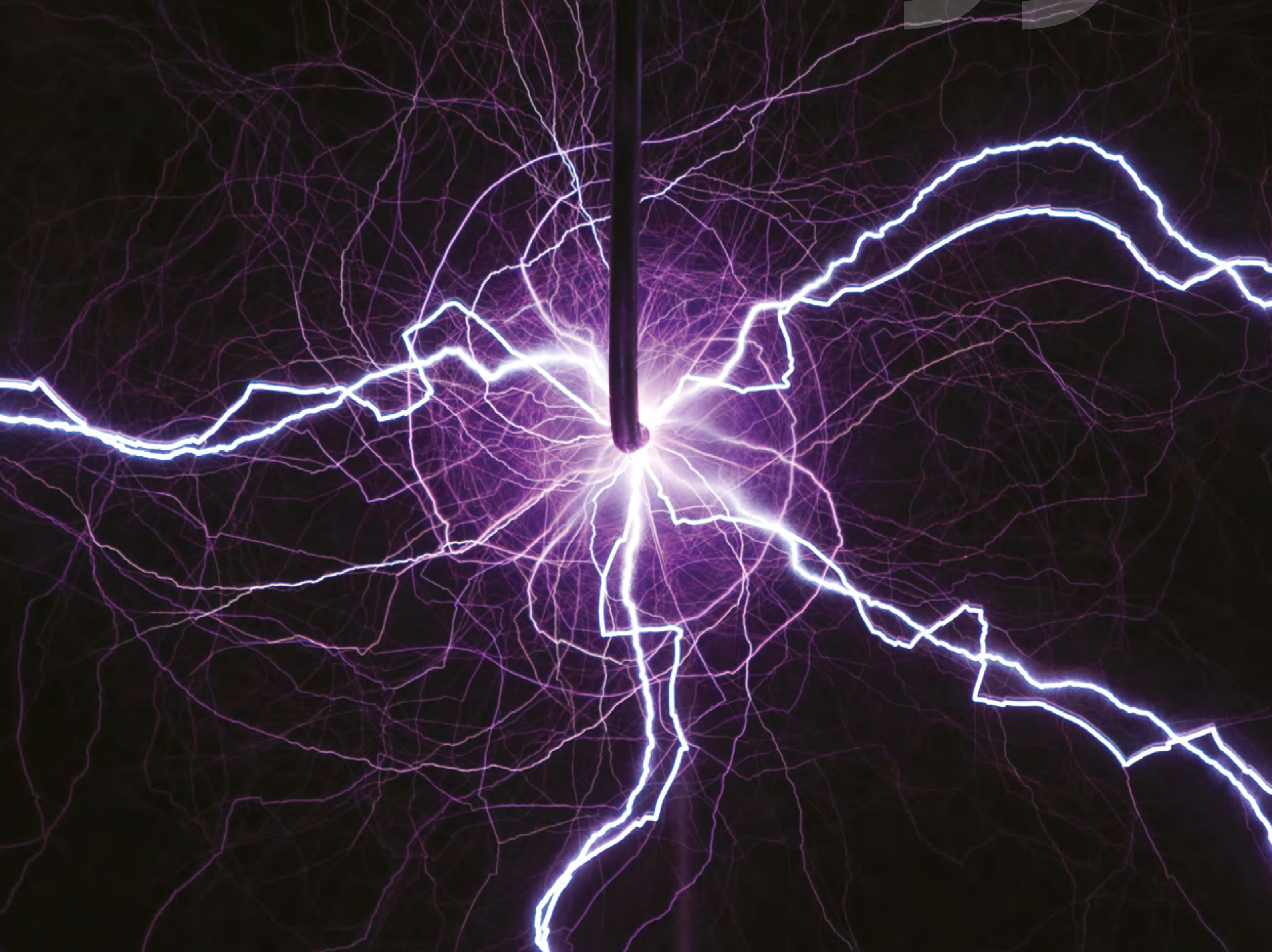
The explosion of the transformer tank due to an electric arc can have severe consequences such as extra costs or can even injure the personnel, so a fast and reliable arc detection method can help reduce those accidents



ABSTRACT

In this article, an application of potential light-sensitive semiconductive elements, including photoresistors and photodiodes as electric arc detection sensors in the transformer tank, is comprehensively investigated. Conventionally, a Buchholz relay (BHR) is implemented for arc fault detection in power transformers. Unfortunately, in some cases, the tripping of the transformer is not fast enough in order to prevent a tank rupture and catastrophic collateral damages. Therefore, an application of light-sensitive elements as optical sensors is investigated for detecting an arc inside a transformer tank faster under various operational conditions. This contribution focuses on the performance of sensors, which are inserted in the transformer tank. Apart from consideration of different factors such as stochastic nature of light in the arc, thermal cycling, the distance effect on the light sensitivity and possibility of light reflection by the tank, challenges and limitations of arc sensing with light sensors in the mentioned approach are comprehensively discussed. The deficiencies and limitations of the arc sensors are revealed through the experimental investigations conducted.

KEYWORDS

transformer tank, arc, light detection, optical sensors, photoconductive elements, ageing

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Possibility of electric arc detection in power transformers by directly embedded photoconductive elements in the transformer tank

Limitations and obstacles - An experimental investigation

1. Introduction

Nowadays, light-sensitive elements are extensively used as a transmitter or detector for a variety of applications in optoelectronic areas [1]. With the recent advances, highly efficient photovoltaic modules are now popular for electricity generation with high efficiency as well [2]. Conventionally, photodetectors such as photoresistors are implemented as a light detection system for switching purposes [1], data transmission, telecommunication, and electrical isolation in a variety of equipment such as switched-mode power supplies. Furthermore, well-known Kerr or Pockels effects change the polarisation of certain crystallised materials, which can be used for the measurement of electrical parameters such as voltage and current [3]. Also, temperature changes the amount of incident reflected light through a photosensor. Thus thermal monitoring of power cables has been commercialised for more than two decades in distributed temperature sensing (DTS) systems [4].

Recently, thanks to advances in semiconductor technologies, the mentioned sensors can be used in a variety of areas under different working conditions. For example, the explosion of the transformer tank due to an electric arc can have several serious consequences. A fast and reliable detection method is of high importance to reduce extra financial costs and prevent accidents, which could endanger the life of personnel. One special idea could be the application of photosensitive elements as an electric arc detection system in power transformers. However, such an application entails choosing an appropriate element with respect to the requirements of transformer service conditions. This contribution focuses on the performance of photoconductive elements, which are embedded or inserted in the transformer tank.

In this regard, several parameters can affect the performance of sensors as well, such as electromagnetic waves (EM) due to the electric arc, the distance of the sensor from the arc, temperature variation, absorption of photons by the oil and ageing of sensors during certain predefined periods. Following, apart from a brief physical introduction about the optical properties of such sensors, the most suitable measuring circuit for this approach is described. In the next section, the effect of the aforementioned parameters on the performance of the sensors is investigated in detail. Finally, in the conclusion section, based on the obtained results, certain recommendations are provided to clear the potential obstacles.

The physical phenomenon behind photosensitive semiconductors has been well-established through semiconductor physics [6]. Briefly, in this term, when the light, which is itself comprised of photons, with specific energy, strikes the substrate of light-sensitive elements, the electrons in the valance band are transmitted to the conduction region, leading to the additional kinetic energy of electron-hole pairs, and as a consequence, current flows through materials.

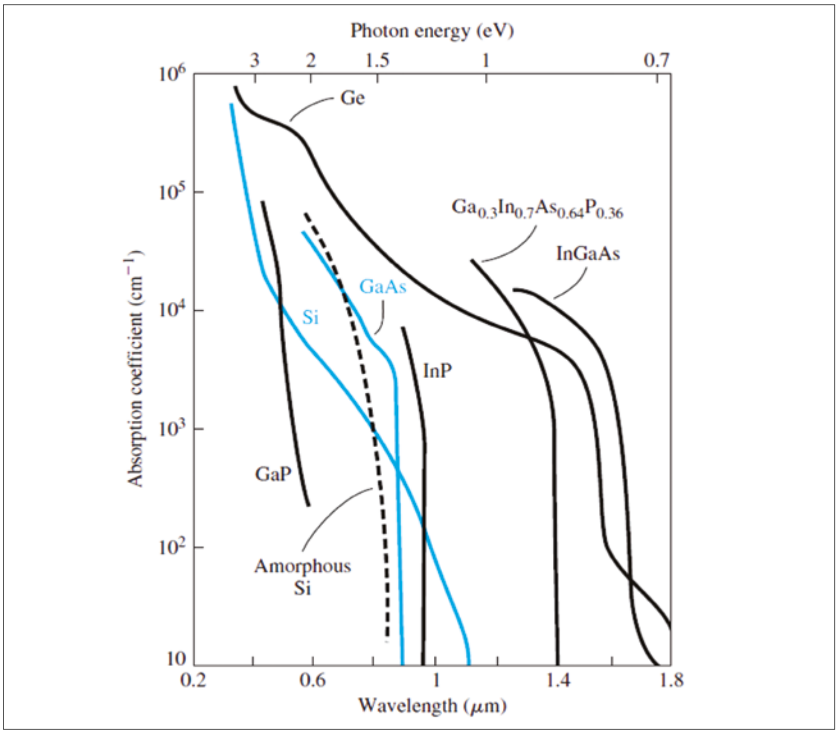

Figure 1. The absorption coefficient of some materials with respect to the wavelength and photon energy [3]

