S.3.2 Experimental study of the Corona Effect behavior as a function of the electric field

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Experimental study of the Corona Effect behavior as a function of the electric field T. Nowicki, S. Fauveaux, F. Thirion R&D Department INDELEC Douai, France tnowicki@indelec.com, sfauveaux@indelec.com Abstract - Many studies performed until now about Corona effect are showing that its development depends on numerous parameters. This preliminary experimental study, done according to a basis of experimental tests under static field inside a very high voltage laboratory, aims to put into evidence the parameters that influence this development. Keywords—Corona Discharge; space charge; photoionization; lightning protection; air terminal; lightning rod I. Introduction It is known that when two electrodes under a sufficiently intense electric field (normal atmospheric conditions), an ionization process takes place creating a continuous current or an electronic avalanche creating plasma above a certain threshold. This phenomenon is called "Corona effect". Its presence is generally characterized by the emission of ultra-violet and acoustic radiation. In general, we consider the Corona effect constituted between a little radius electrode, at the vicinity where the electric is strongly concentrated (point effect), and a very large radius electrode, i.e. a plane. The polarity of the little radius electrode rules the type of Corona effect: positive or negative. Physical phenomenon responsible for these effects mainly take place at the vicinity of the little radius electrode. Amongst other, the mass difference between electrons and ions, physical mechanisms being at stake are not exactly identical according to the polarity of the applied electric field. Generation of Corona effect needs energy, that is subtracted from the electric field source, so that the Corona effect lead to non negligible loss in high voltage transport lines. Moreover, the apparition of the Corona effect in the atmosphere is often associated with ozone generation [1]. Despite this negative aspect, the Corona effect has beneficial effects and numerous applications, particularly the suppression of electric charges formed on aircraft surfaces, water purification, particle precipitation in air conditioning systems, applications in photocopiers, etc... Here, we are particularly interested in the Corona effect as a discharge precursor. Form a microscopic point of view, being positive or negative, the Corona effect has common mechanisms in both types of phenomenon. If a large electric field is applied to a little radius electrode, a random event may trigger the ionization of surrounding gas molecules [2-3]. This event may be, for example, caused by the interaction with a photon. Both opposite polarity particles created by this event get accelerated by the electric field, particularly the electron that gains a large kinetic energy. This highly accelerated electron collides into other molecules and leads to other ionizations, creating new energized electrons. We have been witnessing an electronic avalanche phenomenon creating plasma around the electrode. During this avalanche, some electrons can recombine, therefore creating new photons in the ultra-violet range. That is the radiation that is associated with plasma which gives this particular visual effect distinctive of the Corona effect. Created ions, moving in the direction of the field, will produce a space charge layer, that decreases the electric field at the vicinity of the electrode, and will slow down and even stop the ionization process [4]. Because of interactions with other molecules, dissipation of the entire space charge layer, or partially, takes place so the electric field increases again at the electrode vicinity, thus a new cycle restarts. We are talking about the pulsed regime. There are several means in order detect the Corona effect presence: The direct electric detection (shunt or ammeter) or indirect (Rogowski coil) that consists on measuring the amount of current that is flowing through the electrode. The optical detection (Photodiode, photomultiplier, etc...) that consists on measuring the light radiation (UV) emitted during the Corona effect generation. The acoustic detection that consists on measuring the acoustic radiation (Ultrasound) emitted by the phenomenon. The Corona effect is a rather vast topic, and it was subjected to numerous studies et different thematic, especially: The study of the different regimes according to the electrodes polarity [2-3]. The influence of the electrode shape [5-8]. The influence of the wind speed [9-12]. The spectrometric analysis [13-18]. Etc... The electric field, being the major factor in the proceedings of the process, it is nonetheless defined by several parameters: The value of the field and its polarity, The distance between the electrodes, The shape and the size of the electrodes. This study will aim to better understand the general phenomenon to analyze at the end the effect of theses parameters upon the Corona effect in static field. II. Preliminary tests A. Experimental setup These experiments were performed in the Very High Voltage Laboratory of Calonne-Ricouart. The setup we used for the first test series is sketched at figure 1. This setup is composed of a circular metallic electrode (plateau) connected to DC voltage generator delivering a 70kV maximum voltage for both polarity. A one meter electrode (height h=1m) is located one meter away (H=1m) beneath the plateau and connected to earth. Several sensors are placed, alternatively or at the same time, under the point under test. The measurement systems were intercompared and characterized because most of them were specially adapted or designed by us. Fig. 1. Experimental setup Data were measured by a digital oscilloscope LeCroy LT224 200MHz or by a Digital Storage Oscilloscope TiePie HandyScope HS4 50Mhz. 1) Rogowski coil This is a contact less measurement system that catches the magnetic field radiated by the conductor in which the Corona effect current is flowing through. The sensor is the Pearson Electronics Inc. Current Monitor 2100 model. Its sensitivity is 1V/A and its rise time is 50ns (bandwidth = 20MHz @-3dB). This sensor is electrically isolated and is connected owing to a high quality BNC coaxial cable (RG213/U) in order to guaranty...
