, a quasi-equality between polarities with the overlapping of the p/sf =f(mV) curves, or their knitting, indicating the occurrence of volume PDs within the slot area (category II) was noticed.

In the 3D diagrams (fig.4), on all the phases, the occurrence of the negative and positive PDs at the electric angles of α=0°-90° and α=180°- 270°, respectively, was very dense, indicating the occurrence of volume and surface PDs in the slot area. In 2007, the repetition frequencies were of 80-100 p/sf with low magnitudes and 10 p/sf with high magnitudes and in 2010, of about 60 -80 p/sf with low magnitudes and 10 p/sf with high magnitudes, (category III).

At the same time, for all the phases, the occurrence of PD at α = 15^0, 75^0 , 195^0 , 255^0 with frequency values of about 40-50 p/sf on phase A and B and over 50 p/sf on phase C and relatively high magnitudes were noticed, indicating surface PD in the area of the frontal ends (categories II-III)

At an overall evaluation, there results that the insulation presents volume PD in the slot area due to delaminations and voids in the insulation (thermal effect) between the insulation and the copper conductor (effect of the cyclic load) and surface ones in the frontal area due to their consolidation and the deterioration of the conducting lacquer on the insulation surface. Thus, the insulation on its whole can be included in category II-III with normal, slow deteriorations of medium extent in the entire mass of the insulation having the tendency to worsen. Maintenance works (re-wedging, repainting in the frontal area) and the continuation of periodic PD measurements were recommended. At the same time, a set of supplementary measurements (tan δ, increased voltage, local PD measurement with corona probe) to check the opportunity of the generator re-winding were recommended.

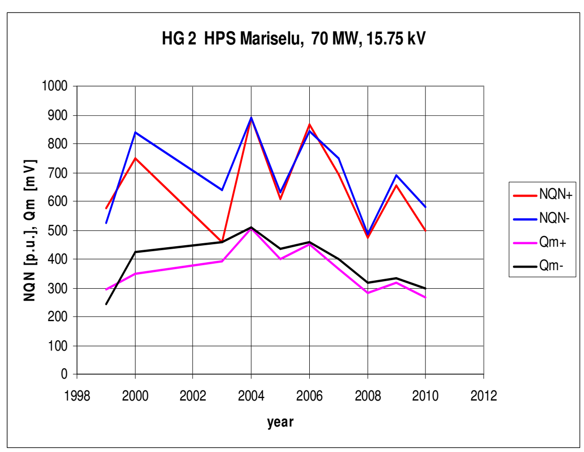

Fig. 2. HG2 HPS Mărişelu NQN, Qmax =f (time)

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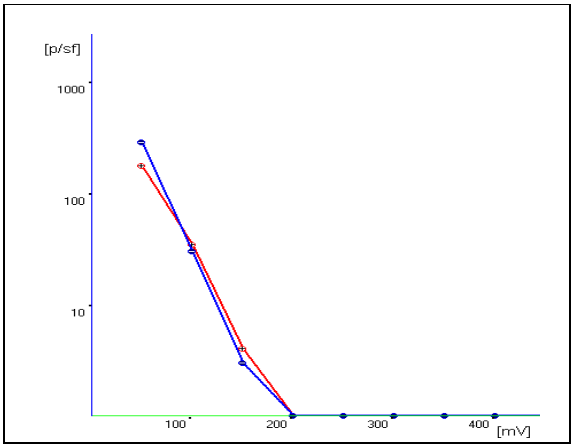

Fig. 3. HG2 HPS Mărişelu, 2D - 2008

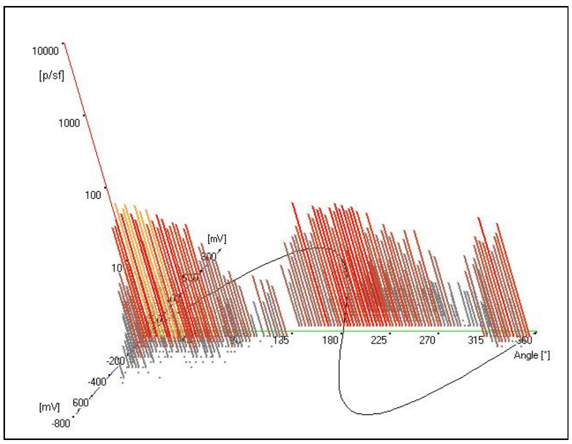

Fig. 4. HG2 HPS Mărişelu, 3D - 2010

At **HG 2 HPS Vidraru**, 50 MW, 10.5 kV, (fig.5) in 2003 and 2010 extensive maintenance works were carried out: the stator bars were replaced (2003), the stator bars were re-wedged, the stator iron was repaired (2010) and the frontal winding ends were re-varnished with semi-conducting lacquer. The PD measurements after all these works showed an obvious improvement in the values of the PD parameters. In between the two extensive maintenance works the evolution of the PD parameters was monotonously increasing (the insulation is of the mica-epoxy type and is about 24 years old).