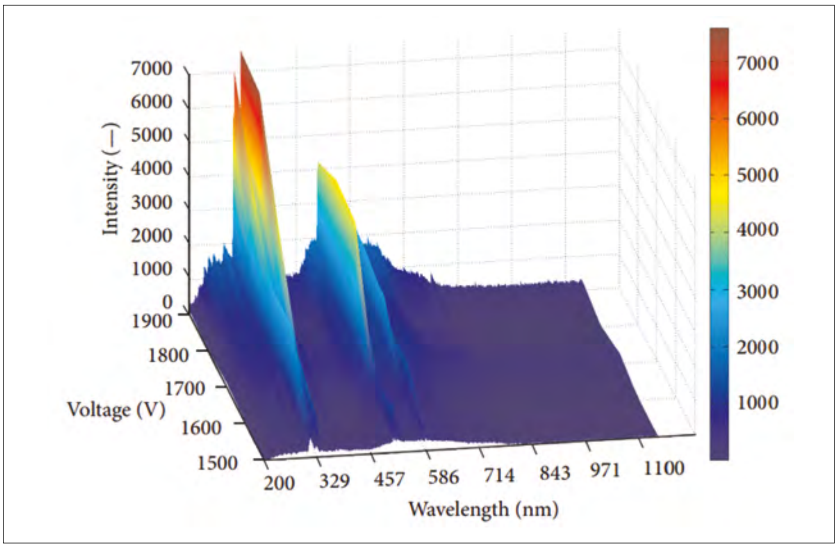

Figure 2. The light intensity of a 50 Hz electric arc at different voltage-wavelength [7]

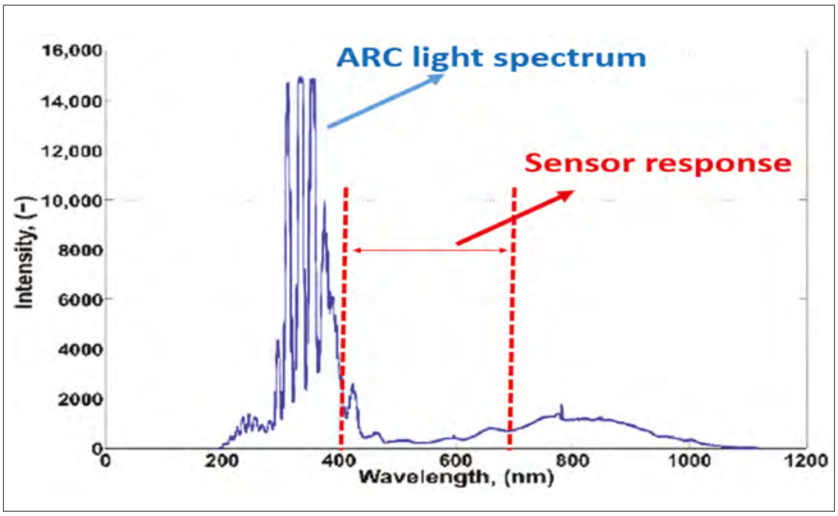

Figure 3. The light intensity of a 100 kHz electric arc at different voltage-wavelength [8]

The electric arc could be generated either due to transients of the power network or due to short circuits, so it is necessary to compare the wavelength spectrum of the electric arc at different frequencies

The amount of absorbed energy by the substrate of a light-sensitive element is indicated by the absorption coefficient. Fig. 1 depicts the absorption coefficient of some popular semiconductor materials used in optoelectronics.

As the electric arc could be generated either due to transients of the power network or short circuit among phases or one phase to ground, it is prudent to compare the wavelength spectrum of electric arc at different frequencies. Fig. 2 shows the light intensity of a typical 50 Hz electric arc source [7]. Besides, Fig. 3 depicts the corresponding value for a 100 kHz electric arc [8].

Clearly, the maximum energy of both electric arcs is below the visible range (400–700 nm); hence, wavelength detection of an ideal sensor should be in the range of 200–400 nm. Electromagnetic radiated waves are another important issue for a detection system adjacent to the electric arc. Fig. 4 illustrates the frequency spectrum of the potential in the cathode pin of a photodiode adjacent to (12 cm) a 50 Hz electric arc at the time of arc formation. Apart from the first strike, there could be some other re-ignitions, which can impose several consecutive voltage impulses to the measuring circuit.

2. Physical structure and electrical models

A brief description for modelling some popular photosensitive elements such as LDRs and photodiodes is presented in this section. Fig. 5 illustrates the internal structure of a typical photoresistor manufactured by CdS technology [9], where an indium tin oxide (ITO) acts as a transparent surface for CdS materials. The substrate of photoresistors is usually manufactured by ceramic as well. Clearly, the electrical model of a photoresistor is comprised of resistive and capacitive elements; hence, an RC parallel circuit is an appropriate model for LDRs. In terms of the internal structure of photodiodes, there are a variety of manufacturing technologies, which can be obtained in [1], which are neglected here. However, as for the electrical model, Fig. 6 depicts the equivalent circuit of conventional photodiodes.

In Fig. 6:

- Iph represents the current generated by the incident light,
- C is the diode capacitance,
- RSH is the shunt resistance,
- Rs is the series resistance,
- IN is the noise current, and
- RL is the load resistance.

There are three different types of noise currents in photodiodes, including Johnson, shot and flicker noise [11]. Johnson noise is attributed to the shunts, series, and load resistance, which is physically expressed by (1).

$$I_j = \sqrt{\left(\frac{4KTB}{R}\right)} \qquad (1)$$

Where:

- Ij is the Johnson noise
- K is Boltzmann constant
- T is the temperature in Kelvin
- R is equivalent resistance lead to noise

Shot noise presents in reversed bias photodiodes and increases with the increment of a DC bias, in particular at high temperatures. The mechanism behind the flicker noise is not well understood, but it is attributed to the stray electromagnetic waves, contacts, surfaces and potential barriers. Usually, flicker noise is smaller than the others but increases dramatically at low frequencies. Fig. 7 depicts the amplitude spectrum of the flicker noise in a typical photodiode [12]. As it can be seen, the flicker noise has several major components at low frequencies (almost between 50–100 Hz). This behaviour will be explained in the following sections by practical tests as well.

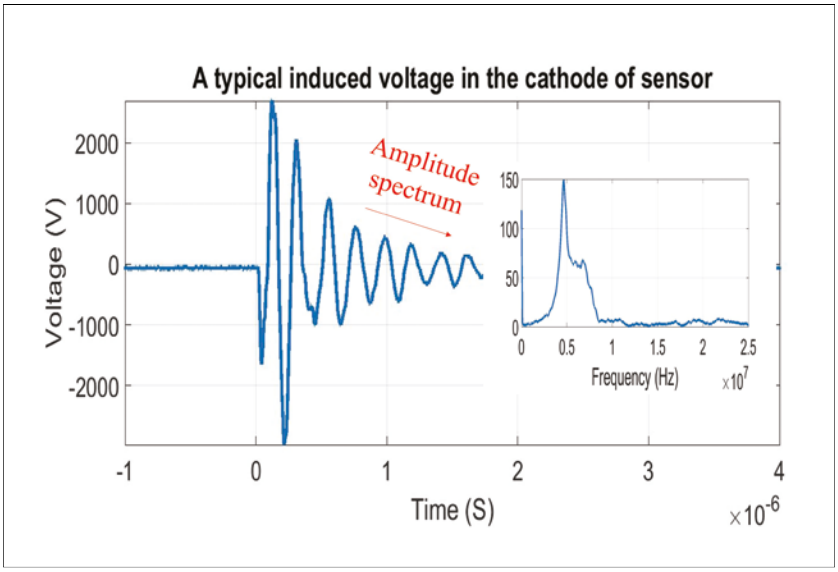

Figure 4. Potential of the cathode in a photodiode adjacent (12 cm) to a 50 Hz electric arc at the time of arc formation

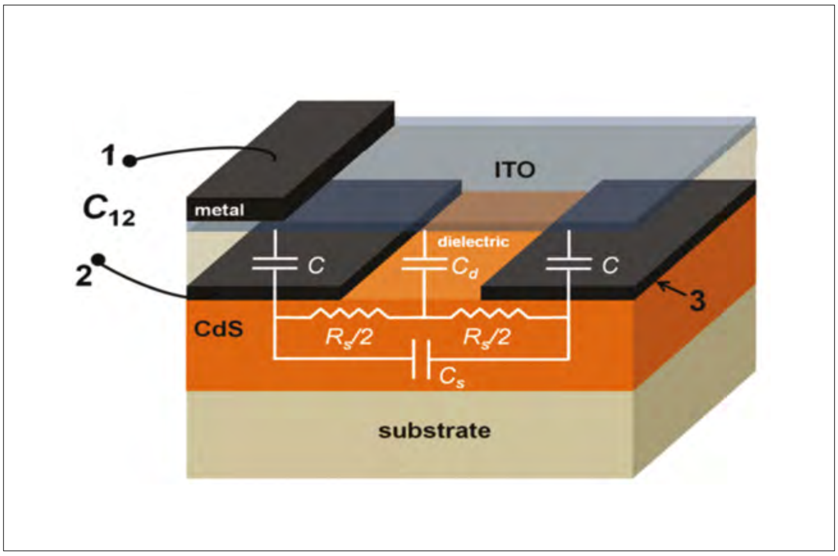

Figure 5. Internal structure of a light-dependant resistor [9]

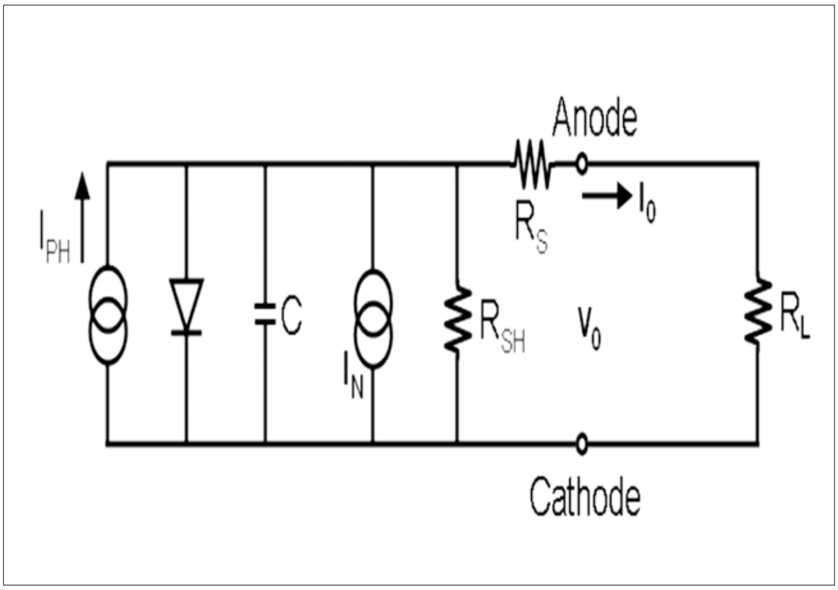

Figure 6. An electrical model for photodiodes [10]

