

Research Article

Ozone Sensor for Application in Medium Voltage Switchboard

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Received 30 December 2008; Revised 30 April 2009; Accepted 6 May 2009

Recommended by Yongxiang Li

The application of a new spectroscopic type fiber sensor for ozone detection in electrical components of Medium Voltage (MV) network is evaluated. The sensor layout is based on the use of an optical retroreflector, to improve the detection sensitivity, and it was especially designed for detecting in situ rapid changes of ozone concentration. Preliminary tests were performed in a typical MV switchboard. Artificial defects simulated predischARGE phenomena arising during real operating conditions. Results are discussed by a comparison with data simultaneously acquired with a standard partial discharge system.

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1. Introduction

The reliability of electrical equipment in Medium Voltage (MV) substations is a prerequisite to guarantee the continuity of the service in an MV distribution network. Failure statistics of different electrical components of substations indicate the MV substation as one of the major causes of outages [1]. In particular, the MV switchboard very often suffers of flashover. The most effective technique to provide an early warning of failure in these electrical apparatus is to detect corona or surface predischARGE phenomena. Since these phenomena, on long term, can give rise to breakdown and consequently lead to out-of-services it is important both to detect their inception and to follow their evolution by monitoring their induced effects, such as light emission, generation of acoustic noise, and ozone production [2]. However in general these signals are relatively low, and the high level of electrical interference exacerbates the problem of the infield measurement.

On the other hand until now high costs of traditional sensing devices heavily limited applications of any diagnostic system for assessing conditions of these low-cost electrical components.

Recently the feasibility of an innovative combined system has been investigated [3]. In this work, the system was assembled using high sensitivity and cheap sensors; these sensors are either commercially available or ad hoc developed prototypes. Fibre-optic-based sensors were chosen, having

the advantages to be not invasive, not affected by unwanted electrical disturbances, chemically inert and also quite cheap. An optical microphone and a fluorescent fibre-optic sensor were used to detect respectively the sound pressure and the light generated by predischARGE inside the MV switchboard.

Further goal of this Research Project was a fibre-optic sensor development to detect the ozone produced by predischARGE. Its integration into the assembled diagnostic prototype takes aim at detecting simultaneously three different predischARGE effects for avoiding occurrence of false alarms.

The ozone sensor chosen by the authors [4] is based on a novel open path optical layout. This optical scheme guarantees a high sensitivity and, at the same time, the survival in the harsh environment of MV switchboard.

In the previous work the validation of the sensor was performed through calibration measurements on a gas flow cell, with different ozone concentrations and in a laboratory mock-up used to simulate a corona discharge simulator.

In this paper for the first time this sensor was mounted directly inside a real MV switchboard for assessing its capability to detect ozone produced by predischARGE phenomena close to phase cable terminations.

2. Sensor Description

The developed sensor is based on the differential optical absorption of UV light by ozone, which strongly absorbs

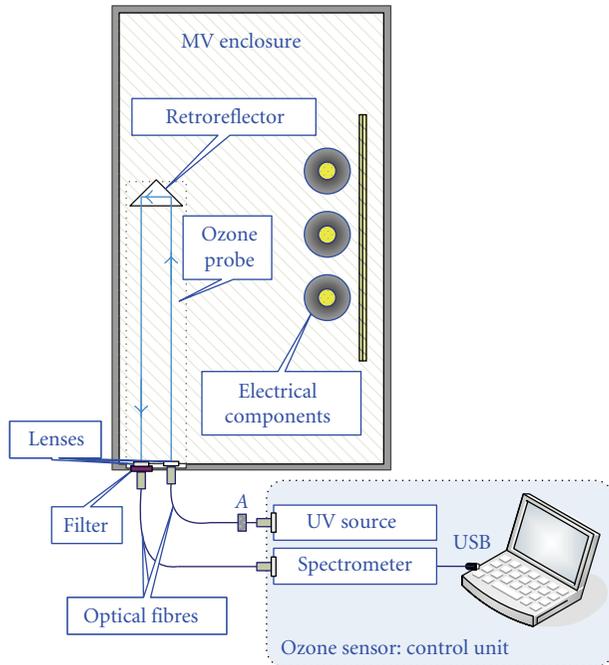


FIGURE 1: Optical scheme of the ozone sensor. The probe (on the left in the figure) mounted inside the MV switchboard is connected to the remote control unit by means of optical fibres.

in a wide spectral band between 200 nm and 375 nm; on the contrary it shows a negligible absorption in the region between 377.5 nm and 450 nm [5].

