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# NOVEL METHOD FOR ON-SITE TESTING AND DIAGNOSIS OF TRANSMISSION CABELS UP TO 250KV


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## ABSTRACT

*For complete on-site diagnosis of transmission power cables up to 220kV by partial discharge detection and dielectric losses measurement it is necessary to energize the disconnected cable system. One of the methods available for this purpose is based on applying damped AC voltages up to 250kV. In this paper, the use of modern technological solutions in power electronics and signal processing as well as in technical design and production methods will be discussed on the basis of ultra light system (300kg) which is able to test cables up to 20km lengths.*



## KEYWORDS

HV power cables, on-site energizing, DAC, partial discharges, dielectric losses


## INTRODUCTION

Condition assessment of HV cables is one of the issues of asset management in power utility business. In particular, due to the importance of HV cables in the transmission network is the knowledge about the initial condition during after-laying as well as the actual condition of HV power cable sections during operation after several years of service of great importance.

With regard to partial discharge (PD) processes and dielectric degradation processes in transmission power cables there is still a need for advanced, sensitive and economical attractive tools suitable for non-destructive PD diagnosis on-site: the after-laying testing as well as the service diagnosis [1, 2].

For complete on-site diagnosis of transmission power cables by PD detection and dielectric losses measurement it is necessary to energize the disconnected cable system. In order to decrease the capacitive power demands for energizing cables as compared to 50Hz test voltages, different energizing methods have been developed in the past. One of the methods available for this purpose is based on applying damped AC voltages [3, 4]. In particular, in the last 8 years [5, 6] the worldwide acceptance of this method has already demonstrated that in the case of power cables up to 40kV by means of advanced PD diagnosis the identification of high-risk cable circuits in the network can be achieved and implemented in utility asset management decision processes.

In this contribution, based on 4 years [7] of utility experiences and laboratory investigations a novel method

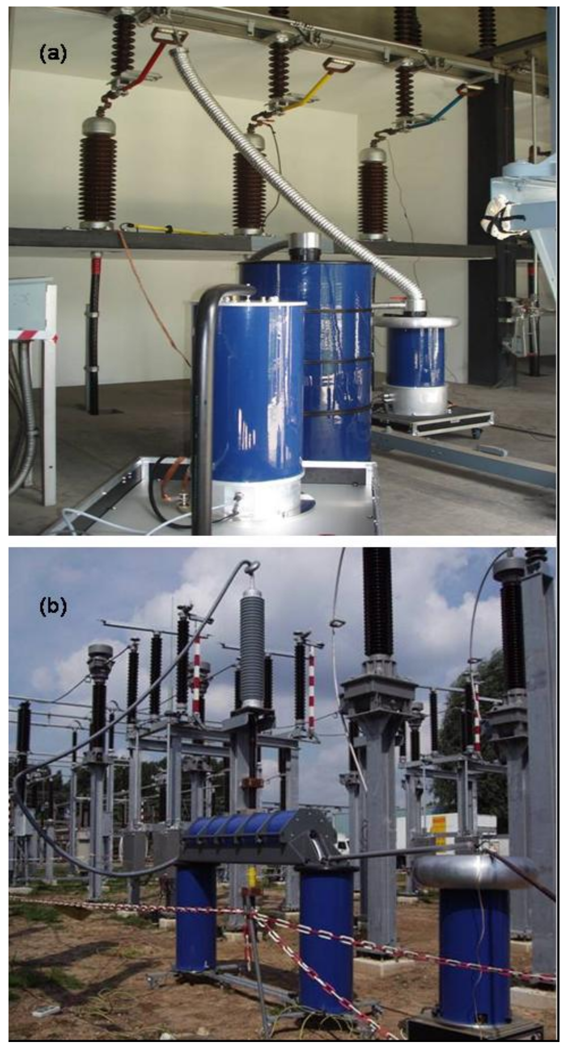


**Figure 1: Examples of on-site testing and diagnosis of HV power cables:**
**a) OWTS HV150 system testing at 23Hz damped AC voltage frequency a 12.4km long 66kV oil-filled cable,**
**b) OWTS 250 system testing at 71Hz damped AC voltage frequency a 2km long oil-filled 150kV cable**

for diagnosis of PD and dielectric losses of transmission power cables using damped AC voltages up to 250kV will be presented. To generate on-site damped AC voltages up to