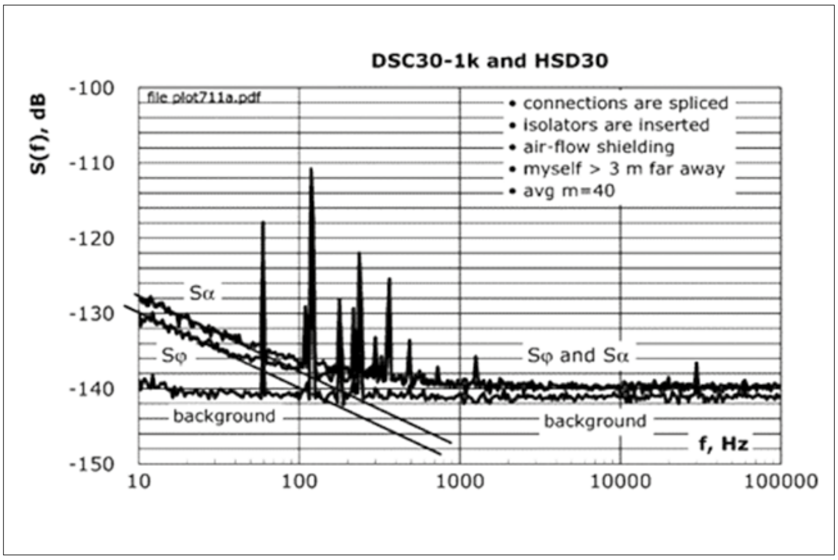

Figure 7. A typical amplitude spectrum of the flicker noise [12]

In the photoconductive mode, the photodiode is reverse biased by a DC voltage, while in the photovoltaic mode, it is used as a light dependant current source

A higher temperature reduces the absorption coefficient of photodetectors, so it is not advisable to use photosensors beyond their recommended working temperature

Typically, the dark current I_{dark} of photodiodes doubles for each 10 °C as the flowing relation [11].

$$I_{dark}(T_2) = I_{dark}(T_1) \times 2^{\frac{(T_2-T_1)}{10}} \quad (2)$$

Also, a higher temperature reduces the absorption coefficient of photodetectors (see Fig. 1). Thus, it may not be advisable to use photosensors beyond their recommended working temperature, e.g., photoresistors (LDRs) have working temperature limitations generally up to 75 °C and photodiodes up to around 100 °C, which are below the maximum transformer operating temperature of > 100 °C.

3. Light detection circuit

Photodiodes can be implemented in photoconductive or photovoltaic modes [10]. In the photoconductive mode, the photodiode is reverse biased by a DC voltage, while in the photovoltaic mode, it is used as a light dependant current source. Although an external DC bias increases the detection speed, it increases both dark and noise current. This behaviour is problematic in the case of low light intensity, where the dark and noise current can saturate the current due to the light. On the other hand, as will be explained in the following section – due to EM in the presence of an electric arc – a very fast response is not achievable (limited by the lower cut off frequency of the filter). Hence, for this application, a transimpedance circuit in zero bias voltage (photovoltaic mode) is preferred. Fig. 8 shows the schematic of the implemented experimental setup in this paper.

In the figure below, the instant light of arc was generated by a spherical (diameter

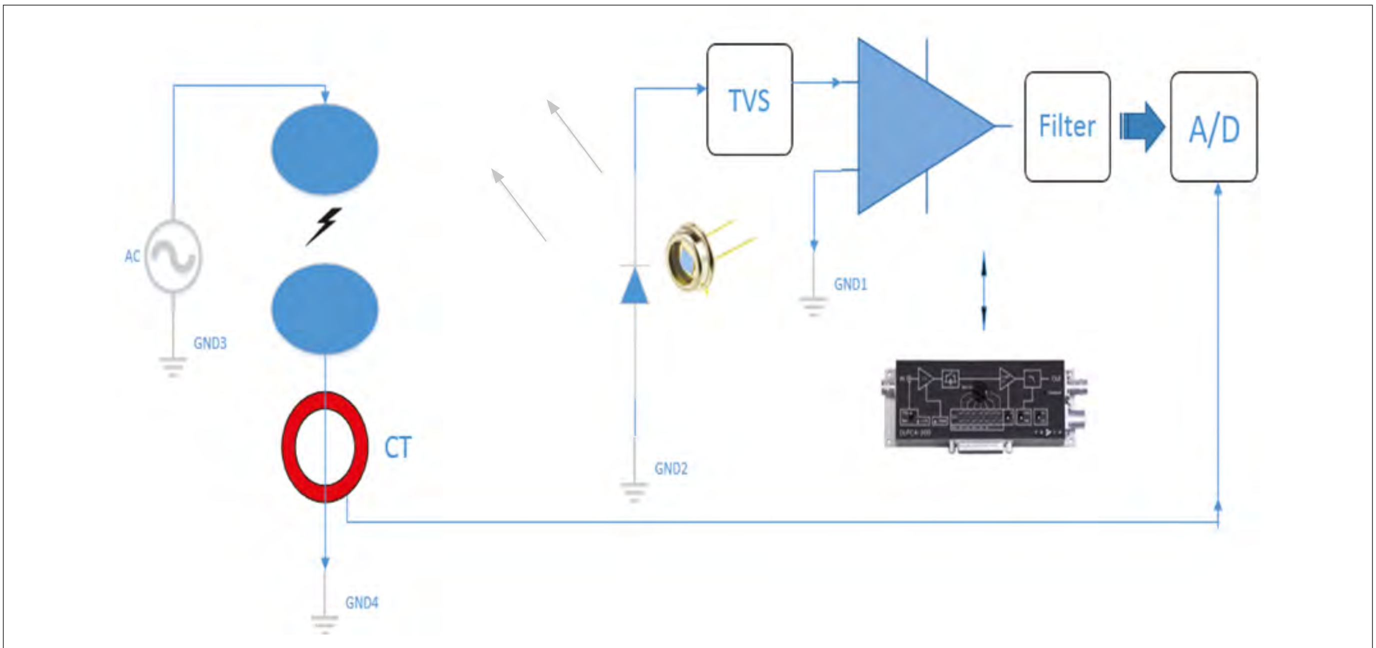

Figure 8. A schematic of the measuring circuit used for photodiodes

Figure 9. Some parts of the measuring circuit as for photodiodes a) Two pairs of photodiodes in a shield box, b) The measuring chamber

2 cm) to a planar ground electrode (diameter 2 cm), where the gap between them was set to almost 2.5 cm. The configuration was excited with a 50 Hz high voltage transformer. The signal of shielded photodiodes (BPX65) is transferred to a variable gain transimpedance current amplifier (DLPCA 200), which is connected to an A/D converter (2 Gs/S, Bw ≈ 70 MHz) after filtering the amplified signal. The triggering signal of the A/D was provided by a current transformer (Bw≈200 kHz) at the instance of an electric arc formation. In order to improve the signal to noise ratio, three photodiodes are used in parallel with each other. Besides, another light-tight pair was also used for more investigations. Fig. 9(a) and 9(b) illustrate some parts of the measuring circuit as well.

Furthermore, a TVS (Transient Voltage Suppressor) was used for the protection of the transimpedance. Also, Teflon coaxial cables were implemented. Thus measurements in the air can also be performed at higher temperatures, e.g., at 120 °C, which may occur in transformers. They were also incorporated in a double shield structure to obtain a better signal to noise ratio. In this contribution, besides photodiodes also LDRs were selected from two different manufacturers, one of which is incorporated in metallic shielded (GL5516 by Senba Sensing Tec.), while another (a generic 5 mm LDR) has no shield. However, in the test, a custom-made shield was also provided. Fig. 10(a) depicts a schematic of the circuit used for LDRs, where a high-frequency current transformer acts as the current measurement device (bandwidth ≈5 kHz–400 MHz). A photo of the setup is also depicted in Fig. 10(b).

EM due to the electric arc contains a wide range of frequencies, so a low pass filter is implemented to reduce the effect of EM on the measuring circuit

4. Results

In order to investigate the effect of the distance on the sensitivity of photodiodes, the arc source was located at some predefined places. As shown in Fig. 3, EM due to the electric arc contains a wide range of frequencies. Hence, in order to reduce the effect of EM on the measuring circuit, a low pass filter is implemented. Clearly, a lower cut-off frequency reduces

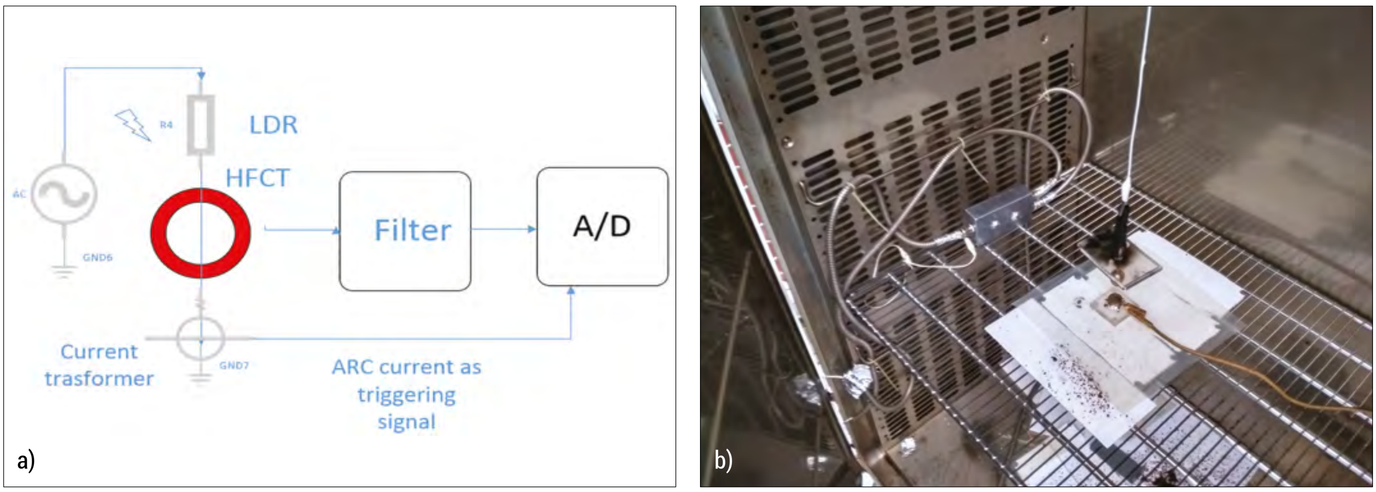

Figure 10. a) A schematic of the measuring circuit b) A part of the setup used for LDRs