the entirety of Corona pulses in spite of the rather large length of the cable, as well as a good shielding. Although the sensor output impedance is 50 , the latter was directly connected to the 1M input of the oscilloscope. Measurement signals are very clean and free from artifacts or interferences. The detection threshold is inferior to 2 mA, the measurement equivalent noise is about 1 mA at the oscilloscope end. This measurement system never gets saturated except in case of breakdown. This sensor only works with dynamic signals so no DC signals can be measured (low cutoff frequency = 125 Hz). 2) Current/Frequency Converter (CFC) This is a system that connects in series between the earth plane and the rod of the point under test. This system integrates every bit of current flowing through it during a given period of time, DC current or current impulses. This system, locally supplied by a battery, sends data in the optical form of luminous impulses whose frequency is a function the current amount integrated by the CFC. The optic impulses, bearing fixed amplitude and width, are injected into a communication optic fiber in order to transport it towards a remote a counting housing with embedded memory (figure 2). The optical link insures a perfect galvanic isolation, very critical in a much polluted environment that is a HV test laboratory. The embedded memory is then interfaced owing to a RS232 port to computer in order to retrieve and process these data. The detection bandwidth was estimated to be superior to 50MHz. The transfer function of the sensor, shown at figure 3, is very regular, monotone and almost linear. The detection threshold is about 0.5µA. This sensor is extremely sensitive and allows us to perform measurements in all the range of the plateau voltage. However, we forbid ourselves to do some breakdowns in order not to damage the sensor that is connected in series to the rod electrode. Fig. 2. Current-Frequency Converter set-up Fig. 3. Characterization of the CFC sensor 3) Optical detection This is a electrically isolated system isolated allowing to catch the luminous radiation at the top of the point. Every item constituting this system is compatible with the emission spectra of the Corona effect. Several silica optic fibers, bearing a numerical aperture equal to 0.39, are placed towards the top of the point owing to a mechanical stand (non metallic) allowing a 360° capture (figure 4). These fibers are connected to a photomultiplier (Hamamatsu H10721-210). Signals are processed by an oscilloscope (Lecroy LT224) 200MHz. Some preliminary measurements were done in order to determine a correlation, between the current and the luminous radiation emitted by the Corona effect, by intercomparison with the Rogowski coil. We noticed that the detection threshold are rather identical (Figure 5) and their behavior identical, that's to say their inability to measure a continuous phenomenon. We can conclude that both measurement systems are consistent. The optical detection threshold is similar to the Rogowski coil one, i.e. inferior to 2 mA. This measurement system never gets saturated except in case of breakdown. Fig. 4. Picture of the optic fiber stand Fig. 5. Intercomparison between the Rogowski coil and the optical system (measurement performed in dynamic owing to a Marx Generator impulse) 4) Micro-ammeter In order to allow us to directly measure the DC current and to clearly identify it (on the contrary of the CFC), we developed a very low noise micro-ammeter which sensitivity is very high (1V/µA). This system is connected in series entre between the rod electrode and the ground plane of the laboratory; it sends an output voltage that is the true image of the current flowing through the point via a shielded coaxial cable (RG213/U) connected to the oscilloscope LeCroy LT224. The detection threshold is superior to 60nA, which is the equivalent noise at the LeCroy screen end. This micro-ammeter has been realized around a, operational amplifier LF356 set in a transimpedance mode which offset is equivalent to 3.5nA. The bandwidth is rather low (5MHz) and its slew rate is 12V/µs, equal to 12µA/µs in our setup, which is sufficient to detect the Corona current pulses too. Owing to this sensor, we are thus able to detect, quantify the DC current flowing through the point but also correlate the