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150kV$_{peak}$ respectively 250kV$_{peak}$ and to perform advanced diagnosis by meaningful PD parameters modular hardware/software solution has been developed (figure 1). In particular, by use of

- modern solid-state technology and laser-control techniques (HV Solid-State Switch),

| Table 1: Maximum OWTS HV –series Test voltage levels | | |
|---|---|---|
| Network voltage [kV] | OWTS HV 150 x $U_0$ | OWTS HV 250 x $U_0$ |
| 50 | 3.6 | - |
| 66 | 2.7 | - |
| 110 | 1.6 | 2.7 |
| 132 | 1.4 | 2.3 |
| 150 | 1.2 | 2.0 |
| 220 | 0.8 | 1.4 |
| 240 | - | 1.2 |
| 330 | - | 0.9 |

- power electronics, digital signal processing (HV Solid-State Switch, HV source),
- digital signal processing and filtering (PD detector),
- wireless communication and embedded computer system (PD detector, Control unit, PD analyzer)

novel system OWTS HV -series type 150 type 250 have been developed for on-site PD diagnosis of HV power cables up to 330kV (table 1).

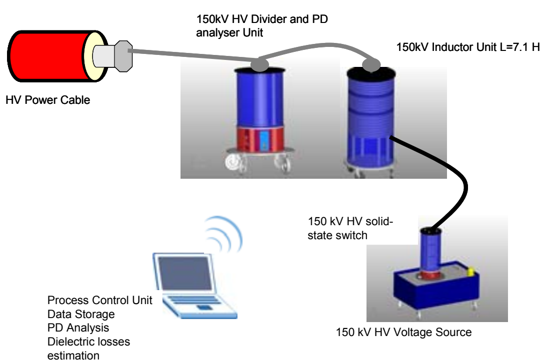


**Figure 2: Schematic structure of OWTSHV150 an on-site system for partial discharges and dielectric losses diagnosis for transmission power cables up to 150 kV; (weight 300kg)**

## ON-SITE ENERGIZING OF HV POWER CABLES

For the on-site detection of PD related defects in power cables, it is necessary to energize the disconnected cable sample for the ignition of the PD sources. The detection and measuring equipment is therefore directly connected to the cable conductors (or through the switchgear). In this way, the different phases of the cable circuit can be energized and the PD pulses can be coupled out. The capacitive power $\boldsymbol{P = 2\pi \cdot f \cdot C_{cable} \cdot U^2_{test}}$ needed to stress on-site the cable insulation is determined by the test frequency $f$, the cable capacitance $C_{cable}$ and the test voltage $U_{test}$. In order to decrease the capacitive power demands for energizing cables as compared to 50Hz test voltages, different energizing methods using specific voltage shaped and frequencies have been introduced for PD diagnostics nowadays [4, 8, 9]. As shown in [9-11] due to several important characteristics such as

1. AC voltage type equivalence in PD inception processes for solid insulating materials,

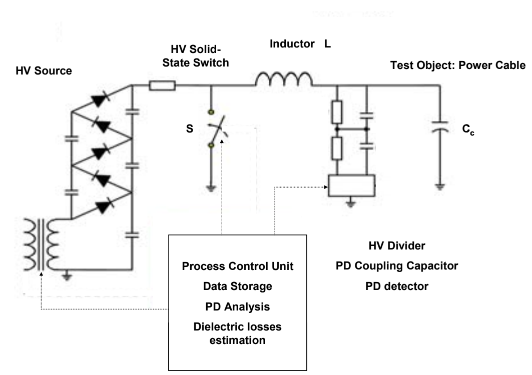


**Figure 3: Schematic view of the damped AC circuit inclusive the partial discharge and dielectric losses measuring system.**

2. non-destructiveness of voltage stress during the diagnosis,
3. real-time advanced analysis of diagnostic data,
4. sufficient immunity for on-site interferences and low level of system background noise,
5. IEC, IEEE standards conformity [2, 3, 4, 12, 13],
6. test cost efficiency based on investment and maintenance costs, transportability and operation of the method in different field circumstances,

the use of partial discharges and dielectric losses diagnosis at damped AC voltages (DAC) has become important solution for on-site testing and diagnosis of HV power cables (figures 1-3).