In order to investigate the oil effect on the amount of light intensity, the test chamber was filled with mineral oil, and there is no noticeable difference between the amounts of the detected light in the experiment

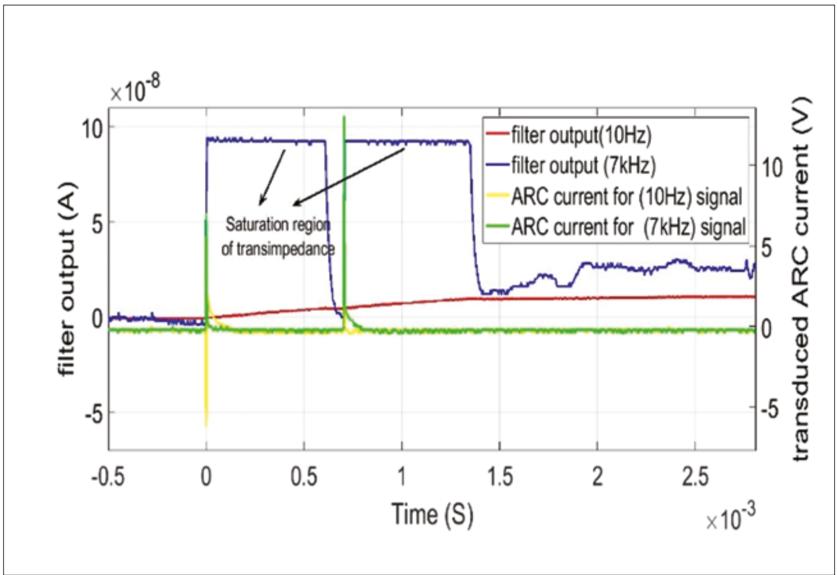

Figure 11. The effect of filtering on the output signal

the rise time of the detected signals and detection speed. This fact is depicted in Fig. 11, in which the output signal is compared between two filters with 10 Hz and 7 kHz cut-off frequency. As can be seen, the output signal at 10 Hz (red trace) is, however, independent of the EM due to the arc (yellow trace). Although, the output signal with 7 kHz has a sharp rise time at the time of arc occurrence (arc has re-ignition), leading to saturation of the output signal. Hence, one should make a trade-off between the detection speed and the noise immunity of signals. In the following, a 10 Hz filter was implemented.

4.1. The effect of distance on the light sensitivity

Fig. 12 depicts the several recorded signals at room temperature for 12 cm, 25 cm, 50 cm and 90 cm. Clearly, with the shortest distance (12 cm), the recorded signal has the highest sensitivity. Although, the sensitivity of the sensors is drastically reduced with an increment of the distance.

4.2. Oil effect

In order to investigate the oil effect on the amount of light intensity, the test chamber

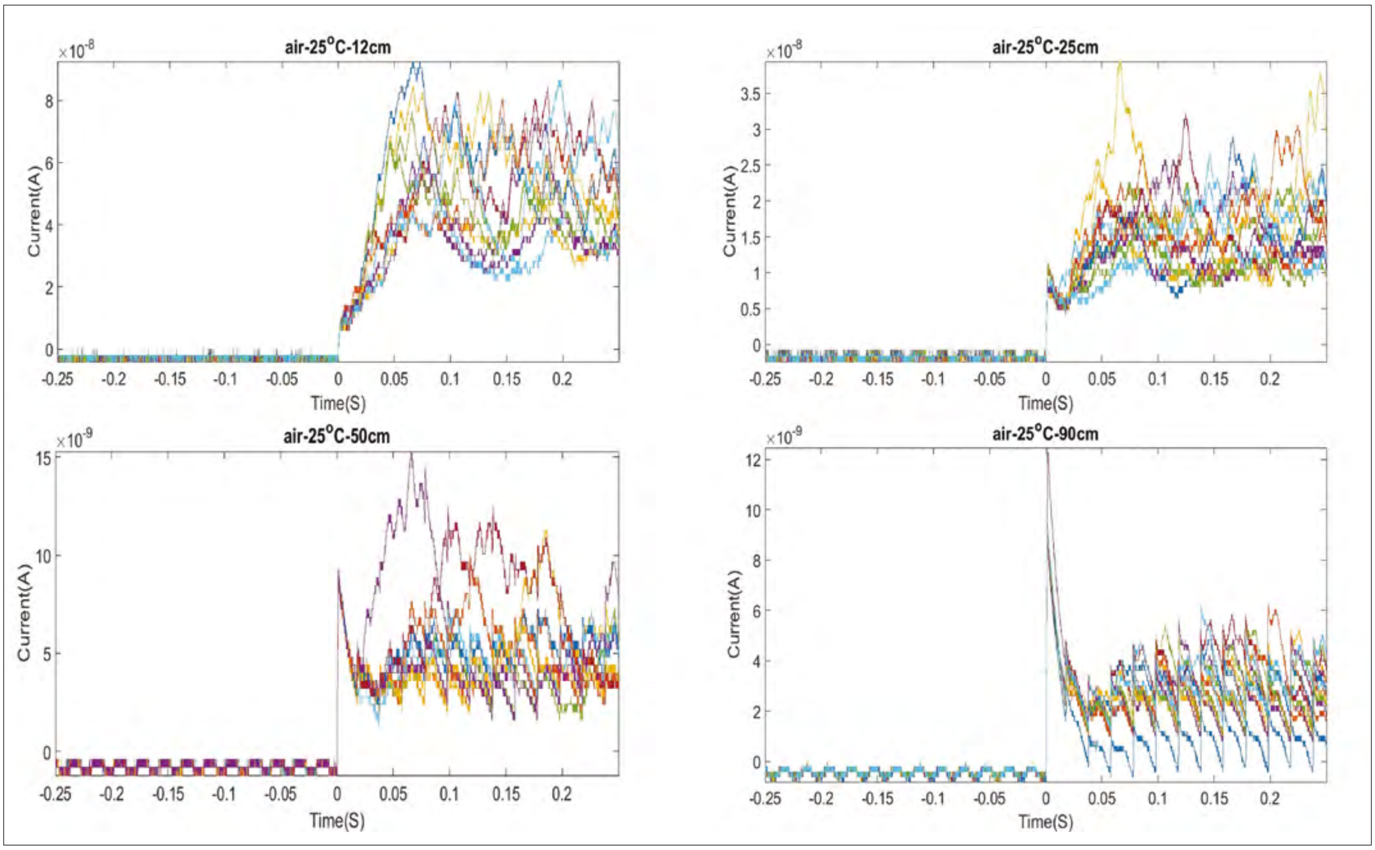

Figure 12. The distance effect on the light sensitivity of photodiodes

was filled with mineral oil, as depicted in Fig. 13. In this case, the arc source is different from the aforementioned one in order to have a much more stable arc column for an accurate comparison. Also, in order to make test the reproducibility of results, a high number of arcs (> 20) were applied to extract any possible effect. By comparison of the following figures, there is no noticeable difference between the amounts of the detected light. However, there could be small differences for transmission properties of oil where the detected signals in oil seem more concentrated. Hence more investigations are required to clear the situation, viz. such effects could be out of sensitivity of the introduced setup in this paper. Also, the amount of ageing in oil is a determining factor because more ageing makes the oil more blur and may change the transmission characteristics of mineral oil.

4.3. Detection wavelength

To investigate the effective wavelength spectrum of sensors, small strip of paper tissue was placed between the electrodes of the previous test setup. When the electrical arc forms, it ignites and partially vaporizes the paper. The presence of carbon

To investigate the effective wavelength spectrum of sensors, a strip of paper tissue was placed between the electrodes, and the sensors became more responsive due to the firing of the tissue