The ozone concentration C is evaluated from the intensity $I(\lambda)$ of wavelength λ measured by a spectrometer, by means of the Lambert-Beer law [6] $I(\lambda)/I_0(\lambda) = \exp(-\epsilon Cl)$, where l is the path length of the region containing the ozone, $I_0(\lambda)$ is the incident intensity and ϵ is the absorption coefficient. Through this law, the sensitivity to ozone concentration depends on the path length l . In the following C is expressed in ppm.

This spectroscopic technique is intrinsically suitable for the implementation of a whole optical fibre-based sensor to be located close to critical electrical components.

Up to now some efforts were already devoted to implement a fibre optic-based solution to assess the applicability of this spectroscopic technique for ozone detection in the industrial environment. O’Keeffe et al. [7] developed a small size probe, based on a PTFE, 5 cm long cell coupled to launching and collecting optical fibres, located on the opposite sides of the cell, to measure concentration of ozone higher than 25 ppm. The purpose of the present Project is the development of an optical fibre sensor able to detect the presence of a lower ozone concentration and to follow its evolution in time inside the MV switchboard. The novel fibre-optic layout schematically shown in Figure 1, has been implemented to fulfil this requirement.

The sensing probe (on the left in Figure 1) consists of a fixed length (40 cm) cylindrical enclosure, designed in ozone compatible material (PTFE). Longitudinal sides of this cylinder are open to allow the passage of the ozone.

A UV fused-silica retro reflector (a circular corner cube with 7 cm clear aperture) is tightly mounted on one end of this enclosure. The introduction of this retro reflector is for doubling the path length of the sensing probe, and for increasing therefore the sensitivity of the sensor to lower ozone concentration.

On the opposite side of this enclosure, two optical fibres are connected to collimating lenses. A UV filter (wavelength peak = 300 nm, FHWD = 140 nm) is positioned in front of the collecting lens, to remove spectral contributions of the UV source out of the two main ozone absorbing (at 254 nm) and not absorbing (at 375 nm) regions. UV solarisation resistant fibres (300 cm long, 400 micron diameter) are used as launching and collecting fibres, for preventing the degradation of fibres to UV exposure.

The launching fibre is coupled to the UV light source (a deuterium tungsten lamp). The collecting fibre is connected to a compact spectrometer, with fixed grating (spectral range 195–950 nm and resolution 0.25 nm). A variable attenuator (A) is mounted between the lamp and the launching fibre to avoid the saturation of the spectrometer.

The initial optical alignment of the back-reflected beam is performed by adjusting three screws on the top of this flange; these are blocked when the optics are aligned.

The spectrometer is USB-connected to the PC notebook and controlled by means of a proprietary software interface developed using Labview.

This interface was conceived as a polyfunctional interface for a smart management of the whole prototype assembled for the diagnostic of predischage phenomena. As this prototype consists of three different types of sensors (acoustic and optical sensors for detecting, resp., the sound and the light emission of the predischage and, presently, the ozone sensor), this interface allows an easily setting of configuration parameters, of measure start and of display and saving functions of the three sensors. Moreover, it is possible to display simultaneously the time behavior of signals coming out from each sensor, correlated to the same event of predischage. This combined analysis allows an efficient and more reliable diagnosis of initial failure of electrical components.

An example of the developed “ozone interface” is displayed in Figure 2. In this figure, a typical acquired spectrum of the UV filtered beam is shown (down in the figure). Settings of monitored wavelengths are shown on the right. The time trace of the transmitted intensity at 254 nm in presence of different ozone concentration is visible on the top.

The program acquires simultaneously also the transmitted intensity at the not absorbing wavelength. In this way any intensity losses within the sensor not correlated with ozone variations can be controlled in real time.

