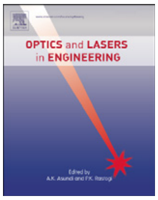
Optics and Lasers in Engineering 50 (2012) 1672–1676

Contents lists available at SciVerse ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Simultaneous fluorescence and breakdown spectroscopy of fresh and aging transformer oil immersed in paper using ArF excimer laser

P. Parvin [a],*, S.Z. Shoursheini [b], F. Khalilinejad [b], A. Bavali [a], M. Moshgel Gosha [a], B. Mansouri [a]

[a] Physics Department, Amirkabir University of Technology, PO Box 15875-4413, Tehran, Iran
[b] Physics Department, Alzahra University, 1993891176 Tehran, Iran

ARTICLE INFO

Article history:
Received 11 August 2011
Received in revised form
6 March 2012
Accepted 28 March 2012
Available online 27 June 2012

Keywords:
Transformer oil
Degradation
Laser induced fluorescence spectroscopy
Laser induced breakdown spectroscopy
ArF (UV excimer) laser

ABSTRACT

HV transformers are taken into account as the heart of the power distribution system. The on-line monitoring based on the oil analysis offers a rapid diagnostic technique to detect the probable faults. In fact, the transformer malfunctions can be detected using UV laser spectroscopic methods. Here, a novel technique is presented based on simultaneous laser induced fluorescence (LIF) and laser induced breakdown (LIB) spectroscopy for hyper sensitive identification of the oil degradation. Oil is mainly degraded due to the internal transformer faults such as overheating and partial discharge. The spectroscopic characteristics of oil in paper substrate were obtained due to ArF laser irradiation. It was shown that the amplitude of fluorescence signal increases when the oil suffers aging and degradation. A couple of additional characteristic carbon and H_α emissions appear in the corresponding breakdown spectra too.

1. Introduction

Today, there are nearly more than one million power transformers operational worldwide. Transformers are a vital of the transmission and distribution system where maintenance and repair are technically and economically essential. It includes the detective, diagnostic and protective methods [1]. The mechanical and electrical properties of the insulators in the power transformer are investigated to assure the efficiency and quality of the network performance. The most critical component of a transformer is immersed in the oil which acts as the insulator and the coolant simultaneously [2]. Transformer oil is a specially processed fraction of petroleum for the use of the electrical apparatus [3,4]. Mineral oil includes the components such as annular and aromatic molecules i.e. C_nH_{2n}, C_nH_{2n+2} It has been vastly used in the high-voltage electrical components since the beginning of the 20th century. Most liquid filled transformers are currently in service and the oil covers the core, windings and fittings that require oil insulation. The flow through the windings and cellulose insulations facilitates the heat removal and also provides efficient insulation between the windings. Transformer oil undergoes varying degree of aging under the normal operation condition. The rate of aging is dependent upon the magnitude of electrical, thermal and mechanical stresses. Insulation breakdown in the windings, coil–coil or coil–ground, lead to the subsequent arcing. Under arcing stress, the oil will generate solid carbon which reduces the heat dissipation capability. Furthermore, it induces a reversal effect on the dielectric strength. Diagnostic equipment provides an assessment of the oil condition inside the transformer [5] by monitoring the degree of degradation. The imminent fault monitoring prevents the damage extension assuring long-term utility operation.

The on-line protection system enables us to detect the fault before the sudden command for switching off the circuit breaker. The advantages include the prevention of unwanted run out, the reduction of transformer damage and the increase of duty cycle leading to a longer lifetime and an optimal utilization. There are two on-line methods which consist of the analysis of the compounds of multi gas components based on the dissolved gases analysis (DGA) within the oil and the Kelman analyzer according to the photo acoustic spectroscopy [6]. However, these techniques face the system complication and multistage sampling. The absorption spectroscopy as an alteration technique relies on the concentration measurement of the chemical compounds. The absorption transition alters significantly for new and faulty oil to be an indication to the insulators. The oil failure is closely related to the changes in the refraction index as a major dielectric property. In this case, oil is continually sampled from the transformer through a closed circuit. Then, oil is exposed by light and tested for the absorbance. The experiments demonstrate the differences between accepted or unaccepted samples. The failed transformers have shown a general increase in the absorbance of light in oil [7]. Recent studies characterize the optical response of the oil absorption using a laboratory grade spectrophotometer.

---

* Corresponding author. Tel.: +98 9121936156; fax: +98 2166492469.
E-mail address: parvin@aut.ac.ir (P. Parvin).

0143-8166/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.optlaseng.2012.03.015

Absorbance increases for the oil degraded in the laboratory or that sampled from in-service transformers over a range of wavelengths. This is substantiated by the theoretical aging analysis including arcing, thermal stress and excessive exposure to atmospheric air [8].

Regarding the molecular absorption schemes, the optical properties are among the material characteristics. In fact, the excitation of molecules by laser results in the subsequent radiative deactivation, leading to the emission from particular transitions accordingly. The spectral emission is unique for any molecular species. So far, LIF was done for several hydrocarbon compounds and has proven to be an accurate, sensitive, and selective method for measurement of trace atmospheric species throughout the troposphere and stratosphere [9]. The environmental pollutants were monitored in order to diagnose the petrochemical derivatives and the hydrocarbon aromatic molecules [10–13]. The usefulness of the fluorescence technique is approved for the identification of aromatic cycle aliafatic carbonyl and the compounds with the structure of double bond conjugates. Hence, LIF exhibits several advantages respect to the competitive techniques particularly the detection becomes much simpler when it does not require high resolution dispersive elements [8,10].