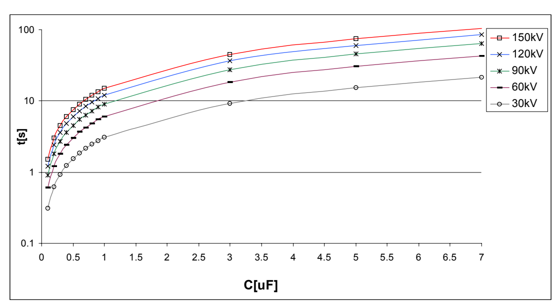


**Figure 4: Charging time in function of power cable capacitance for different voltage levels.**

## DAMPED AC VOLTAGE GENERATION

For the generation of damped AC (DAC) voltages, the power demand is low due to the charging the cable capacitance (figure 4) with a current of 10mA and a continuously increasing DC voltage, after which the cable capacitance (represented as a capacitance $C_c$) is switched by S in series with large inductance L, resulting in an sinusoidal damped AC voltage form with a frequency between 20Hz and few hundreds of Hz (figure 5). In particular, the cable sample is linearly charged with continuously increasing HV voltage, directly followed by a switching process and period of several sinusoidal AC cycles (figure 6). As a result, during the charging time no ''steady state'' DC conditions occur in the cable insulation [14]. As soon as the cable is charged, the HV supply is disconnected and a specially designed HV solid-state switch (150kV type or 250kV type) connects the cable sample $C_c$ to an air-core inductor L =7.1H in a closure time of less than 1µs. In this way, and LC loop is created and an oscillating voltage wave is applied to test the sample. The test frequency of the oscillating voltage wave is approximately the resonant frequency of the circuit:

$$f = \frac{1}{2\pi\sqrt{L \cdot C}}$$

This means that the test frequency of the applied DAC voltage is dependent on the cable capacitance, see figure 5. The HV power cable capacitance varies due to parameters like the cross-section of the conductor and the thickness and the type of the insulation. In table 2 examples are shown for different types of HV cables and cable length and the damped AC frequencies to be generated using system as shown in figure 2).

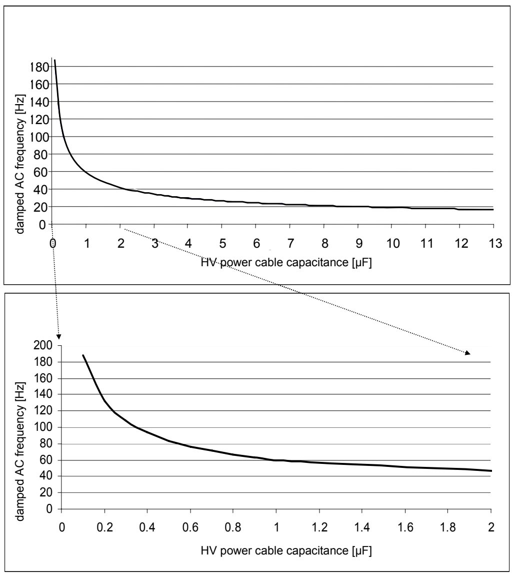


**Figure 5: Dependence of the frequency of damped AC test voltage on the power cable capacitance.**

**Table 2: Examples of the typical damped AC voltage frequencies in [Hz] for different lengths of two typical 150kV power cables**

| Length [km] | XLPE (C=154pF/m) [Hz] | Oil filled (C=373pF/m) [Hz] |
|---|---|---|
| 0.25 | 300 | 194 |
| 0.5 | 213 | 137 |
| 1 | 151 | 97 |
| 2 | 107 | 69 |
| 4 | 76 | 49 |
| 8 | 53 | 34 |
| 16 | 38 | 24 |
| 20 | 34 | 22 |

Due to the low loss factor and design of the air-core, the resonant frequency is close to the range of power frequency of the service voltage: 20Hz to 300Hz.