Figure 13. The test chamber for the investigation of oil effect

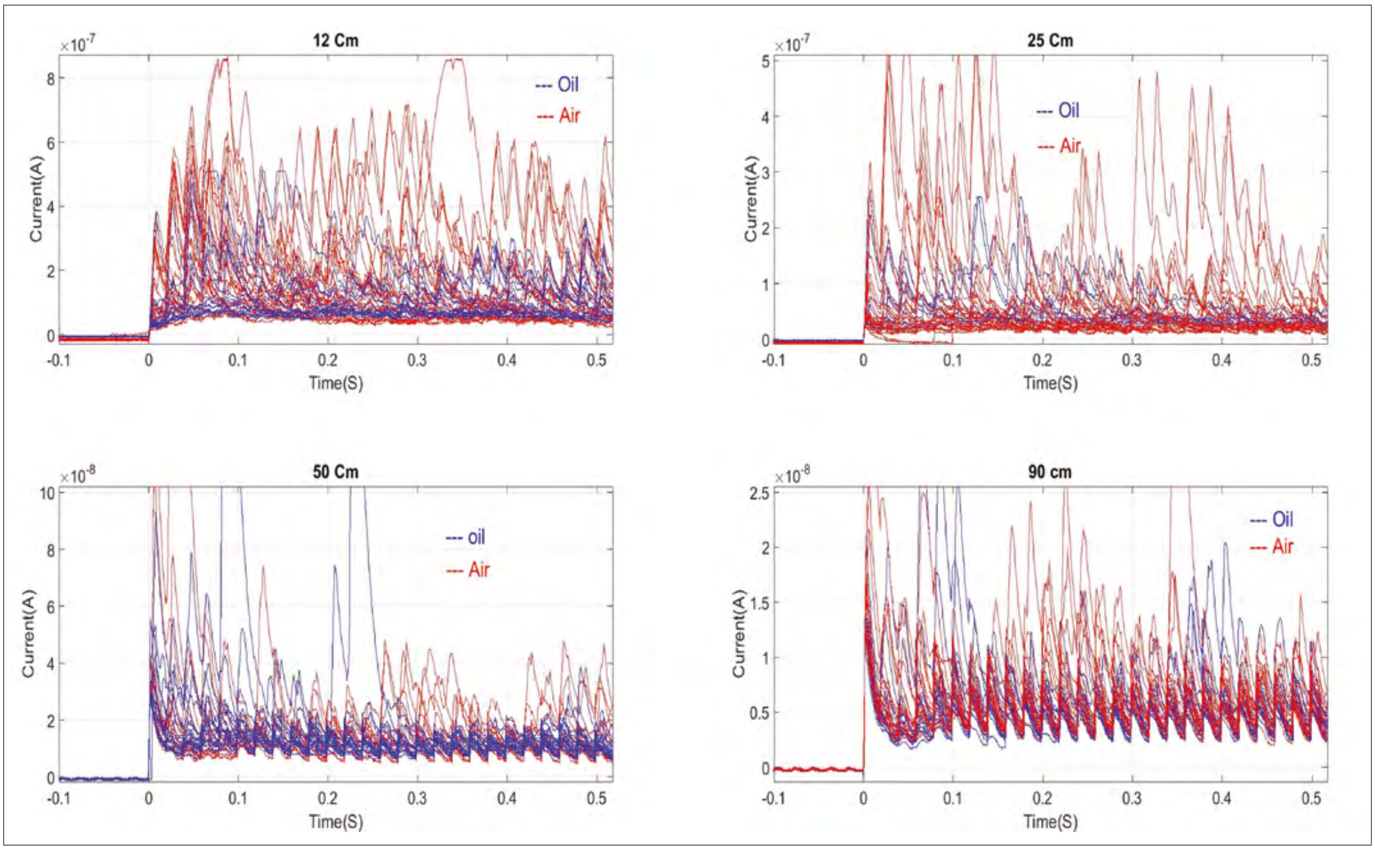

Figure 14. Comparison of the measured current in oil and air for a high number of arcs

The temperature has a noticeable effect on the sensor's signal to noise ratio and the flicker noise at the low-frequency range

from the paper in the arc plasma changes the brightness and spectrum of the emitted light. As shown in Fig. 15, the sensors are more responsive due to aditional wavelengths of the carbon. This behaviour shows that the sensors are appropriate for visible range rather than the arc light wavelength (see Fig. 2). However, as explained, those sensors working in lower wavelengths are much more expensive.

4.4. The effect of temperature on the light sensitivity

As mentioned in section II, the noise in the photodiode's current is comprised of Johnson, shot and flicker noise. Based on equation 2, the temperature has a noticeable effect on the performance of photodiodes. On the one hand, as explained above, due to EM, the output signal should be filtered for a higher signal to noise ratio. On the other hand, the flicker noise exists at

The electric arc could happen at different areas of the transformer active parts, while the sensors may be placed somewhere else, which means they are not directly exposed to the arc light, which was also investigated

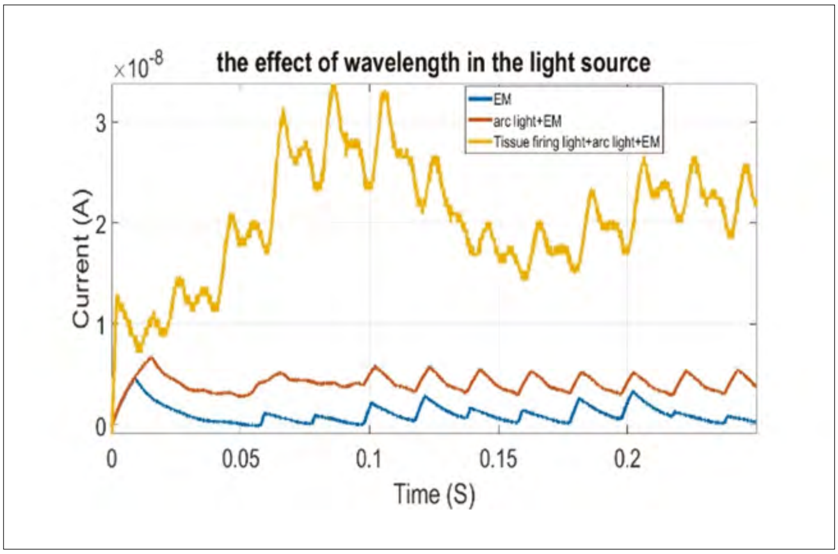

Figure 15. The effect of wavelength on the light sensitivity

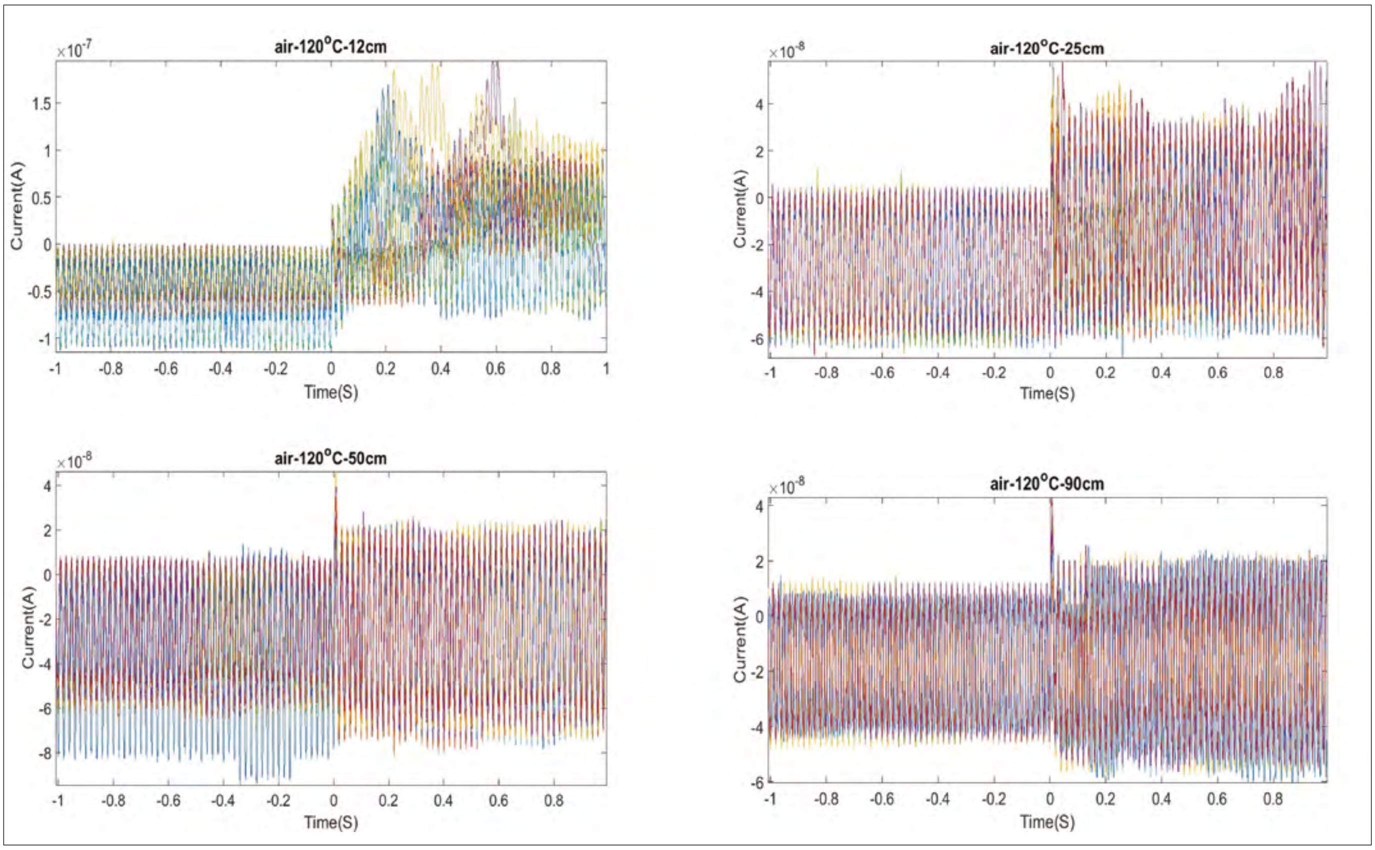

Figure 16. The temperature effect on the performance of photodiodes

the low-frequency range and is dramatically intensified with temperature both for DC and almost 50 Hz component. Clearly, the dark current could saturate the DC component due to the light. Fig. 16 depicts the stochastic nature of ten different arcs at 120 °C, at some predefined distances. Worthwhile to mention that due to the variation of the internal shunt resistor of the photodiodes (see Fig. 6), the effect of coaxial cables can be higher. Hence, a shorter coaxial cable is recommended, in particular at high temperatures.

The electric arc could happen at different areas of the transformer active parts, while the sensors may be placed somewhere else. Thus they are not directly exposed to the arc light. However, the light could be reflected from the tank to the sensors. For investigation of this occurrence, the gap between electrodes was increased to 4.5 cm (for the bottom electrode, another one was also selected with a diameter of 14.5 cm). The distance between the arc source and the sensors was 80 cm, and the barrier was placed in the middle at 40 cm, as shown in Fig. 17. In this case, the response of one sensor (rather than three sensors) was recorded, and the results were compared with the barrier placed. Regarding Fig. 18(a) and 18(b), there are several spikes due to the re-ignition of the electric arcs, which should not be attributed to the light. By comparison of mentioned figures, it is concluded that the DC offset of signals is lower than the case without a barrier in the case with a barrier. However, the DC component of signals when the barrier was placed shows that a part of light could still be reflected by the transformer tank. Also, the inside surface of a transformer tank may not be reflective enough, similar to the one under the experimental setup, and multiple reflections may further limit reflection due to the complex core of the transformer.

5. Ageing factors

Based on the performed tests, there are some dominant ageing factors, which reduce the performance of photodiodes. These factors are explained in the following section, and typical results for each part are mentioned in the corresponding sub-sections. It is important to note that the presented results are relative with respect to the specified condition of tests. For instance, the length of coaxial cables may change the reported results.