Moreover, the laser induced breakdown spectroscopy (LIBS) is used to determine the elemental compositions in different atmospheres. This technique offers fast data acquisition avoiding sampling preparation. When a powerful pulsed laser is focused on a surface, a tiny amount of the material is vaporized and by further photon absorption, is heated up to be ionized. The laser-induced plasma is a micro-source of light that can be analyzed using a suitable spectrometer. The obtained spectra involve the characteristic lines of atoms and ions within the plasma which are attributed to the elements evaporated from the sample.

The plasma in liquid induced by a single laser shot characterizes a short lasting and weak emission due to the strong quenching and broad spectral lines originated by collisions and stark effect. Moreover, the plasma excitation by two laser pulses, separated in time by tens of microseconds, has been already demonstrated to improve the analytical performances both in air and liquid surroundings [14,15]. Furthermore, a comparison between single and double pulse LIBS for the quantitative elemental analysis of the used engine oils was recently reported. The paper substrate has been utilized to provide better limit of detection, while the undesired splashing does not take place and the sample handling is easier. In general, the single-pulse LIBS analysis of oil in paper substrates doubly improves the limit of detection [16].

In this work, the simultaneous LIF and LIBS were demonstrated for the samples (paper + oil) using ArF laser irradiation at 193 nm. The breakdown emission identifies the elemental constituents of the targets. It accompanies with a couple of excessive emerging characteristic emission of carbon due to oil degradation as well as an obvious H_α characteristic line. In addition, it was shown that the fluorescence signals of fresh and aging oil are noticeably distinct and distinguishable.

2. Apparatus

The experimental setup consists of a couple of UV coherent sources, conducting and focusing optics, laser pulse diagnostics, delay generator, spectrometer, and the processor as shown in Fig. 1. A fourth harmonic generation of a Q-switched Nd:YAG laser at 266 nm, 4 mJ/pulse, 10 ns duration, pulse repetition rate of 1–20 Hz, has been used to generate the micro-plasma on the oil with paper substrate and the excitation of the oil molecular transitions too. Alternatively, a homemade ArF excimer laser at 193 nm (50 mJ/pulse, 10 ns) was employed [17]. The laser beam is focused through a quartz lens with 20 cm focal length which is situated in front of laser beam to enhance the incident power density. A semiconductor detector (PIN diode, EG&G, FNT100), a 300 MHz digital storage Tektronix 30145, a 2.5 Gb/s oscilloscope and a 400 MHz Tektronix 7844 oscilloscope, and a Coherent^{TM} joule/power meter (Field Master, LM-P10 and LM-P5 100 heads) were used for the relative and absolute power measurements.

The light emission of the plasma was collected by a fiber bundle (UV 600/660 type with SMA-905 fiber connector NA 0.22 and 1 m length) using a quartz lens (25 mm diameter, 50 mm focal length) placed 80 mm away from the sample. The fiber output was coupled to the entrance slit of a compact wide-range spectrometer (200–1100 nm) model S150 Solar Laser Systems^{TM} (50 mm focal length, transmission diffraction grating with 200 grooves/mm having 0.02 mm × 33.0 mm entrance slit and 0.5 nm spectral resolutions). A charge-coupled device (CCD) detector array model Toshiba TCD 1304AP with 3648 pixels was used to detect the dispersed light, subsequently. Furthermore, because of strong quenching, the CCD camera (with 30 μs gate) was triggered ~0.5 μs after the onset of the laser shot. It corresponds a relatively large stark broadened line-width. A temperature controlled electrical oven was employed to heat oil at 110 °C for various heating duration (120–200 h) to provide thermally degraded oil in the laboratory [8,16].

3. Results and discussion

At first, the oil transformer were filled in a typical quartz cell with 2 cm × 1 cm × 5 cm dimensions for the subsequent UV laser irradiation. The fourth harmonic generation of Q-switched Nd:YAG laser beam (266 nm, 4 mJ/pulse,10 ns) was focused through a quartz lens on to oil. The optical emissions were collected via an optical fiber connected to a grating spectrograph coupled with CCD camera. However the emission taken from the oil was notably weak based on the strong quenching effect. In fact, the plasma emission produced in the bulk liquid is generally lower than that of solid. There are several factors responsible for this effect including the laser absorption by liquid and the consequent plasma emission, the corresponding scattering on suspended particles and the micro-bubbles, the radiation shielding by dense plasma and eventually the fast quenching in dense medium [18].

LIF spectroscopy exhibits high UV absorption leading to an intensive molecular excitation within a skin layer of oil. Therefore, the collisions significantly increases and causes to drop the fluorescence emissions. The paper substrate (cellulose insulator)

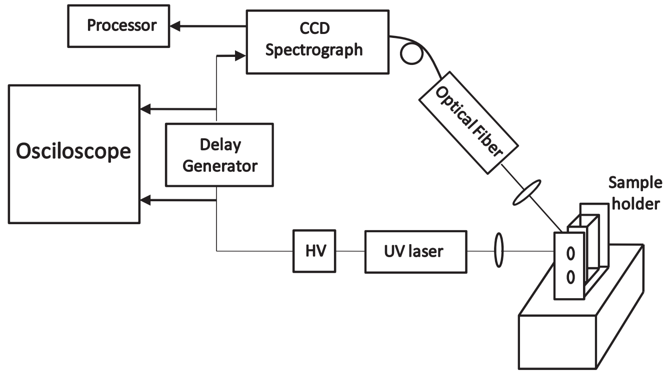


Fig. 1. Experimental array for laser induced LIF/LIBS of both transformer oil and paper substrate.