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CHARACTERIZATION OF PARTIAL DISCHARGES IN TRANSFORMER OIL INSULATION UNDER AC AND DC VOLTAGE USING ACOUSTIC EMISSION TECHNIQUE

Ramanujam Sarathi [*] — **Prathap D. Singh** [*] — **Michail G. Danikas** [**]

Convertor transformer is the heart of HVDC power system network. The insulation of the transformer is stressed by AC and DC voltages. At the time of installation, AC and DC voltage tests are routine test to understand the withstand capability of the insulation structure for the rated voltage. The Acoustic Emission (AE) technique can identify any incipient discharges in the insulation structure generated by different voltage profiles. In the present work, a methodical experimental study was formulated to characterize the AE signals produced due to partial discharges under AC and DC voltages, in transformer oil insulation. It is realized that the AE signals generated due to partial discharges under AC and DC voltages are different.

It is observed that an AE signal generated due to AC voltage is of long duration pulse compared to that generated under DC voltage. The amplitude, rise time, counts, duration and energy content of the AE signal produced, due to partial discharges under positive DC, are high compared to the negative DC voltages.

K e y w o r d s: transformer oil, converter transformers, acoustic emission, partial discharges, corona, FFT

1 INTRODUCTION

High voltage DC power transmission has acquired considerable prominence in recent times and the converter transformer forms a vital part in it. With an increasing rating of the size of the converter transformer, it has become essential to design and develop a compact, cost effective and reliable insulation system to it. Transformer oil forms a major insulation in transformers, which acts as an insulant and coolant. The major cause of failure of transformers is due to the incipient discharges that occur due to defects present in the insulation system.

The performance characteristics of converter transformer insulation are tested by carrying out certain routine tests in the factory, *eg*, AC voltage withstand test, DC voltage test, polarity reversal voltage test *etc* [1, 2]. The DC voltage test is severe compared to AC voltage test due to space charge formation under the test. Under certain conditions, the DC voltage test can aid the process of degradation and can indicate the presence of some defect in the insulation structure of the transformer. The voltage test which is carried out as a routine test, can identify only if the amount of insulation provided by the manufacturer is sufficient or not, for the operating voltage. The routine tests cannot indicate any defect present in the insulation structure causing incipient discharges during the test. The defect may be due to some protrusion in the winding conductor or due to floating particle (conducting/non-conducting) introduced in the transformer oil from the feedstock or during operation.

The presence of any defect in the insulation structure, under normal operating voltages can cause local field enhancement near the defect site causing incipient discharges/corona/partial discharges in the insulation structure and consequently local perturbation in the steady medium due to the release of certain amount of energy in the form of burst/impulsive pulses (acoustic energy) that radiate in all directions from the discharging source. The released energy can be detected by mounting a transducer over the surface of the structure. This process is known as Acoustic Emission. The signals detected are called acoustic signals, which are used for diagnostic study [3]. A common problem in AE signal processing is to extract physical parameters of interest. Acoustic Emission (AE) technology is recognized as an effective tool for Non-Destructive Testing (NDT) and can identify any active defect [4, 5]. However, its application in the high voltage field limited. AE technique is highly appreciated due to its immunity of acoustic detection to electromagnetic interference in the high field environment [6]. By adopting the AE technique, it is possible to identify any incipient discharge that occurs during the AC/DC voltage test and therefore remedial action could be taken before installation at site.

Considerable research work was carried out to understand the partial discharge activity in transformer oil insulation under AC voltages [7–10]. The literature on partial discharge activity study under DC voltages in transformer oil insulation is scanty. It is essential to obtain a complete database to understand the characteristics of AE signal generated due to incipient discharges formed under positive and negative DC voltages. Having known all this, in the present work, a methodical experimental study was formulated to characterize the AE signal produced due to the partial discharge activity under DC voltages in transformer oil insulation. For the purpose of comparison, the study under AC voltages is also carried out.