There are some dominant ageing factors, which reduce the performance of photodiodes, such as exposure to electromagnetic waves, short-term thermal cycling in the transformer tank and medium-term ageing in oil

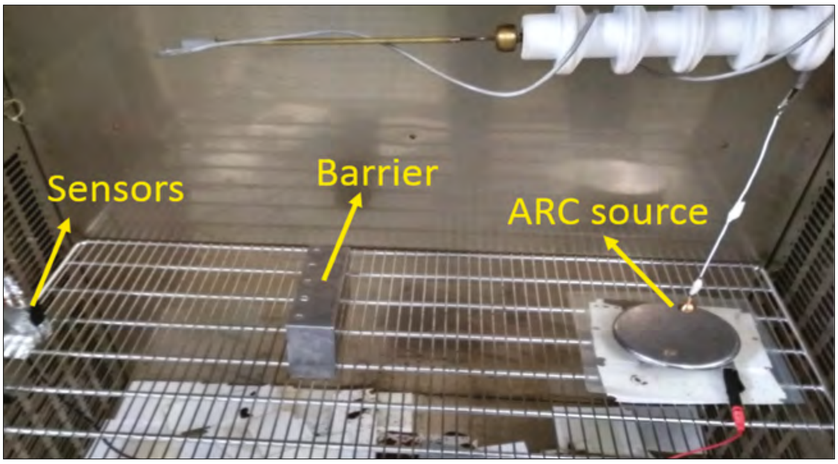

Figure 17. A typical configuration for the barrier effect

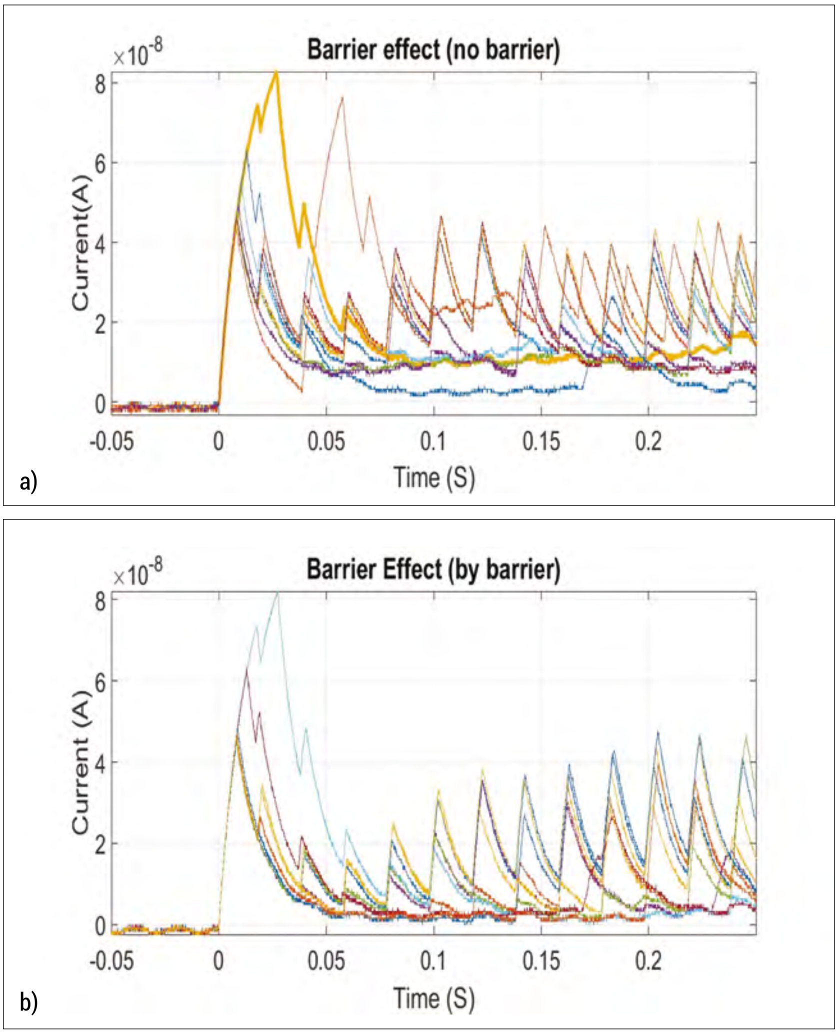

Figure 18. a) the recorder signals when the barrier was not placed. b) when the barrier was placed

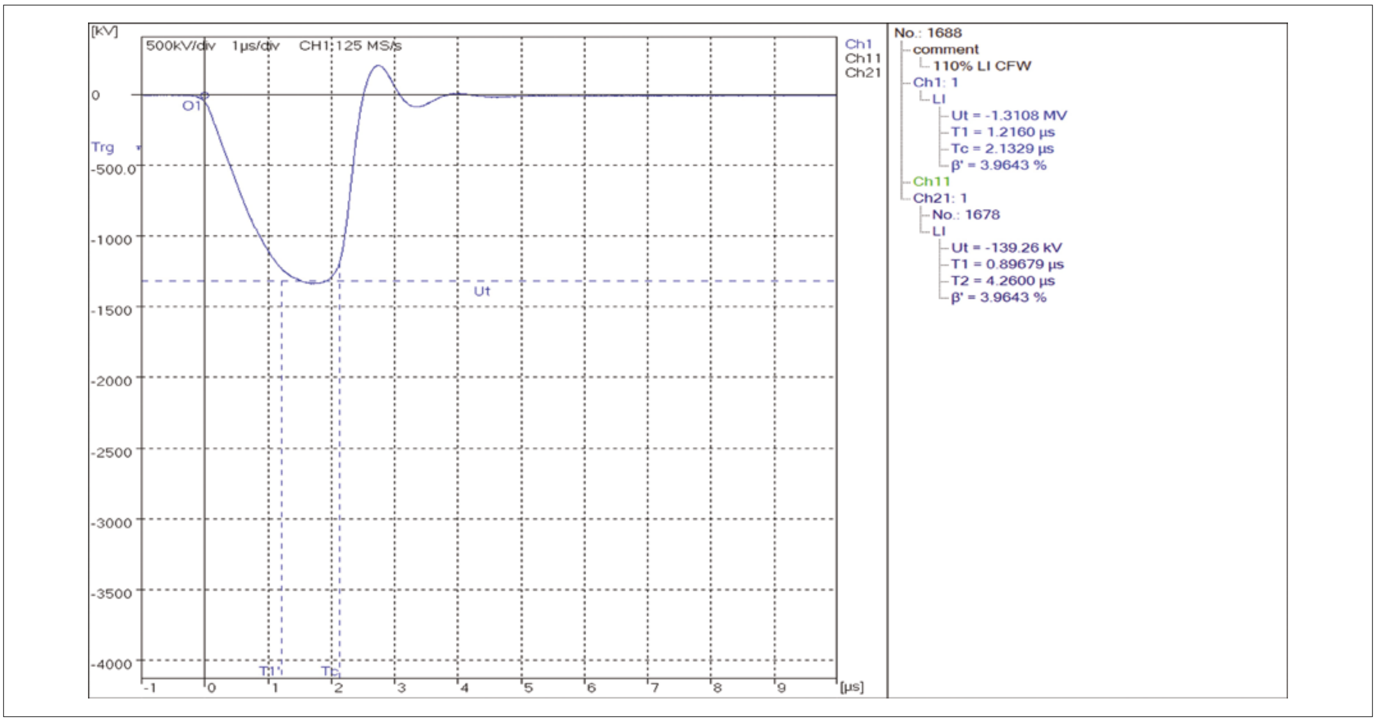

Figure 19. A typical profile for an applied high voltage impulse in EMI tests

5.1. Electromagnetic waves

Lighting impulses are the inevitable consequence of transients in power networks. Hence, EMI tests should be performed to assess the performance of sensors as well. For this aim, the sensors were placed inside the transformer tank, and lightning impulses were applied at some distance away from the sensors. In this case, due to overvoltage problems, the current was measured with a 10 MΩ shunt resistor when the sensor was biased (12 V_{DC}) in photoconductive mode. Fig. 19 depicts a typical applied 1300 kV impulse voltage for the EMI test. The corresponding recorded signals from the sensors is also depicted in Fig. 20. As the sensor has capacitive behaviour, by placing a resistor for current measurement, the current signal cannot contain high-frequency components (due to the low pass filtering behaviour of the RC circuit in this case) but, as depicted in below figures, the sharp rise time of signals illustrates high-frequency components. Hence one conclusion is that the recorded signals from the sensor are due to the induced potential rather than a generated current by the sensor. Furthermore, although the transformer tank was effectively grounded, the induced voltage could be through the bushing, which acts as an antenna for capturing the radiated EM from the lighting source. Also, as the impulse has a high amount of energy, the thickness and property of the transformer tank are also other determining factors in the effective penetration depth of radiated EM at high frequencies.