3. Sensor Calibration

Performances of the ozone sensor were validated in laboratory in presence of different ozone concentrations [4]. The lateral sides of the sensing probe were sealed to form a flow chamber. It was equipped with two gas accesses, located,

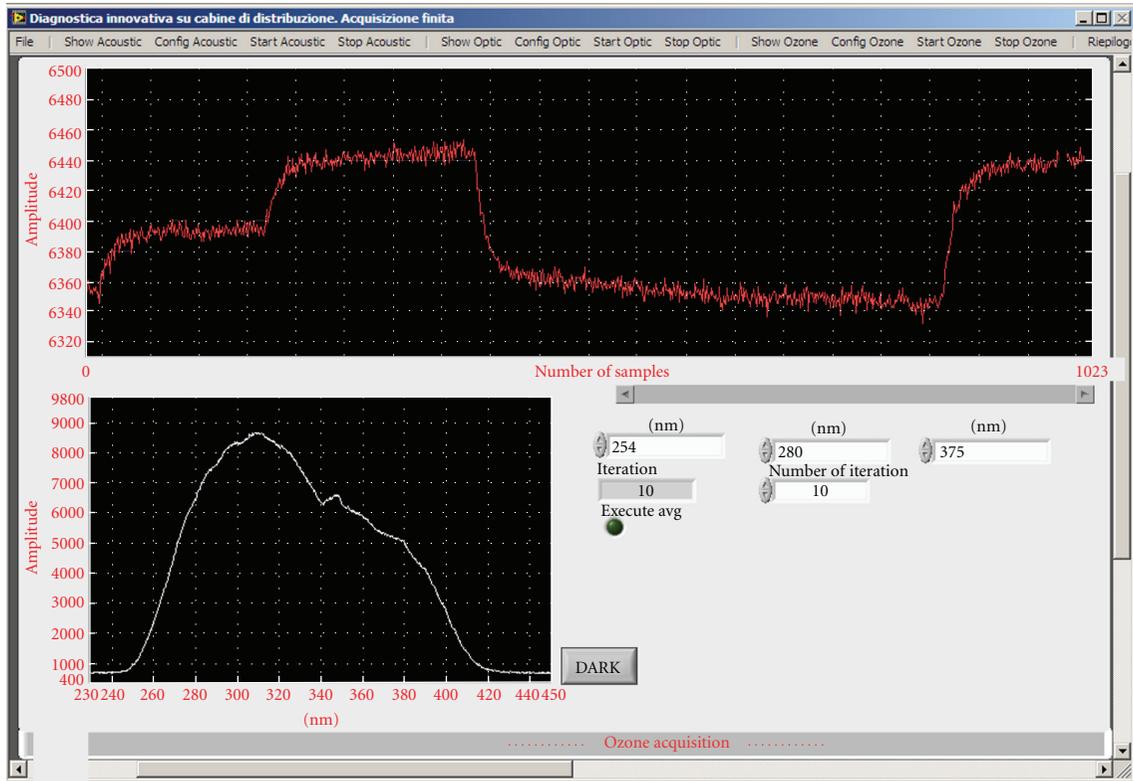


FIGURE 2: Control Panel of the ozone sensor, displaying the acquired spectrum (lower) and the time trace (upper) of the intensity at 254 nm monitored with change of ozone concentration.

respectively, close to the retro reflector and close to the output collecting lens to keep a uniform gas path with a constant flow rate (1 litre/min).

To test the response time and the linearity of the sensor two devices were used as reference ozone generators. A multi gas calibrator (mod. Series 100 EnviroNics manufactured) was used for generating calibrated ozone concentrations up to 2 ppm \pm 0.01 ppm; secondly an alternative laboratory system, used for determining the efficiency of NO/NO₂ catalytic converters (Gas Phase Titration method), was applied for producing calibrated higher ozone concentrations (range: 2–10 ppm) [8]. During all tests, spectra were averaged over 10 acquisitions and the acquisition time was 2.5 seconds long.

With the multigas calibrator, the ozone concentration was increased with maximum step of 0.5 ppm from 0 to 2 ppm; three series of measures were repeated for each concentration value. For each step, 5 minutes duration, time traces of intensities of both absorbing and not absorbing bands were recorded.

The linearity of the sensor was evaluated as $\text{Log}_{10}(I_0/I)$ versus the calibrated ozone concentration C (ppm), where I is the transmitted intensity at 254 nm measured for each step of concentration over stationary conditions.