[*] Department of Electrical Engineering Indian Institute of Technology Madras, Chennai-600 036, India. E-mail: rsarathi@iitm.ac.in
[**] Democritus University of Thrace, Department of Electrical and Computer Engineering, GR-671 00 Xanthi, Greece

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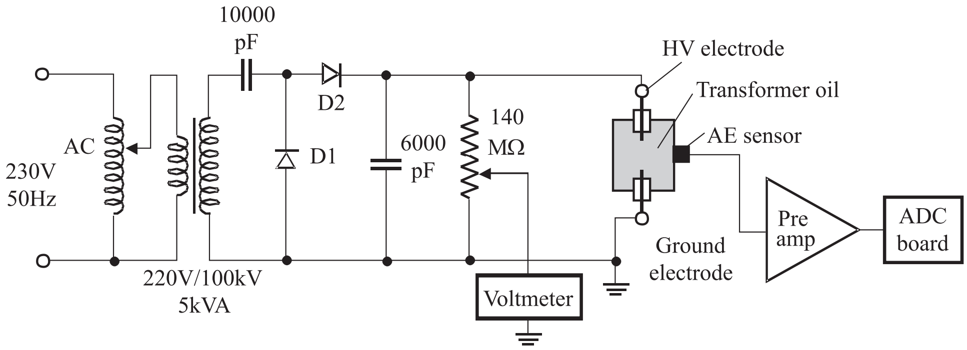

Fig. 1. Experimental setup

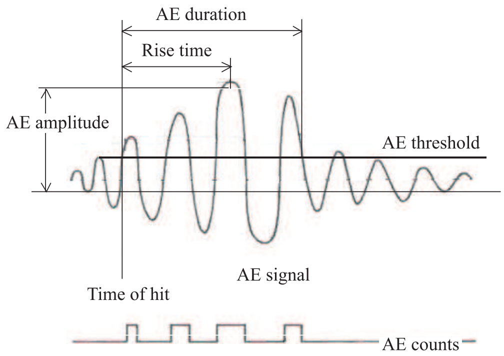

Fig. 2. Typical acoustic emission signal characteristics

2 EXPERIMENTAL ARRANGEMENT

The experimental setup used for the measurement of acoustic signal generated due to partial discharges in the transformer oil, under the AC and DC voltages is shown in Fig. 1. For the application of AC voltage, the rectifier part is disconnected and the transformer output is directly connected to the test chamber. The experimental setup for the present study could be sectioned into three parts. The first, second and third parts of the experimental setup include a high voltage source, an oil test chamber with an acoustic emission sensor mounting (Test Apparatus) and a pre-amplifier with a data acquisition system for post analysis of the acquired acoustic signals.

(i) High voltage source

The high AC voltage of power frequency is produced from a transformer rated for 5 KVA, 50 Hz, 100 kV unit. The AC voltage is measured using a capacitance voltage divider. The DC voltage is generated through a Greinacher voltage doubler circuit and measured using the resistance method. In the present work, the study is carried out by applying 15 kV peak for AC and DC voltages.

(ii) Test Apparatus

The experimental setup used in the present work is shown in Fig. 1. The mild steel, leak proof chamber is of a rectangular cross-section with dimensions of 12 cm × 12 cm × 12 cm fitted with a high voltage bushing at the top and the bottom plate, filled with transformer oil. A needle-plane configuration is used to generate partial discharges, simulating the condition of protrusion of the conductor from the high voltage electrode/non-uniform field condition. A gap spacing of 2 cm is chosen between the needle and the plane. A needle electrode with a radius of 100 μm and the plane diameter of 100 mm are used. Transformer oil, obtained from the transformer manufacturer, is used for the study without any further treatment. The AC/DC voltage is increased at a rate of 500 V/s up to the pre-determined voltage level. The acoustic emission sensor is mounted in one side of the chamber.

(iii) Acoustic emission instrumentation

The acoustic emission signal is basically a non-stationary signal and it consists of overlapping bursts with unknown amplitudes and arrival times. The main problem in acoustic emission signal analysis is the estimation of acoustic emission parameters, to understand the characteristics of incipient discharges in the transformer oil. The important components of the acoustic emission instrumentation system are the integrated pre-amplifier with sensors, reliable cables and connectors, digital signal processing card, personal computer and signal processing software module. The basic requirement of the instrumentation system should be capable of providing useful information to assess the state of operation of the test object. In addition, it should discriminate the useful signal from the noise/EMI produced.