Thus, the ±NQN values increased from approximately 110-250 p.u (category I-II) to approximately 320 p.u. (category III) and the ±Qmax values of about 120 mV (category I) to 270 mV (category II). After the maintenance works of 2010, the ±NQN values decrease to about 200 p.u. (category II) and the values ±Qmax decrease to 120 mV (category I).

In 2D diagrams, all the phases, for all the measurements, had quasi-equal values of the positive and negative pulses, the ratio +Qmax/-Qmax ≈ 1 and the p/sf=f(mV) curves are knitted in all the operating conditions, or presented a slight preponderance of the negative polarity. This has indicated the occurrence of volume PD in the slot area due to delaminations between the layers and the voids in the insulation, as a result of the thermal effect, (category II).

In the 3D diagrams, in 2009, the occurrence of negative PD on all the phases in the angle range of $\alpha = 0^{o} - 90^{o}$ was noted with a repetition frequency ranging between 40 and 100 p/sf (category III) but of low magnitudes of 8-12 p/sf and higher magnitudes. At the same time, the occurrence of positive PD in the angle range of $\alpha = 180^{o} - 270^{o}$, with the repetition frequency of 80-100p/sf (cat. III), but of low magnitudes was noticed. At the same time, the occurrence of PD in the frontal area, respectively, at angles $\alpha = 15^0, 75^0, 195^0, 255^0$ with repetition frequencies of 30-100 p/sf and low magnitudes (category III) were noticed.

After the measurements carried out since 2009 the re-wedging of the entire stator winding, injection of conducting lacquer in the slot part and re-varnishing with semi-conducting lacquer of the frontal coil ends have been recommended.

In 2010, in the 3D diagrams (fig.6), the decrease in the repetition frequency to 10 - 40 p/sf (category II) on all the phases for the negative PD in the angle range $\alpha = 0^{o} - 90^{o}$, with low magnitudes and to 5 p/sf with higher magnitudes wad noticed. The persistence of negative PD indicates the occurrence of volume PD especially between the insulation and the copper conductor. At the same time, a decrease in all the phases of the repetition frequency to 10 - 40 p/sf (cat. II) for the positive PD in the angle range of $\alpha = 180^{o} - 270^{o}$ is noted. The persistence of positive PD indicates the surface PD occurrence in the slots. The decrease in the frequency of repetition at 10 - 40 p/sf (category II) of PD in the frontal area is also noticed, which indicates an improvement in the condition of the surface at the ends of the frontal coils.

Therefore, the maintenance works carried out in 2010 resulted in the reduction of the PD parameter values and in the reduction of the pulse repetition frequency and, therefore the overall insulation condition was improved, especially relating to its surface. Thus, the insulation passed from category III in 2009 into category II in 2010 . Continuation of periodic PD measurements was recommended. A set of supplementary measurements (tan δ, increased voltage, local measurement of PD with corona probe) were also recommended.

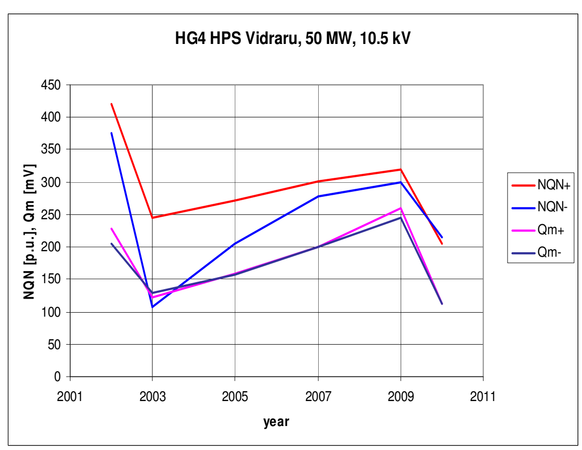

Fig. 5. HG 4 HPS Vidraru , NQN, Qmax =f (time)

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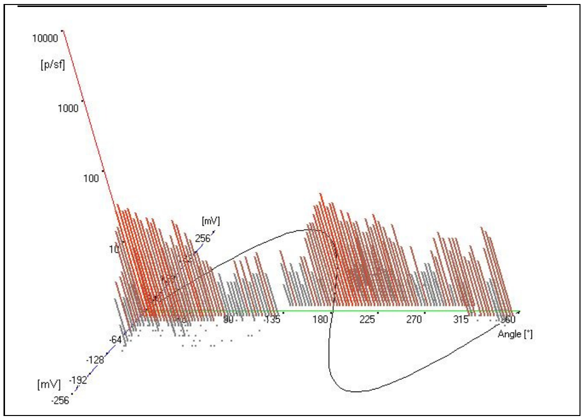