Figure 3 shows an example of the sensor linearity in the range 0–2 ppm; the mean value and the standard deviation over three repetitions are shown.

The sensitivity of the sensor is equal to 0.01; that is, $\Delta C = 1$ ppm corresponds to $I/I_0 = 0.97$, corresponding to 200

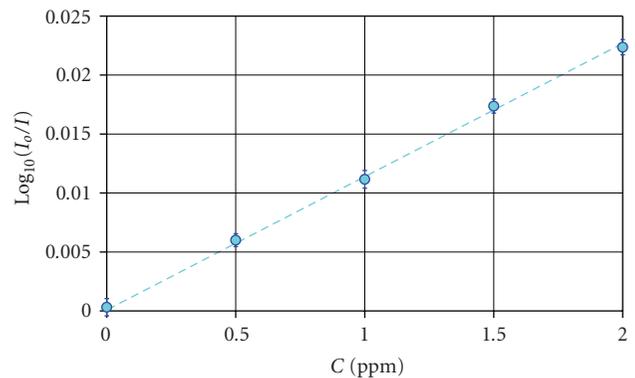


FIGURE 3: Linearity of the assembled ozone sensor; C (ppm) is the calibrated ozone concentration (provided by the Multigas calibrator).

counts. The repeatability is equal to $2\sigma/(\sqrt{3}\bar{x}) = 0.08$ ppm, where σ is the standard deviation of the mean, \bar{x} , with a coverage factor of 2. The concentration resolution is lower than 0.15 ppm.

The same sensitivity has been obtained with the other set-up in the range 2–10 ppm [4], but with a worst resolution.

During all tests, a very fast response time (seconds) to changes of the concentration in the flow chamber has been evidenced; this confirms that the sensor is suitable to follow

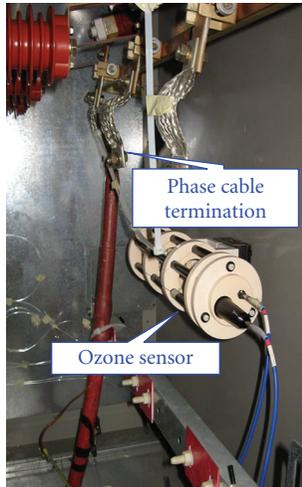


FIGURE 4: Experimental layout.

quick changes of ozone concentrations along the measuring path.

4. Experimental Details

To assess the feasibility of the new sensor in detecting ozone concentration under a real operating condition, a typical MV switchboard configuration was reproduced in the laboratory. Normalized components exploited in Italian distribution network (12/20 kV) were used. Inside, two different artificial defects were introduced once at a time to simulate predischarge activity. A wire (300 mm long and 1 mm diameter) was used to generate a corona phenomenon. A strip of electrical semiconducting tape (70 mm long and 15 mm wide) was attached to the phase cable termination to simulate a surface predischarge.

A standard Partial Discharge (PD) electrical system was used to monitor the predischarge activity [9]. This method provides the value of the predischarge amplitude in terms of apparent charge (picoCoulomb, pC).

For each type of defect, a series of tests were carried out by increasing the voltage applied to cable termination from 0 kV to the predischarge inception level (U_i), detected by the PD system, and then progressively up to 25 kV.

The ozone probe was installed inside the MV switchboard and connected to the control unit located outside of the MV enclosure, as schematically shown in Figure 1. The probe was located on a lateral wall of the enclosure as shown in Figure 4.

To check the presence of ozone concentration in the MV switchboard, a commercial ozone sensor with a typical acquisition times of one minute, was also located inside the metallic case.