presence of very low pulses (undetectable by the optical system and the Rogowski coil). However, large amplitude pulses (those detected by the other systems) saturate the micro-ammeter because of its very high sensitivity on the contrary of the CFC. B. Results and discussion For the first comparative measurements, the electric field is increased step by step in negative voltage between the plateau (circular energized electrode) and the ground plane (and thus the electrode under test), Fig. 6. Measurements of the Corona effect in DC field. The blue plot represents the current measurement and the purple plot is the optical one The graph above (figure 6) allows confronting the current measurement done by the Rogowski coil (upper red plot) with the measurement of the luminous phenomenon done by the photomultiplier (lower green plot). We observe, like in figure 5, that the Corona current pulses are perfectly correlated to those luminous pulses. In a second step, we perform a comparative measurement owing to the CFC with and without fibers and its stand that are mandatory positioned at the close vicinity of the point tip, in order to determine their influence upon the Corona effect. A field of 25 kV/m is applied in both cases and we observe a large decrease of the amount of the Corona effect in presence of the stand. Following these results, we decide not to use this optical measurement system anymore. As the Rogowski coil system is giving equal measurement data (sensitivity, bandwidth; noise floor) and is not disturbing, we prefer to use it instead of the optical one. Fig. 7. DC current measurement flowing through the point (lower green plot in AC mode, upper purple plot in DC mode) Owing to an oscilloscope, the micro-ammeter DC current measurement is done, taking the AC mode signal as a reference point subtracted to the DC mode signal. We observe on this graph (figure 7) the periodical apparition of a current arch at a frequency of 50Hz. The occurrence of current arches is linked to half-wave rectifying diodes integrated to the DC electric field generator. Also, this micro-ammeter allows verifying the functioning of the system developed to quantify the Corona current induced in the electrode, especially the DC one. Fig. 8. Comparison of the induced current and the amount of Corona effect as a function of the voltage applied to the plateau, on a sharp point We are able to spot (figure 8) that both systems are very well correlated : we get the same detection onset and they follow the same linear slope. We observe, a priori, that the DC current is hugely majority and thus that the integration of current pulses is negligible against the DC current integration. III. Static electric field tests A. Experimental setup These static field tests are aiming to observe the influence of the shape of the rod electrodes in negative polarity as a function of the applied electric field and as a function of the hanged circular electrode (plateau) position relative to the rod electrodes. The equipment used in this test series is identical to the previous setup except the different tested rod electrodes. The shapes of these electrodes are the following (figure 9): Fig. 9. Types of electrode used. Sharp point (a), Intermediate point (b), Rounded point (c). B. Results and discussion 1)
Sharp point The graph in figure 10 shows the evolution of the detection onset as a function of the electrode/plateau distance (H) for a fixed electrode height (h=1 m), the first electrode to be tested is represented at the figure 6.a. The blue plot determines the onset detection of the CFC sensor: we call it as CIDT (Current Integrator Detection Threshold). The red plot represents the onset of the dynamic detection of the Rogowski coil: we call it as 1st RPDT (First Rogowski Probe Detection Threshold) (or optical). The green plot represents the end of the dynamic detection: ERPDT (End of Rogowski Probe Detection Threshold). The purple plot points out the apparition onset of the « intense pulse » regime of the Corona effect that we called as 2nd RPDT (Second Rogowski Probe Detection Threshold). The light blue plot shows the breakdown voltage threshold between both electrodes: BVT (Breakdown Voltage Threshold). The red straight line represents the maximum reachable voltage level delivered by the DC voltage generator MV (Maximum Voltage).