The quality factor $Q_C$ of the resonant circuit, which is responsible for the attenuation of the oscillations, can be expressed by:

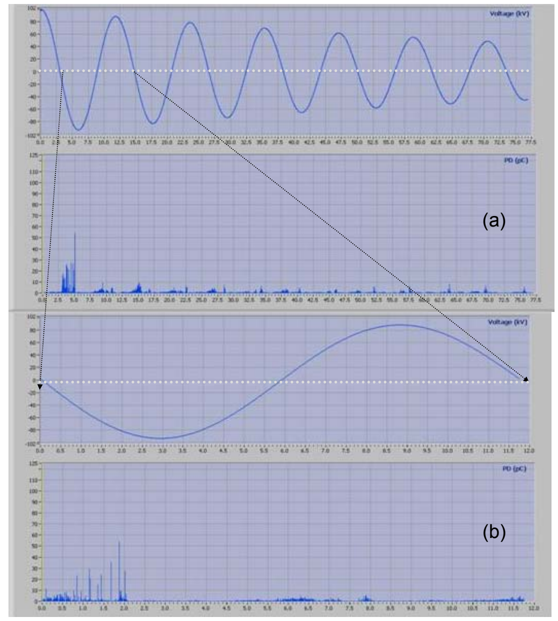


**Figure 6: Example of sinusoidal damped AC voltages as generated to energize at 100kV a capacitive load of 0.5µF and the measured PD pattern:**
**a) full AC wave of 86Hz**
**b) single AC cycle of 12ms**

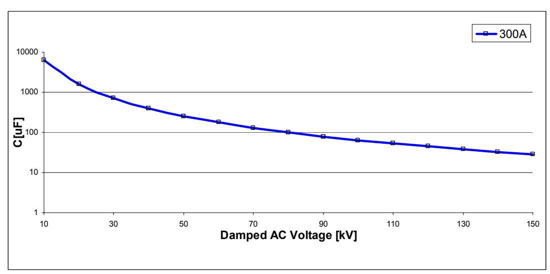


**Figure 7: Maximum power cable capacitance in function of the applied damped AC test voltage for max current of 300A.**

$$Q_C = \sqrt{L / ( C * R_A^2 )}$$

Here is $R_A$ the equivalent circuit resistance. The quality factor *Q* of the resonant circuit remains high depending upon cable (30 to more than 100), as a result of the relative low dissipation factor of power cables. A slowly decaying sinusoidal waveform (decay time up to 0.3 second) is applied as test voltage to energies the cable sample.

The maximum power cable capacitance which can be tested at DAC stresses using OWTS HV system can be calculated in dependence of maximum voltage applied and the AC current in the resonant circuit. (figure 7):

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$$C_{\max} = \left(\frac{I}{V}\right)^2 \cdot L$$

- Due to the fact that the maximum short-duration current as specified for the solid-state switch is in the range of 10 kA the accepted max current in the test circuit is determined by the system earthing of the test circuit and set to hundreds of Amp's (figure 6). It follows from this figure that at 150kV test voltages e.g. by circuit current of 300A the max capacitive load will be in the range of 28μF, which theoretically may represent a HV cable length of 76km of oil filled cable with e.g. capacitance per unit length 373pF/m).

## HARDWARE SYSTEM

Based on the OWSTHV150 system the hardware and software solutions will be discussed below (figure 8). With regard to OWTS 250 kV system the technical information is given in [7]. In the table 3 the basic parameters are given.

**Table 3: Technical parameters of OWTSHV150 system**

| | |
|---|---|
| Max. DAC output voltage | 150 $kV_{eff}$ / 106$kV_{peak}$ |
| DAC frequency range | 20 Hz … 500 Hz |
| Test object capacitance range | 0,025 μF ... 13 μF |
| HV charging current | 10 mA |
| PD measuring range | 1 pC ... 100 nC |
| PD detection | acc. to IEC 60270 |
| Bandwidth for PD-localization | 150 kHz ... 45 MHz |
| Dissipation factor | 0,1 % ... 10 % |
| Power supply | 115/230 V 50 / 60 Hz |
| Weight | app. 300 kg |

***150 kV HV Source*****:** to load the power cable capacitance 150kV HVDC voltage supply is used with a circuit effective load current of 10mA. During charging the test object the linear and continuously increasing HV voltage is controlled by the computer. In figure 4 the charging time in function of the load capacities is shown. The switching discharge current of the power supply are limited by 15kΩ series resistor to max. 16A.