5. Results and Discussion

Figure 5 shows an example of the ozone trend (red points) measured by the optical sensor versus time during three consecutive voltage applied ramps. The ozone level was

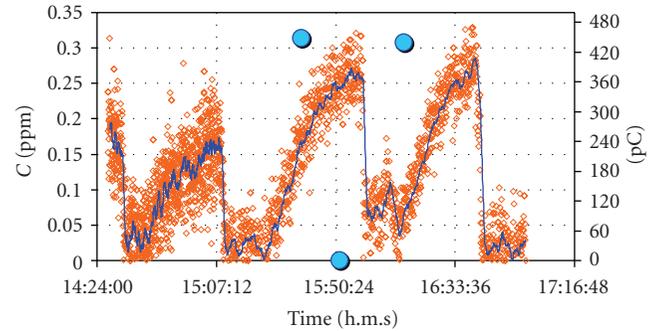


FIGURE 5: Ozone sensor response versus time measured in presence of the corona defect. The right vertical axis reports predischarge amplitudes (pC) by the standard PD electrical method.

evaluated by means of the calibration curve shown in Figure 3. Data shown in Figure 5 refer to ozone values measured inside the MV enclosure in presence of a corona defect. The acquisitions were 2.5 seconds long. The solid line (blue line) represents the average over 20 points. The vertical axis on the left shows predischarge amplitude values (in pC) measured by the standard PD system (blue dots in figure).

As shown in Figure 5, similar trends were obtained with the corona defect over three measure repetitions. This behavior is in good agreement with data registered by the PD system; it was confirmed that the corona phenomenon was quite stable. A slight delay in detecting both the corona inception and extinction was observed, even if a time of tenth seconds was confirmed. The ozone levels measured by the optical sensor were between 0.2 and 0.3 ppm (on plateau); these values were in good agreement with the average value measured by the commercial ozone system (0.23 ppm). As shown in Figure 5 the sensor started to detect ozone presence over three repetitions, when the amplitude of the corona predischarge was equal to 400 pC. This value was measured by the PD system at a voltage level equal to $1.25 U_i$. This is the minimum applied voltage necessary to record an ozone activity by means of this optical sensor. This value was compared with detectable threshold values of both the optical microphone and the fluorescent fiber-based sensor of the diagnostic prototype, respectively, equal to $1.15 U_i$ and to $1.1 U_i$. As evidenced, the sensitivity of the ozone sensor is slightly lower than sensitivities of optical and acoustic sensors. A lower sensitivity was obtained in presence of surface predischarges. The sensor began to appreciate the presence of ozone (0.15–0.2 ppm) only when the predischarge activity was higher than 1500 pC (equal to $2.5 U_i$). The amplitude of the surface predischarge, measured by the PD system at inception was about 600 pC. This is probably due to the high instability of this of phenomenon. To improve the sensitivity to both predischarges inception an optimization of the path length will be performed.

6. Conclusion

This paper was aimed at giving a contribution to the ongoing development of a combined diagnostic system for detection of predischarges in electrical components of MV distribution

network. In particular the application for the first time of a new fibre-optic sensor for detecting ozone variation induced by predischARGE in a MV switchboard, was evaluated. A novel layout of the spectroscopic type sensor, based on the use of an optical retroreflector, was adopted to improve its sensitivity. Optical fibres were used to connect the sensing probe, installed into the MV enclosure, to the remote control unit located outside.

Main advantages of this whole optical configuration are its installation inside the MV compartment without affecting service performances of electrical components; Moreover, any mutual interference between the optical sensor and the ozone produced by predischARGES is avoided, since the sensor is based on a spectroscopic technique. As a consequence a long life in service is expected.

Main features of this sensor are linear response from 0.1 to 10 ppm and a concentration resolution lower than 0.15 ppm.

The validation of this sensor in a typical MV switchboard configuration either with a "corona defect" or with a semiconducting strip (surface predischARGE) has evidenced the sensor feasibility to follow predischARGE activities and to provide a correct measure of the ozone concentration produced. The minimum detectable threshold of the ozone signal in presence of a corona phenomenon was $1.3 U_i$, slightly higher than these of acoustic and optical sensors, and higher ($2.5 U_i$) with surface predischARGE.

Further developments will be sought to improve both the sensitivity and the speed of the sensor response, in presence of surface predischARGE phenomena.

Acknowledgments

This work has been financed by the Research Fund for the Italian Electrical System under the Contract Agreement between CESI RICERCA and the Ministry of Economic Development - General Directorate for Energy and Mining Resources stipulated on June 21, 2007 in compliance with the Decree no.73 of June 18, 2007. The authors also gratefully acknowledge Mr. R. Marini and Mr. P. Serragli for their technical support and Dr. L. Fialdini for helpful discussion.

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