The sensors are piezoelectric transducers, which convert the acoustic signal into corresponding electric signals. The choice of acoustic emission sensor depends on certain fundamental considerations. Electrical discharges generate acoustic activity across a very broad range of frequencies, from audible to several MHz. Two important aspects should be considered while choosing the frequency response of the detection transducer. These aspects are interference from extraneous sources and attenuation of the signal in the insulation system. In general the acoustic energy produced by a partial discharge is in the audible range. The partial discharge signals are wide band signals. When a signal propagating in the medium hits the walls, it is partly reflected and partly transmitted because of the low absorption coefficient of the material. When a signal hits the surface of the enclosure, only a fraction of energy is transmitted and the remaining energy is reflected. Also,

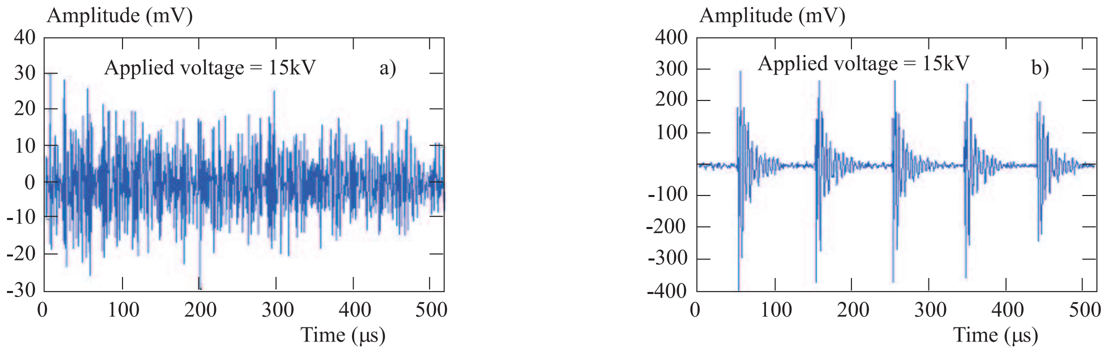

Fig. 3. Typical acoustic signal generated in transformer oil due to partial discharges: (a) burst type signal, (b) impulsive type signal.

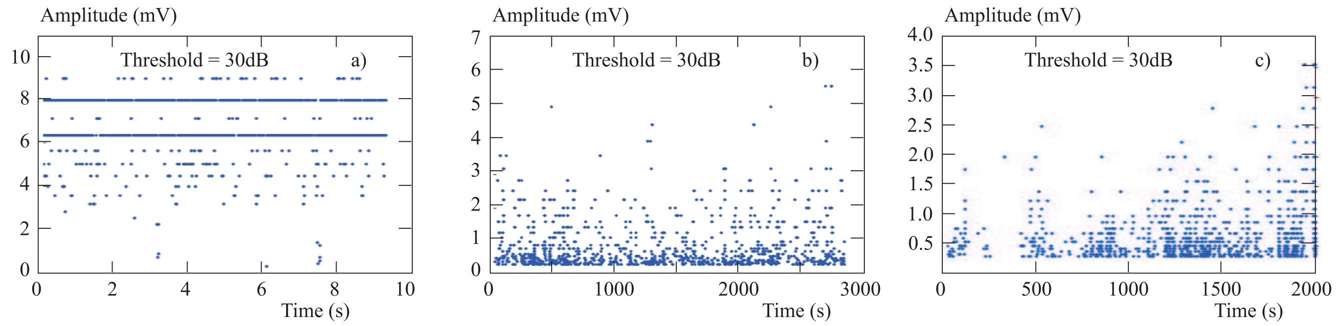

Fig. 4. Typical variation in magnitude of AE signal generated due to partial discharge in transformer oil under different voltage profiles: (a) ∼AC, (b) +DC, (c) −DC.

the partial discharge inception is identified as a voltage at which the first acoustic emission signal is captured for the defined conditions, as the partial discharge inception voltage. In the present work, a wide band sensor with frequency response in the range 100 KHz–1 MHz was used. Optimization between the bandwidth and sensitivity is an important factor. To get a maximum sensitivity, the sensor must be attached to the test specimen in such a manner that acoustic energy passes into the transducer with minimum loss at the transducer material. The required contact was achieved by applying a thin layer of gel between the sensor and the surface of the chamber. On a microscopic level the surface of the chamber will be rough and only few points will be in contact between the chamber and the sensor. The viscous gel will fill the gap and transfers the partial discharge produced acoustic energy to the surface of the sensor effectively. In the present work, silicon grease was used as the couplant. The sensor was placed at one location by fixing it using a rubber band.

The signal generated by the sensor has to be amplified to the required voltage magnitude. This is accomplished with a pre-amplifier placed close to the sensor to minimize the pickup of electromagnetic interference. The pre-amplifier has a wide dynamic range and can drive the signal over a long length of cable near the data acquisition system. Pre-amplifiers inevitably generate electronic noise, and it is the noise that sets the sensitivity of the acoustic emission system. The gain of the integrated pre-amplifier is set to 30 dB with a 1 MHz bandwidth. In the present study, PCI-2, a 2 channel acoustic emission System of Physical Acoustic Corporation was used.