***150 kV HV solid-state switch*****:** The function of the 150kV switch is to establish a series resonance circuit between charge HV power cable capacitance and the air inductor L. As a result sinusoidal damped AC voltages may occur in the cable sample. The switch is permanently installed on the HV power supply.

***150kV Inductor Unit*****:** the system inductor consists of three in series connected air coils with a total inductance of 7.1H. To make it sure that the damping of the voltage waves is mainly depending on the test object losses the inductor is air core type. Also the epoxy insulation of the windings provides PD freedom of this part.

***HV Divider / PD coupling capacitor*****:** to measure the damped AC voltages and to couple PD signals a PD free AC/DC divider C= 1nF/R= 800 MΩ is integrated in the unit costing the PD detection system.

***PD detection system*****:** to detect PD signals a coupling device is connected to a PD-free coupling capacitor 1nF. The signals as detected in this way are process by digital PD detector. In particular this embedded system controlled by the PD Analyser Control Unit consists of IEC60270 conform signal processing and display in [pC] and to provide HF signals for localisation purposes wideband signal amplification and processing is used.

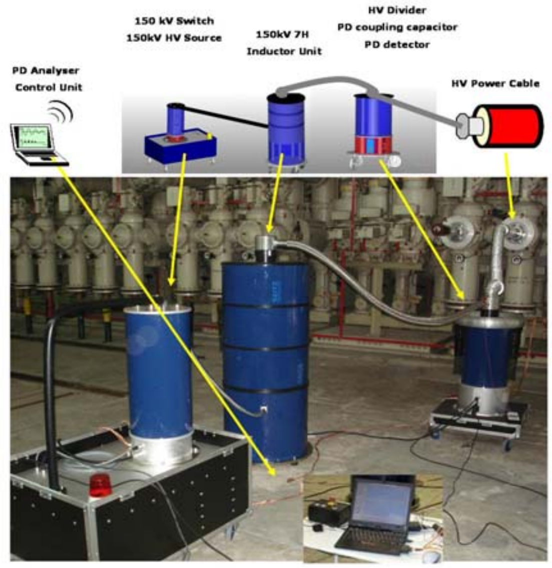


**Figure 8: OWTS HV 150 System for on-site diagnosis of HV power cable circuits.**

***PD Analyser Control Unit*****:** Using special User interface software installed on a laptop the HV generation process, data measurement process, data storage and analysis are possible. Moreover, this unit communicates with PD detection system by wireless or optical link.

## SOFTWARE SYSTEM

The operation of the hardware system as described in previous section is supported by software concept as shown in figure 9. It follows from this figure that the whole on-site process of testing and diagnostic data gathering is divided into four steps.

***Cable System Definition*****:** for practical reasons, a cable section may be constructed from multiple parts of cable, which are connected to each other with cable joints.

Moreover such relevant information as the voltage ratting, insulation type, type and the position of the accessories are used to identify particular test, figure 10.

***Test Circuit Calibration*****:** PD calibration of a measuring circuit means the reading adjustment of the PD detector. This calibration consists of a process where two calibrations procedures are automatically performed:

- Calibration of the PD reading; in accordance to IEC60270 recommendation a PD pulse calibrator as defined in the IEC 60270 has to be used.
- Calibration of the PD pulse propagation velocity reading: for this purpose the same as in 1 mentioned PD pulse calibrator can be used.

If possible in particular cases, on the basis of additional reflections as observed on the calibration signals the location of individual joints can be done (figure 11).

***On-site Diagnosis of Power Cable*****:** during application of HV voltage to the test object diagnostic parameters are measured (figure 12). The test voltage level selection and correct selected PD measuring range are important