After thermal cycling tests conducted on the sensors with the highest temperature of 120°C, some of the sensors could not recover their dark current

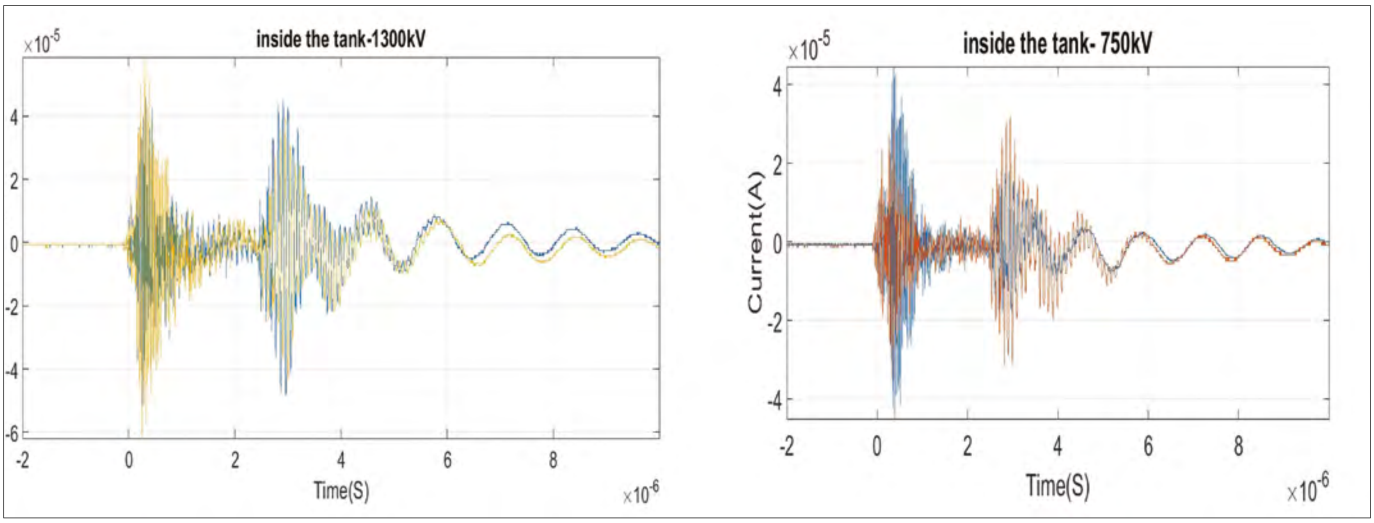

Figure 20. Performance of sensors for the defined EMI tests

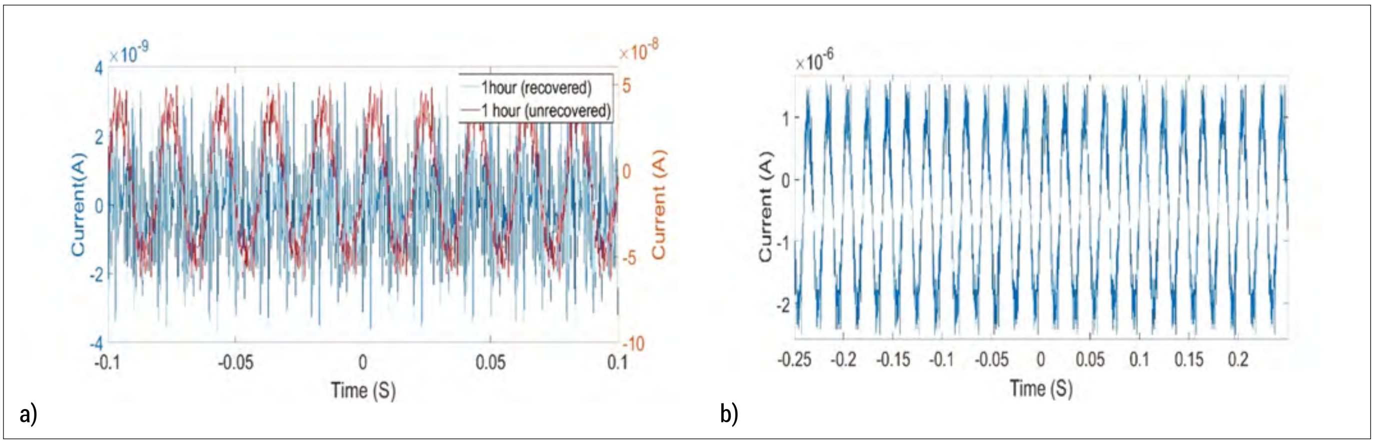

Figure 21. a) Comparison of dark current in recovered and unrecovered sensors. b) A dramatic increment of the dark current as for a typical sensor

To evaluate the behaviour of sensors after ageing in the transformer tank, the sensors were aged in mineral oil at a certain time, and then they were compared to the unused sensor

5.2. Short-term thermal cycling in the transformer tank

In terms of temperature effect, two types of thermal cycling tests were applied to the sensors in transient and stable conditions. In the first state, a transient temperature (120 °C) was applied to the sensors and tests were performed for almost one hour. In the second state, the sensors were placed for 2 hours at 120 °C, and the tests were performed for the next one hour (2 hours +1 hour). After thermal cycling tests, some of the sensors could not recover their dark current. That is, a permanent increment of dark current was observed for some sensors, which is shown in Fig. 21(a) and 21(b). It should be emphasised that the dark current shown in these figures was measured with the actual length of coaxial cables.

5.3. Medium-term ageing in oil

To evaluate the behaviour of sensors after ageing in the transformer tank, the sensors were aged in mineral oil at certain periods. Fig. 22 compares the increment of dark current after 10 and 18 days in comparison with an unused sensor. The sensitivity to the electromagnetic waves is also depicted in the corresponding figure for each sensor. Clearly, as a rule of

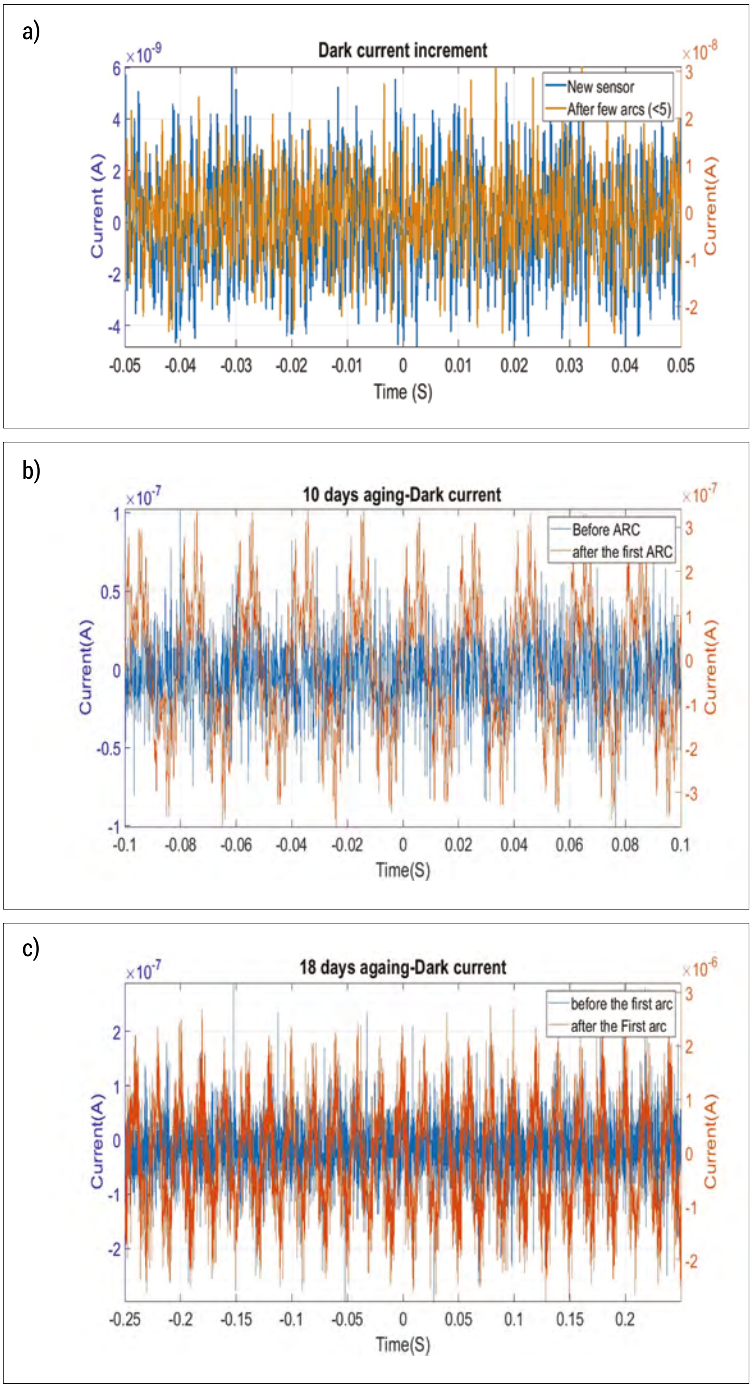

Figure 22. The effect of thermal ageing in oil on the amount of dark current: a) unused sensor b) after ten days ageing c) after 18 days ageing

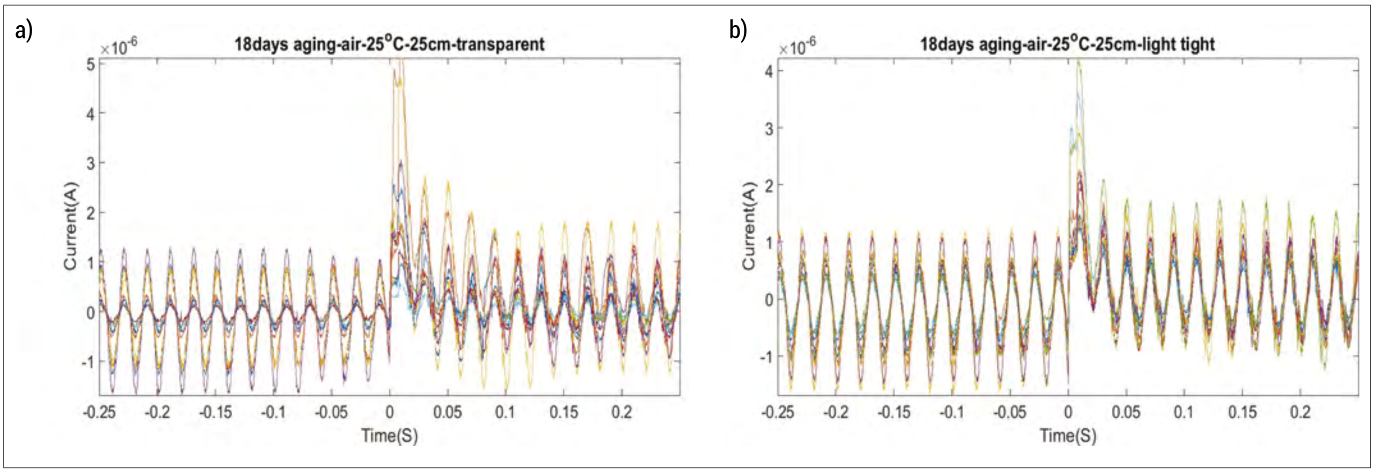

Figure 23. a) the output signals for a transparent sensor after 18 days ageing, b) corresponding signals for a light-tight sensor

Photoresistors (LDRs) were discarded completely due to their non-compatible behaviour under ageing tests as required for a reliable sensor application for transformer application

thumb - regardless of amplifier bandwidth at different gains - the dark current level for a 10 days aged sensor is almost 20 times greater than an unused sensor, and the corresponding value for 18 days aged sensor is 40 times.