Necessary precautions are made to eliminate mains-related disturbances. All units requiring their own supply were fed with voltage via an isolation transformer. Protection grounding and insulation screens were used to reduce the effect of electromagnetic coupling between the elements of the measuring system and high voltage units. The flow of equalizing currents was eliminated by connecting the grounding wires to a common point.

3 DEFINITIONS OF ACOUSTIC EMISSION SIGNAL PARAMETERS

The acoustic emission signal measured in the present study is an elastic wave generated by the rapid release of energy from the partial discharge site [11]. The PCI-2 AE system operates on the hit principle. Figure 2 shows the typical acoustic emission hit features diagram. The hit can be expressed as detection and measurement of an acoustic emission signal on a channel. This principle involves the measurement of important parameters of the signal that crosses the threshold. The acoustic emission signal was sampled at the rate of 1 Mega samples per second. Based on preliminary studies, in the present work capturing the signal for $1024\,\mu s$ was identified as the optimized length of the signal. The number of samples acquired is 1024 discrete points sampled at $1\,\mu s$. The amplitude, energy, counts and the partial power measurement of the signals were measured to identify incipient

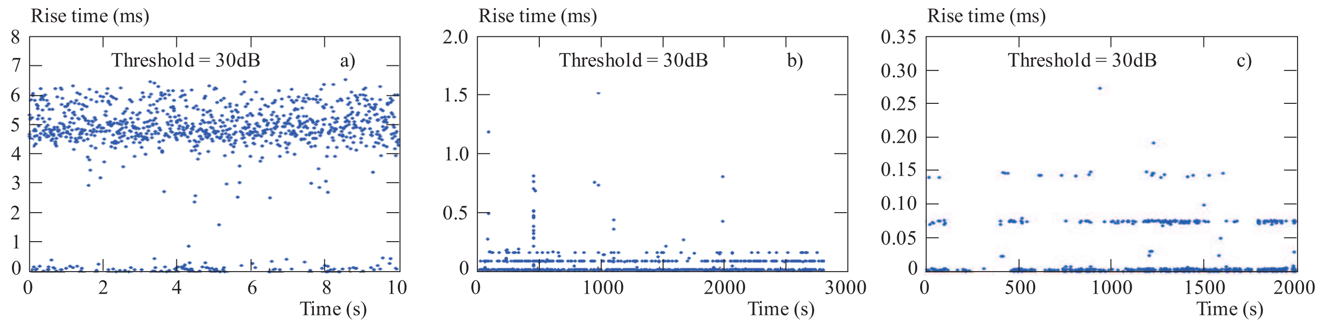

Fig. 5. Rise time of AE signal generated due to partial discharge in transformer oil under different voltages: (a) AC, (b) +DC, (c) −DC.

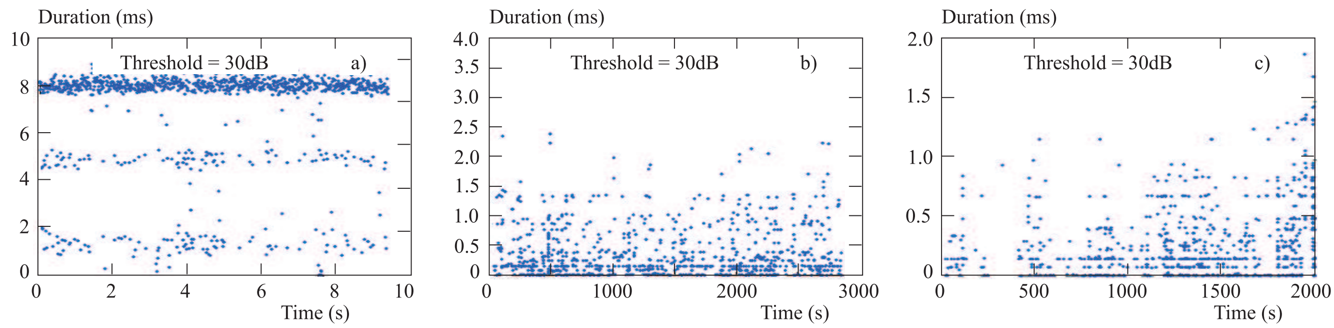

Fig. 6. Duration of AE signal generated due to partial discharge in transformer oil under different voltages: (a) AC, (b) +DC, (c) −DC.

discharges produced due to partial discharges in transformer oil using the AE win software [12].