Fig. 10. Detection thresholds for a plateau height variation (electrode Fig.9.a) at a fixed point height of 1m. Speaking of the first observed pulse regime (1), we are able to see that this zone enlarges itself as a function of the increase of the electric field. Moreover, it is composed of relatively low amplitude Corona effect pulses bearing a low apparition frequency. This frequency depends on the applied voltage and is equal to about ten milliseconds (figure 11). The pulse amplitude is equal to about 2 to 2.4 mA. Fig. 11. Digital capture of the Corona effect during the 1st regime (1) of « low pulses » (Rogowski coil). Also, we are able to see a zone (2) where the dynamic detection, as it happens the total disappearance of the luminous effect that reappears at a larger value of electric field. Nevertheless, our measurement systems record a growing Corona effect activity that is essentially composed of DC current and a regime of « micro pulses » bearing very low amplitude and variable appearance frequency spreading from 1 ms to several tens of milliseconds (figure 12). Fig. 12. Digital capture during the 2nd regime of Corona effect composed of DC current and a «micro pulses» regime (2). A third regime of « intense pulses » (3) (figure 13) appears at higher voltage threshold (purple plot). This regime is composed of higher amplitude pulses and a higher appearance frequency than the other regimes (about 5 kHz). Fig. 13. Digital capture of the Corona effect during the 3rd regime of « intense pulses » (3) (200µs of mean period) The following graph (figure 11) show the evolution of the detection threshold as a function of the distance electrode/plateau (H) for a fixed plateau height (h=2.5m). The point height is varying. We are able to see that detection steps are rather identical to the previous configuration. However, this kind of experiment seems to be reproducible with a lower incertitude. Indeed, moving the plateau at every measurement leads to a higher air volume variation beneath the latter. This may modify noticeably the experimental conditions. Fig. 14. Detection thresholds for a point height variation (electrode Fig.9.a) at a fixed plateau height 2.5m. For both configurations, the micro-ammeter measurements show the presence of DC current when the first pulse regime is occurring (1). This current proportionally increases to the amount of the Corona effect (figure 8) detected gradually as soon as the voltage applied to the plateau is increasing. 2) Intermediate point These experiments are repeated in the same conditions using an intermediate shape point (Fig.9.b). The figure 15 represents the variation of the plateau height (at fixed point height) and the figure 16 represents the variation of the point height (at fixed plateau height). Results using this point clearly show the influence of the shape on the regimes of the Corona effect. In this configuration, we observe that the « low pulses » régime (1) disappears at the benefit of an earlier apparition of the « intense pulses » régime (3). The current quantization system triggers at identical voltage threshold, that means that there is no activity prior to the apparition of the « intense pulses » régime (3). We are able to see that this « intense pulses » régime appears much earlier than the sharp point and persists much longer when the point-plateau distance increases, namely until 1 meter (experimental limit at ~65kV) instead of 25cm (experimental limit at ~65kV). The intermediate point clearly favors the apparition of an « intense pulses » régime mode as well as its persistence over the distance. Fig. 15. Detection thresholds for a plateau height variation (electrode Fig.9.b) at a fixed point height 1m. Fig. 16. Detection thresholds for a point height variation (electrode Fig.9.b) at a fixed plateau height 2.5m. During the variation of the point height, which is a geometrical configuration that increases the point effect (because the height of the latter spreads from 1.0 to 2.4m instead of being constant at 1m above the ground plane), we notice that the Corona effect quantization system detects current occurrences at lower voltage levels, creating a zone (2) where the presence of Corona effect is not detectable by the Rogowski coil. In this zone, the micro-ammeter does not measure any DC current, but the presence of very low amplitude pulses corresponding to the « micro-pulses » régime (2) observed with the sharp point. The « intense pulses » régime does not present any DC current, according to our micro-ammeter, on the contrary of the sharp point. Fig. 17. Digital capture in the zone of apparition of the Corona effect only composed of a «micro pulses» régime (2) 3) Rounded point The last tested point shape is the rounded one (Fig.9.c). The figure 18 represents the plateau height variation and the figure 19 represents the point height variation. Fig. 18. Detection thresholds for a plateau height variation (electrode Fig.9.c) at a fixed point height 1m. With this point shape, we notice that the « intense pulses » régime disappears. No DC current is detected, but we observe the apparition of micro pulses at relatively high voltage values. We notice a larger incertitude about the detection of these Corona effect appearance thresholds, which are occurring in a more variable way but are very similar and comparable to those ones of the intermediate point. Fig. 19. Detection thresholds for a point height variation (electrode Fig.9.c) at fixed plateau height 2.5m. Like in the case of the intermediate point, the modification of the geometrical conditions does influence the Corona effect appearance thresholds in a more obvious way than in the case of the sharp point. Although the voltage thresholds at which the Corona effect appears are rather high, the incertitude of the first Corona pulses detection is higher. However, this graph is comparable to the one about the variation of the plateau height set up. These measurements done on the rounded point show that the breakdown values are repelled beyond the experimental limit (~65kV). Also, we spot that the apparition of the “intense pulses” mode is occurring at the same time as the apparition of the breakdown, when this level of voltage is reachable. IV. Complementary tests on the effect of wind In order to characterize the presence of space charge, that are created when Corona effect occurs, upon the development of the latter, several tests that vary the point height were performed under windy conditions (flowing air propelled by a fan). Air speed was measured owing to an anemometer, and fixed to 2m/s for the whole test (figures 20, 21 and...

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