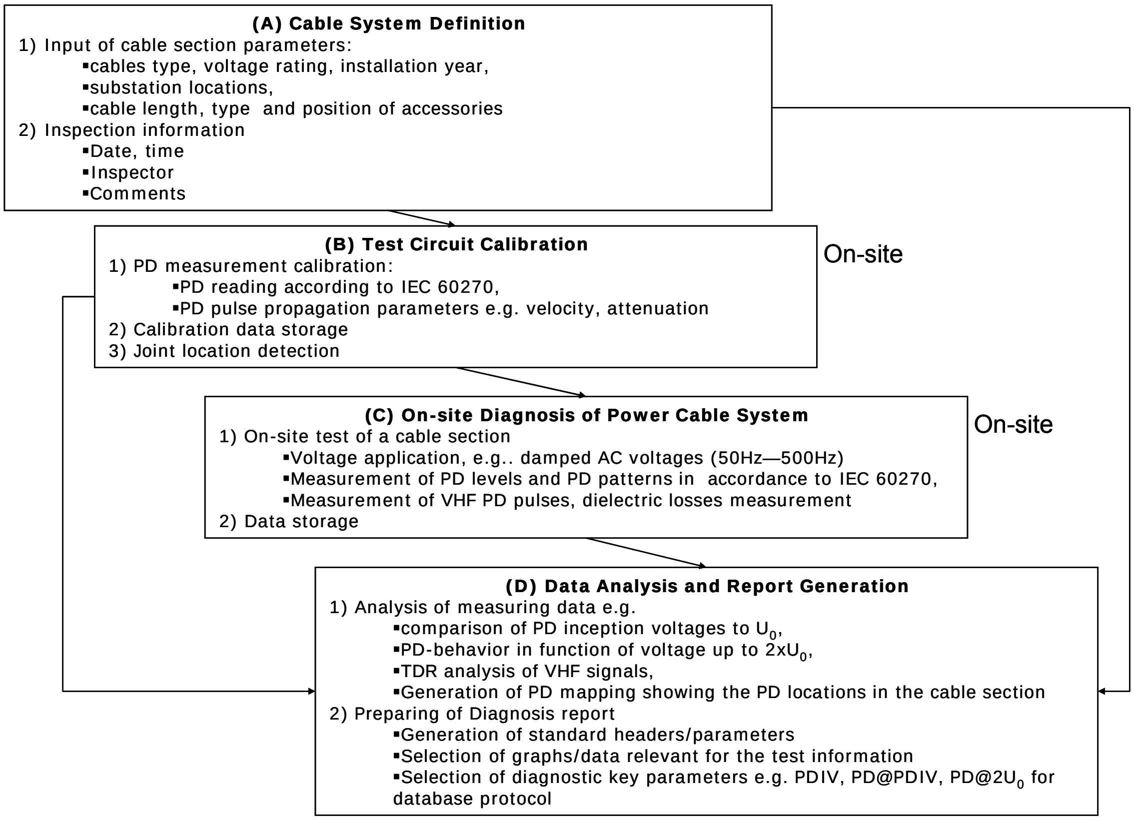


**Figure 9: Integral concept of on-site testing and data gathering of HV power cables.**

parameters in obtaining correct measuring data. In particular, real-time registration of PD inception voltage (PDIV), PD extinction voltage (PDEV), PD-patterns is crucial for the execution of the on-site tests. For instance, during increase of the test voltage a sudden increase of PD activity may be used to identify and real-time localize serious discharging defects.

***Data Analysis***; after during an on-site test diagnostic data have been collected analysis of data can be done. In particular with regard to PD data the location of discharge sites can be determined on the basis of VHF records. As a result, PD mapping can be obtained shown on the power

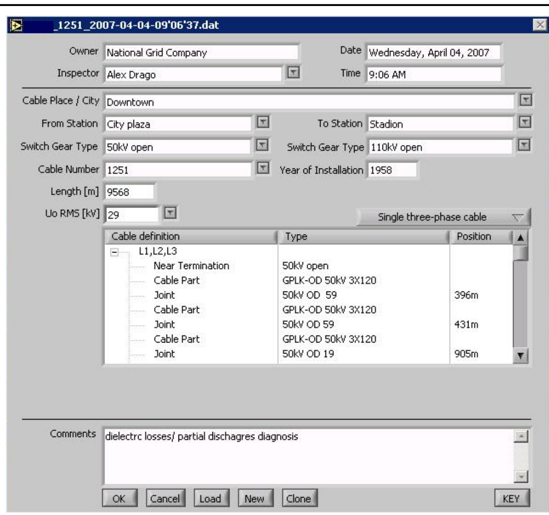


**Figure 10: Example of cable system definition.**

cable the PD levels and PD concentration in function of the applied test voltages (figure 13). This information and all other data [15] can be used to asses the condition status of a particular HV cable system.