The amplitude is the highest peak voltage reached by the AE waveform. This is an important parameter because it senses and identifies the AE events. The amplitude of the acoustic emissions is customarily expressed on a decibel scale, in which 1 μV at transducer is defined as 0 dB acoustic emission, 10 μV is 20 dB acoustic emission and so on. The amplitude of the AE signal depends on the magnitude of partial discharges occurred at the discharge site in the oil medium.

The rise time of the pulse is defined as the time for the acoustic signal to reach maximum peak amplitude from the time instant it crosses the threshold, at every hit. Duration of the pulse is defined as the time from the point of crossing the threshold level till it crosses back lower than the threshold setting. The energy of the signal is the measured area under the rectified signal envelope over the time. Energy measurement is preferred because it depends on the amplitude and the duration of the acoustic emission signal and it is independent of threshold setting and operating frequency. The energy content of the signal is time varying and depends on the intensity of the partial discharge formed. Counts are defined as the number of times the AE signal crosses the threshold in one inspection cycle. A 16 bit counter was used in the system. It is capable of counting events in a single inspection cycle.

The partial power is calculated by summing the power spectrum in a user specified range of frequencies, dividing it by the total power and multiplied by 100. The power spectrum is calculated up to 1 MHz and then it is split equally to calculate the partial powers (p1, p2, p3 and p4) at four zones.

4 CONCEPT OF MOVING AVERAGE TECHNIQUE

The method of moving averages is widely used to understand the characteristic variation with time. The partial power level is time varying. By creating an average magnitude of the partial power at each level that moves with the addition of new data, the characteristic variation is smoothened out so that the fluctuations with time are reduced and what remains is the stronger indication of the trend in the variation of partial powers over the period being analyzed. The basic understanding of a moving average is that it is the average magnitude of partial power at a specific point of time. There are different moving average techniques present. They are simple moving average, exponential moving average, time series moving average, triangular moving average, variable moving average, volume adjusted moving average, *etc* [13]. In the present work, the simple moving average technique was adopted. A window consisting of k points was chosen to find the moving average using the formula

$$X_i = \frac{\sum_{N-i}^{N-i+k}}{k} \tag{1}$$

where X_i are the newly calculated moving average points corresponding to Y_N raw data points. In the present work, a 240 point window frame is used.

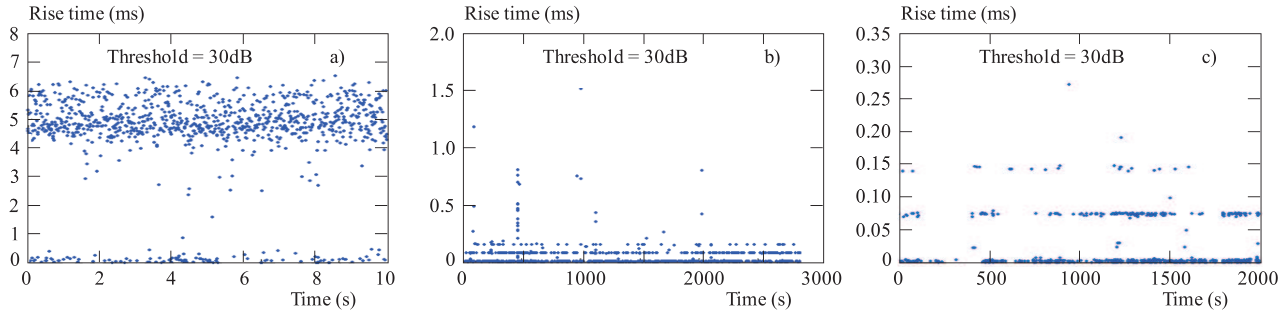

Fig. 7. Counts of AE signal generated due to partial discharge in transformer oil under different voltages: (a) AC, (b) +DC, (c) −DC.