Clearly, the increment of dark current can saturate the generated signal due to the light. That is, the sensitivity of sensors is drastically reduced where their responsivity even to the ordinary light sources in the visible range decreased. Fig. 23 compares the performance of two transparent and light-tight sensors when they are subjected to some electric arcs. By comparison of the mentioned figures, there is no variation that can be attributed to the light. As the tests were started by the transparent sensor, a gradual increment of the dark current is clear in the mentioned figure as well. Even after applying the first arc, there is no response, and the output signal is only correlated to the electromagnetic waves and the dark current.

The increment of dark current after each electric arc could be attributed to the formation of certain defects over the substrate of sensors. For more explanation, Fig. 24 magnifies the substrate of 10 days aged photodiode after subjecting to some electric arcs. The situation for photoresistors was even worse, i.e. before the thermal cycling, a permanent increment of the dark current was observed after applying each arc which is depicted in figure 25 as well. As shown in Fig. 26, a substrate magnification for the mentioned photoresistor can attest the reason behind such a behaviour. Thus, photoresistors (LDRs) were discarded completely due to their non-compatible behaviour under ageing tests as required for a reliable sensor application for transformer application.

6. Conclusion

In this article, the performance of light-sensitive semiconductor elements for the detection of arcs inside a transformer is investigated based on theoretical discussions as well as on fundamental experiments. The obtained results can be summarised as follows:

- In general, simple light-sensitive semiconductors are able to detect arcs under favourable circumstances in air, although they react particularly well in the visible light range, while arcs have the most concise spectrum in the non-visible range. Thus, sensors which are responsive to lower wavelengths

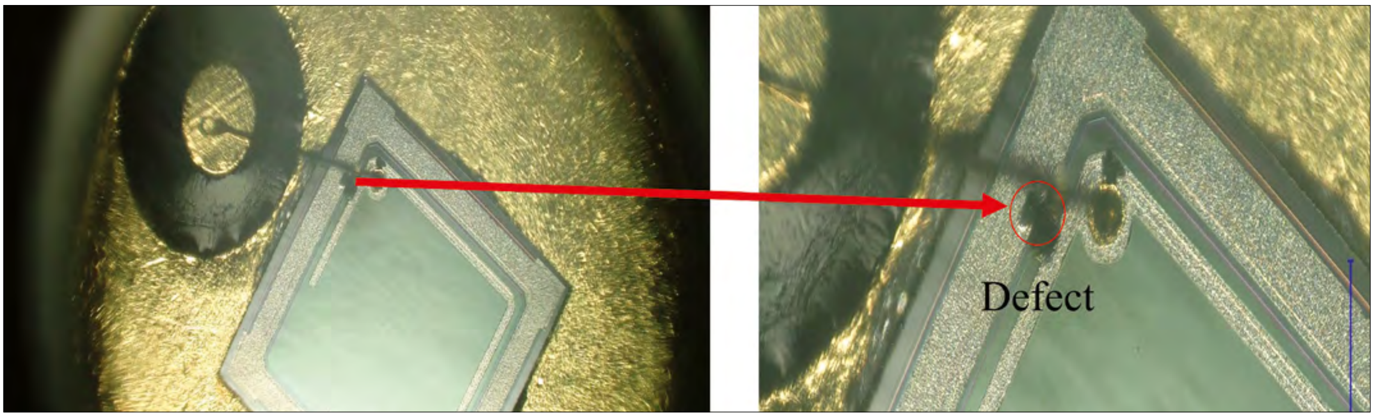

Figure 24. The substrate of a photodiode with certain defects due to proximity to the electric arc

Based on the experiments conducted so far, the value addition of photosensors is questionable in the early detection of transformer arc faults

(200–400 nm) might be more suitable for such applications, but they are also more expensive, and temperature requirement for transformer applications may limit their use for arc sensing.

- It seems that photodiodes can be more favourable than LDRs because LDRs aged extremely fast under an EM environment and seem less reliable and more error-prone. Thus during the investigations, several LDRs were permanently damaged due to the electromagnetic waves caused by an arc.
- Also, the performance of photodiodes at high temperatures, typically at 100°C, is drastically reduced, thus in a harsh environment - as it exists inside a transformer, with high temperatures and EM-fields – the performance and lifetime of the arc detection system based on LDR or Photodiode are significantly reduced, unreliable and unstable.
- Furthermore, almost all sensors react to strong EM waves not originating from an arc. Thus a distinguishing between an arc and an EM-impulse, e.g., due to a lightning strike or switching operation, seems difficult and can lead to false tripping so that the transformer is switched off without any reason or failure, which in turn makes acceptance of such an arc detection system appear doubtful.
- In addition, a longer distance between the arc source and the sensor reduces the sensitivity of sensors drastically – even in the air. This effect will be much stronger in the dark and for the aged oil. Therefore, many sensors have to be theoretically placed within the tank, which will increase the costs of such a system.
- There are still more investigations necessary in order to come to a final conclusion, but based on the actual experiments, it is clear that such a system is influenced by many parameters and will not have the same reliability and lifetime as expected for a power transformer.

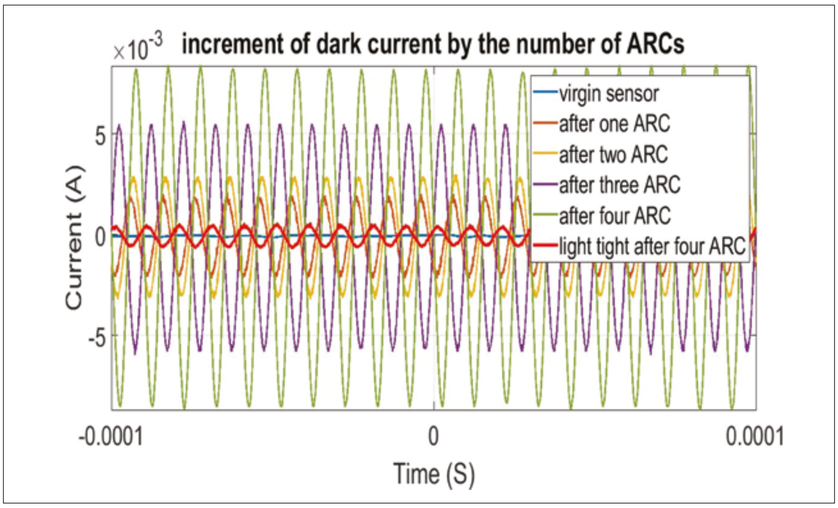

Figure 25. Increment of the dark current after each arc for the photoresistors

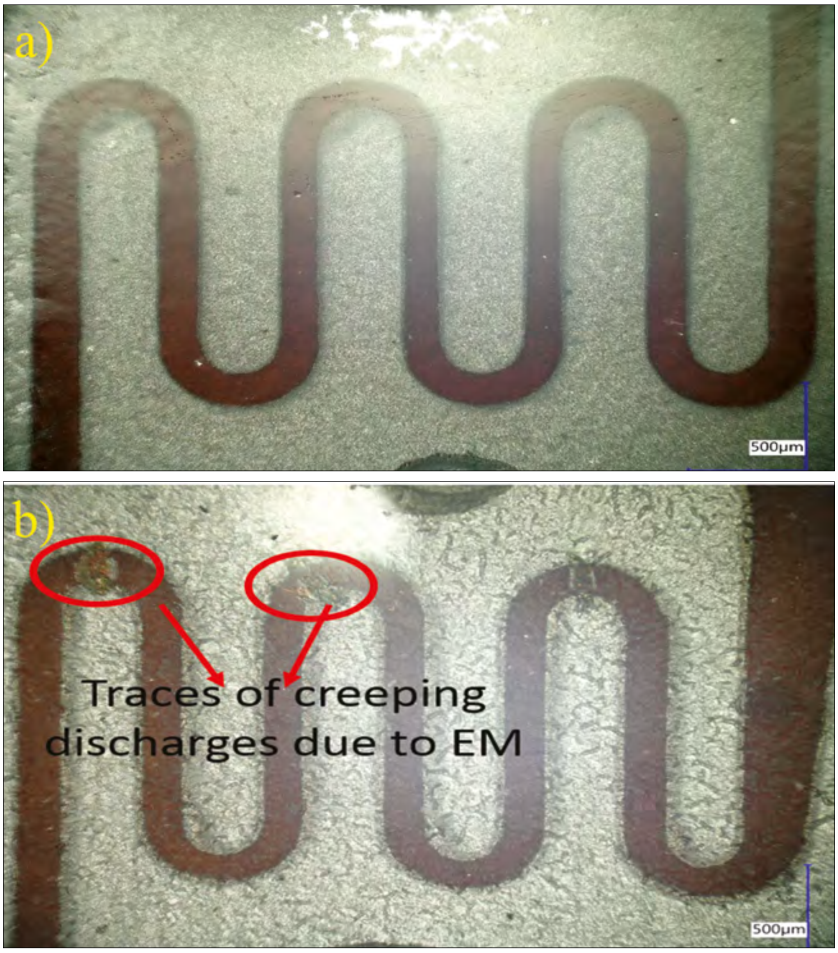

Figure 26. The magnified substrate of two photoresistors: a) an unused photo resistor b) after subjecting to some arcs

If it is furthermore considered that the time to disconnect the transformer is at best halved because the reaction time of the Buchholz relay is reduced, but that of the circuit breaker of course not, it is questionable whether the reduction of the total disconnection time can prevent a tank-rupture including the mentioned collateral damages in any case. Furthermore, such a system can, of course, not replace the Buchholz relay, especially working in conjunction with differential relay and rapid pressure rise relay and / or over current relay, because besides the fact that the Buchholz relay can detect much more failure modes, the reliability, non-error-proneness and lifespan are superior. Also, based on the experiments conducted so far, the value addition of photosensors is questionable in the early detection of transformer arc faults.

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