Fig. 6. HG 4 HPS Vidraru 3D - 2010

At **HG 2 HPS Remeți**, 45 MW, 10.5 kV, (fig.7) during the entire period 2000 – 2010, the ±NQN and ±Qmax values on all phases had a monotonous increasing evolution. Thus, the ±NQN parameters increased from 150 p.u. to 450 p.u. (surpassing the maximum limit) indicating an expansion with time of the deteriorations of the entire insulation (category III). The ±Qmax parameters increased from 50 ...100 mV to 270 ... 350 mV nevertheless remaining within the reference range (170-400 mV) thus indicating the development of slow, normal deteriorations (category II) in the course of time. In the period 2004-2005 maintenance works were carried out (radial re-wedging, re-varnishing of the frontal part) that led to the temporary diminishing in the ±NQN and ±Qmax values.

In the 2D diagrams, all the phases, all the measurements presented values almost equal of the positive and negative pulses, the ratio +Qmax/-Qmax ≈ 1 and the curves p/sf=f(mV) knitted, in all the operating conditions. This indicated the occurrence of volume PD in the slot area due to the delaminations between the layers and the voids in the insulation as a result of the thermal effect, (category II).

In the 3D diagrams (fig. 7), the occurrence of positive PD at α= 180° -270° that evolved with time from the repetition frequency of about 10-20 p/sf in 2007 to the repetition frequency of 30 -50 p/sf in 2010 with low magnitudes and the development with time of negative PD in the α= 0° -90° range with the repetition frequency of 10-15 p/sf and low magnitudes and frequencies of 5 p/sf and higher magnitudes was noticed. These evolutions indicated an expansion of the volume PD due to the cavities (voids) between the insulation and the copper conductor (effect of the cyclic load), of medium extent (category II -III) and the surface PD development in the slot area, between the insulation and the slot wall due to the deterioration of the conducting lacquer.

It was also noted the expansion with time of PD, from electric angles of α=195° to electric angles of α =15°, α=195° and α=255°, indicating the occurrence of surface PD in the frontal end area, with frequencies up to 0-30 p/fs and low magnitudes (category II). After the maintenance works carried out in the period 2004-2005, the occurrence of these DP diminished, but in 2010 they re-occurred.

Therefore, the insulation on its whole was included in the category II –III, with normal, slow deteriorations in the entire insulation, tending to expand in the entire insulation.

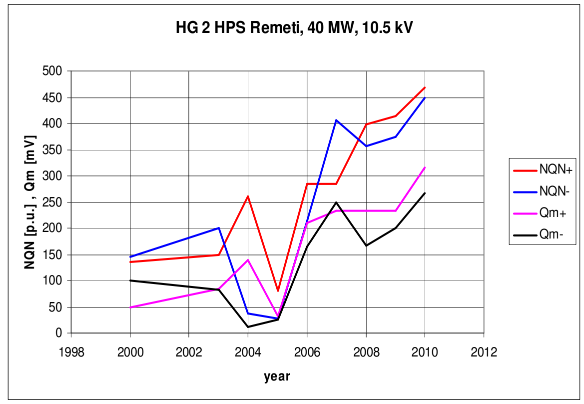

Fig. 7. HG2 HPS Remeti, NQN, Qmax =f (time)

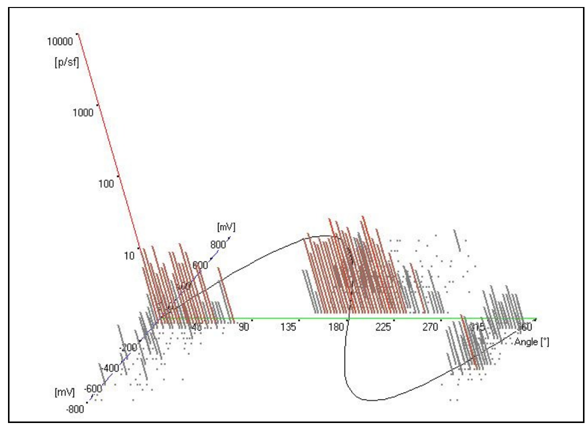

Fig. 8. HG 2 HPS Remeti 3D - 2010

The insulation was affected in its entirety as volume PD were noticed in the slot area due to delaminations between layers and voids in the entire insulation as a result of the thermal effect and the delaminations (voids) between the insulation and the copper conductor (cyclic load effect), of medium value with worsening tendencies. At the same time, the deterioration of the conducting lacquer in the slot area and of the semi-conducting lacquer at the ends of frontal terminal ends was noticed.