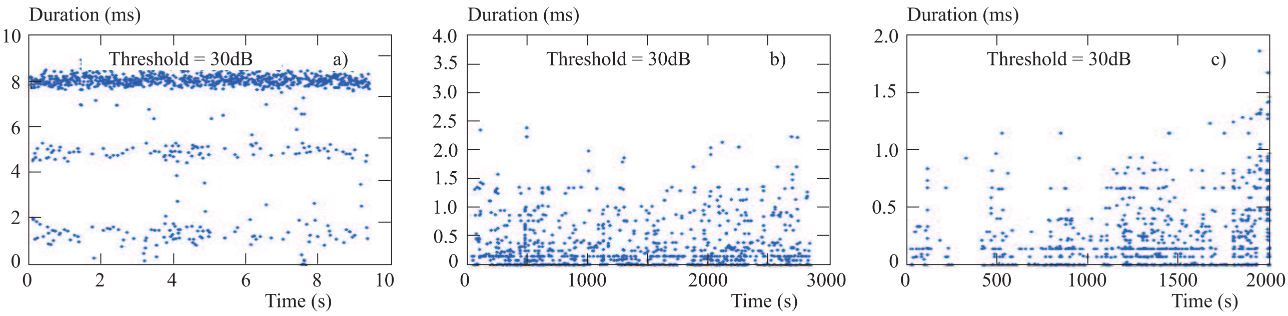

Fig. 8. Energy content of AE signal generated due to partial discharge in transformer oil under different voltage profiles: (a) AC, (b) +DC, (c) −DC.

5 RESULTS AND DISCUSSION

Partial discharges are those discharges which will not bridge the gap between the high voltage point and the ground. The acoustic emission signal generated by the partial discharges in the medium may vary widely from a continuous signal from a corona stabilized zone to a pulsed shaped signal. For example, moving particles produce burst pulses. The shape of the AE signal measured depends on the type of the source, the propagation path of the signal and the type of sensor. The local defect present in the oil medium can cause divergent electric field in the medium causing corona/incipient discharges/partial discharges to occur [14]. Any discharges from the defect site, however, first cause perturbation in the steady state fluid medium allowing a pressure wave to form and then excites the enclosure and finally is picked up by the acoustic emission sensor [15]. Usually a partial discharge in the insulation medium produces a spherical pressure wave which diffuses rapidly and the sound pressure level reduces inversely in proportion to distance [6]. Figure 3 shows the typical acoustic emission signal measured due to partial discharges. A burst type signal and impulsive type signal can occur due to discharges in liquid insulation under AC and DC voltages.

Figure 4 shows a typical variation in the amplitude of the acoustic emission signal generated by the partial discharges in liquid insulation formed with the needle-plane configuration under AC and DC voltages. It is observed that, irrespective of the voltage profile, the intensity of the acoustic signal due to the partial discharge action is time varying, indicating that the magnitude of discharges is not the same at all instants of time confirming that the partial discharge activity in the insulation medium is a highly intermittent process. It is realized that the amplitude of AE signal is high with the AC voltage compared to the DC voltages. Abdel Salam and Taschner [16] have shown that in gas insulation, under an AC voltage, the corona pulse appears first in the negative half cycle, and when the applied voltage magnitude is increased, corona pulses appear over the positive half cycle, and at even higher voltages the corona pulses appear on both sides of the peak of the AC voltage. Hence, the spread in amplitude of the acoustic signal produced under the AC voltage is constant with time.

Figures 5 and 6 show the characteristic variation in the rise time and the duration of the acoustic signal generated due to each hit, due to partial discharge activity under AC and DC voltages. It is realized that the rise time and the duration of the acoustic emission signal generated under AC voltage is high compared to that of the DC voltage. Comparing the rise time and duration of the positive and negative DC voltage generated AE signal, it is observed that positive DC has a high rise time and duration of the signal compared to negative DC voltage. Under DC voltages, when the high voltage electrode is positive, electrons quickly move towards the high field region leaving positive ions and after a short period the positive ions start diffusing into the medium. The rapid movement of electrons and the motion of positive ions gives a steep fronted pulse, while a further drift of positive charges will form the tail of the pulse long. When the high voltage electrode is negative, electrons move into the medium and the positive charges move rapidly to the high field zone causing a much sharper pulse (Trichel pulse) than when the applied voltage is positive [13]. Thus the