## CONCLUSIONS

In this contribution novel solution for on-site testing and diagnosis of HV power cables up to 250kV is presented. In particular the following can be concluded.

1. Applying modern solid-states materials, power electronics technology and advanced signal processing allows developing compact system to generate on-site damped AC voltages up to 250kV.
2. PD and dielectric losses diagnosis at damped AC voltages can be used for non-destructive on-site testing of new and service aged HV power cables.
3. Due to digital signal processing and filtering as well as due to the fact that during application of damped AC voltages no active voltage sources are switched on, sensitive on-site PD detection (few pC's) can be achieved.
4. The complete solution for on-site testing and diagnosis complies with international standards and recommendations [2-4, 12, 13].
5. Testing, measuring, analyzing and reporting processes are supported by embedded hardware/software solutions as well signal processing tolls like wavelets and digital filters.
6. Such characteristics like
   - AC sinusoidal and non-destructive stresses,

- the available testing power (cables with length up to more than 20km) and voltages (up to 250kV),
- efficiency in transportation (300kg… 400kg) , setting up and on-site test execution (1/2 hrs/phase),
- diagnostic information as generated for HV power cables: PD detection localization, dielectric losses [15],

may make to transmission and service companies as well as cable manufacturer this novel method as an very attractive option for on-site tests and diagnosis of new and service aged power cables.

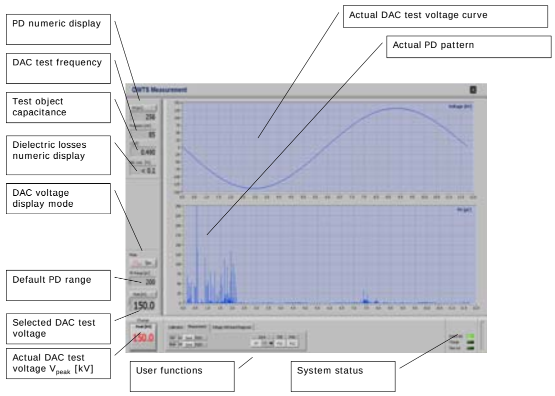


**Figure 12: Example of the user main screen during on-site testing.**

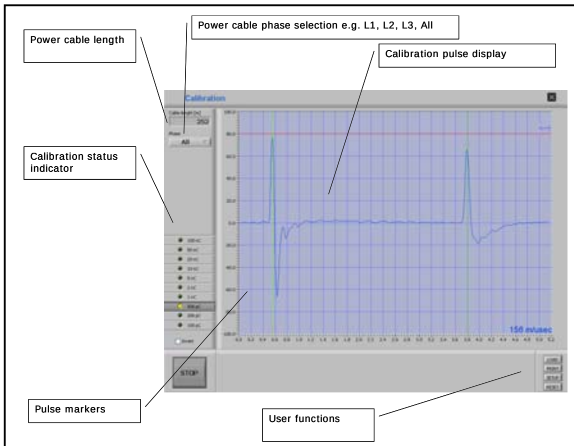


**Figure 11: Example of test circuit PD calibration.**

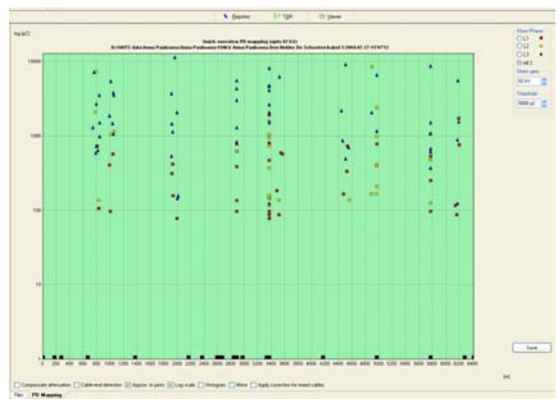

**Figure 13: Example of PD mapping (PD activity versus cable length) as obtained during on-site tests using OWTSHV 150 system up to $2xU_0$ for three phases (red, yellow, and blue) for a 6.4km long 50kV mass-insulated HV power cable. The X-axis represents the length of the power cable including the position of the individual joints (black dots)**

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