At **HG 2 HPS Munteni**, 31 MW, 10.5 kV, (fig. 9) there are results only for the period 2007-2010. In 2006, the generator was rewound. In the period 2007 – 2010 the ±NQN and ±Qmax values, on all phases, registered a slightly monotonous increase. Thus the ±NQN values increased from about 20 p.u. to about 70-80 p.u. and the ±Qmax values increased from about 10-15 mV to about 35 mV. These values are below the minimum reference limits (100 p.u. for ±NQN and 170 mV for ±Qmax), the insulation being included in category I, very good condition, for both criteria.

In 2D diagrams (fig.10), on all the phases an equality between the polarities with the overlapping or knitting of

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the curves p/sf =f(mV) was noticed, the presence of the PD being of very low intensity (cat. I)

In 3D diagrams (fig. 11), on all the phases, under all operating conditions and for all the measurements, the PD occurrence on the sinusoid is rare, being insignificant in general, having low magnitudes and low frequencies of 5-10 p/fs (category I)

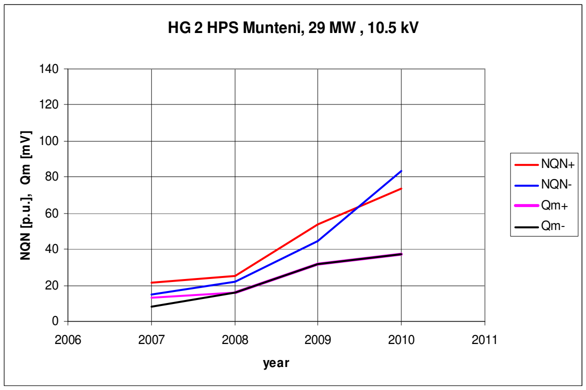

Fig. 9. HG 2 HPS Munteni NQN, Qmax =f (time)

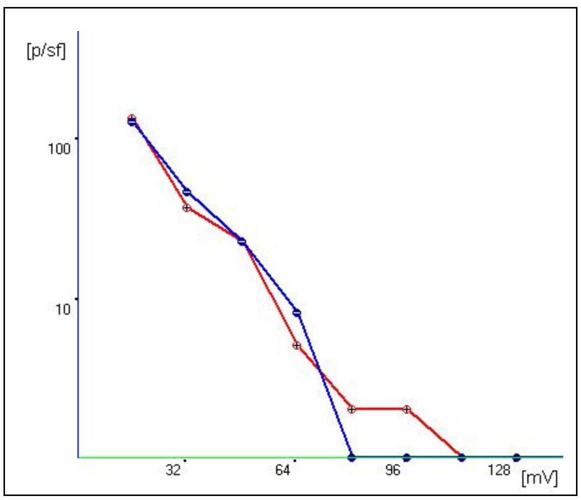

Fig. 10. HG2 HPS Munteni 2D - 2010

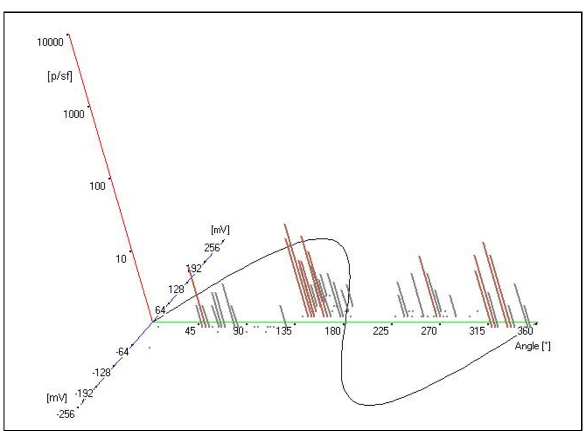

Fig. 11. HG 2 HPS Munteni 3D – 2010

To conclude, after 4 years of operation, the insulation is in very good condition, the PDs having insignificant values (category I). It was recommended to continue the annual PD measurements paying special attention to the condition of the semi-conducting lacquer coating from the frontal area during the maintenance works.

5. CONCLUSIONS

The PD measurements and the careful analysis of the results have enabled the assessment of the stator winding insulation condition, their classification and recommendations for the maintenance works.

The criteria can be improved by monitoring the evolution of the PD parameters with time and the correlation with the maintenance works carried out. It would be ideal to perform a set of measurements before and after maintenance works.

In the case of the generators analyzed in this report, the periodic measurements and the utilized evaluation have enabled the correct assessments of the condition of the respective insulations and substantiated decisions for the maintenance works. In general, these works have had the expected result and improved the insulation condition.

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