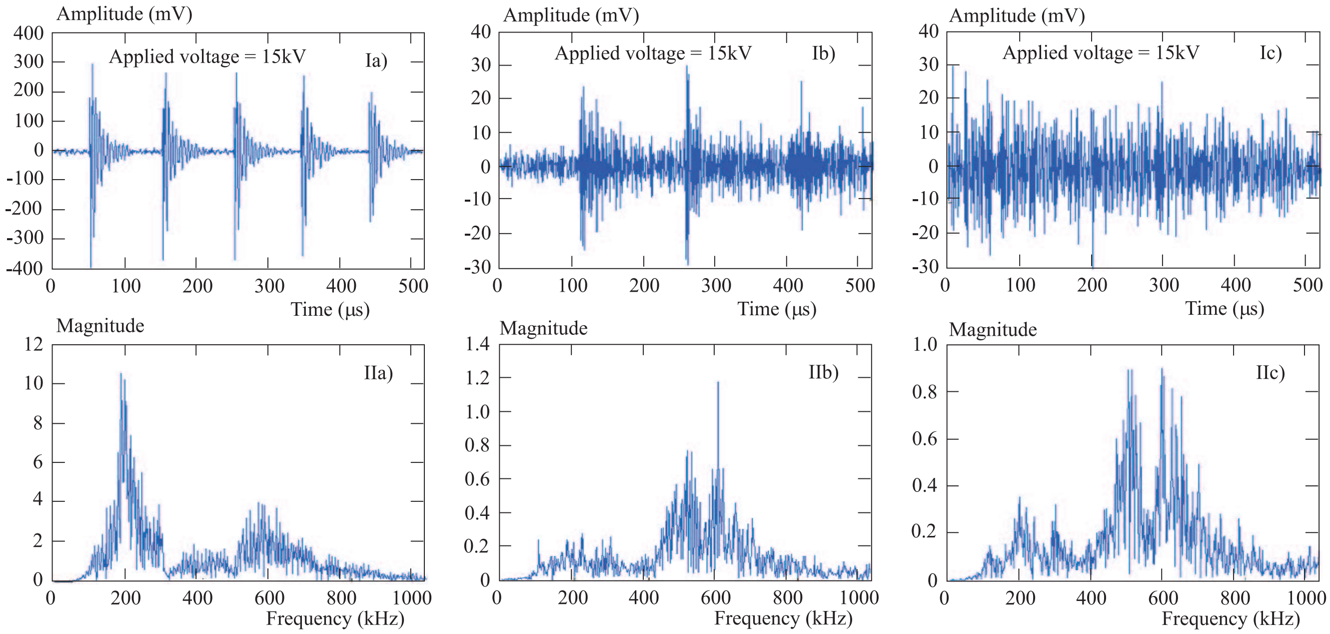

Fig. 9. Typical AE signal generated due to partial discharges in transformer oil under different voltages and its corresponding FFT plot: (I) time domain, (II) frequency domain, (a) AC, (b) +DC, (c) −DC.

negative discharge pulses are lower in magnitude, having much shorter rise and tail times with a high repetition rate. Considering the physical phenomenon that occurs during the discharge process, it is easy to realize the cause for the AE signal with high rise time and duration, generated under positive DC compared to that under negative DC voltage.

Figures 7 and 8 show the characteristic change in counts and the energy content of the acoustic emission signal generated due to partial discharge activity under AC and DC voltages. It is observed that the counts/ energy content of the AE signal measured due to the partial discharge formation under the AC voltage is high compared to DC voltages. Also it is noticed that the counts and energy content of the AE signal measured due to partial discharges under positive DC are high compared to negative DC voltage, indicating the severity of the discharges under positive DC voltage. As the voltage is increased, positive corona begins as low level electron avalanche of low repetition rate and then develops into avalanches accompanied by relatively large streamer pulses that are usually precursors of pulse bursts. For negative corona, an electron originates from the well defined zone, especially the point electrode, and once the field is high enough, corona will develop rapidly. It is well known that once the magnitude of positive DC is increased, the initial streamer formation is enhanced causing positive ions and free electrons in the medium (free electrons move towards the point electrode leaving positive ion in the medium) and positive ions cause field intensification in the medium leading to increase in magnitude of discharges in the form of burst pulses.

Figure 9 shows a typical acoustic emission signal and its corresponding FFT plot of the acquired signal measured under AC and DC voltages It is observed that dominant frequency of AE signal generated under AC voltage (∼ 200 kHz) is less compared to the DC voltages (∼ 400 to 600 kHz). Kweon and co-workers [9] have observed that the dominant frequency of AE signal generated due to corona in transformers lies in the range 100–150 kHz. Characteristic variation of the dominant frequency with respect to time, under AC and DC voltage, is realized using the partial power analysis. Figure 10 shows the typical time averaged partial powers variations measured from the power spectra of the acoustic signal, generated due to the partial discharges under AC and DC voltage. Under AC voltage the partial power-1 is the maximum indicating that the dominant frequency and the energy content of the signal is maximum in the range 0–250 kHz. Similar characteristics were observed by Boczar [5]. Figures 10b and c show that the partial power 2 and 3 is high for the AE signal generated under DC voltages indicating that the maximum energy content of the signal lies in the frequency range 250–750 kHz. This allows one to conclude that the discharge characteristics are different under AC and DC voltages.

6 CONCLUSIONS

The important conclusions obtained, based on the present study, are the following:

1. It is observed that the partial discharge activity in transformer oil under AC and DC voltage is time varying.
2. Comparing the characteristics of AE signal produced due to partial discharge formation under AC and DC voltages, it is realized that the severity of discharges is higher under AC voltage compared to severity under DC voltage.

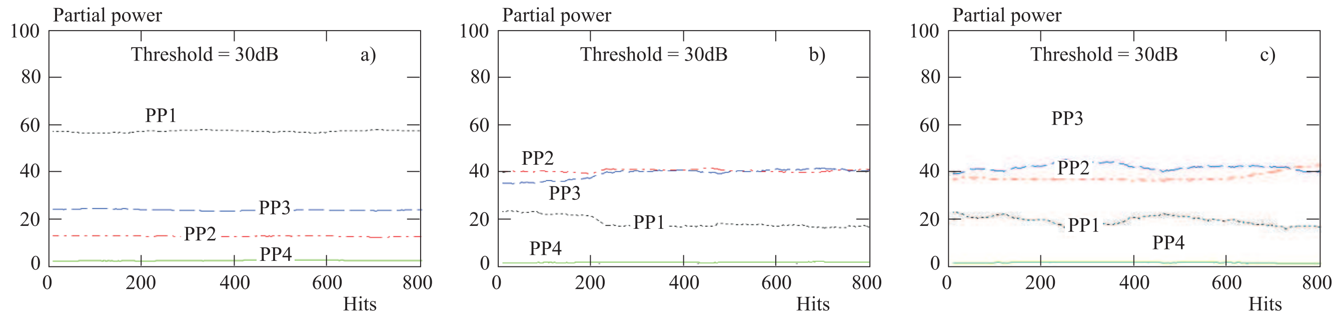

Fig. 10. Typical partial power analysis of the acoustic emission signal generated due to partial discharge formation in transformer oil under different voltages: (a) AC, (b) +DC, (c) −DC.

3. The characteristics of AE signal produced due to partial discharge formation by positive and negative DC voltage are different. It is noticed that the rise time, duration, energy content and the counts of the AE signal generated due to partial discharges under positive DC voltage are higher compared to those of negative DC voltage. It could be realized that severity of discharges is higher under positive DC voltage compared to negative DC voltage.
4. The time averaged partial power analysis of the AE signal analysis clearly indicates that the energy content of the AE signal is high in the frequency range of 250–750 kHz under DC voltages. The energy content is maximum for AC voltage generated AE signal in the range 0–250 kHz.

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Ramanujam Sarathi is currently an Associate Professor and Head in charge of High voltage Laboratory, in the Department of Electrical Engineering, Indian Institute of Technology, Madras. He obtained his PhD from the Indian Institute of Science, Bangalore in 1994. post-doctoral work at the Akita University. His major area of specialisations is outdoor insulation, treeing studies, and Condition Monitoring of Power apparatus. He is member of IEEE.

Prathap D. Singh, born in 1977, India received his BE (electrical and electronics) from Osmania university and M Tech (power systems) from IIT Madras, in 2002 and 2006 respectively. He worked as Engineer with Northern power distribution company of Andhra Pradesh, India. At present he is working as Scientist with Nuclear Power Corporation India Limited. His Research areas include condition monitoring of power apparatus.

Michail G. Danikas, born in 1957, Kavala, Greece, received his BSc and MSc degrees from the University of Newcastle-upon-Tyne (England), in electrical and electronic engineering, and his PhD Degree from Queen Mary College, University of London England, in 1980, 1982 and 1985 respectively. From 1993 he has been with Democritus University of Thrace, Department of Electrical and Computer Engineering, since 1998 as Associate Professor. His current research interests are breakdown in transformer oil, simulation of electrical tree propagation in polymers, study of partial discharge mechanisms in enclosed cavities, magnitude and surface phenomena in indoor and outdoor high voltage insulators.