Journal of Zhejiang University-SCIENCE C (Computers & Electronics)
ISSN 1869-1951 (Print); ISSN 1869-196X (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Review:

Partial discharge diagnostics in wind turbine insulation

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Received July 19, 2010; Revision accepted Dec. 27, 2010; Crosschecked May 5, 2011

Abstract: The purpose of this paper is to review work undertaken on partial discharges and their influence on the insulation of wind turbines. No matter whether partial discharges can be considered as the main cause of deterioration of the insulation material, the initial cause of failure or not but an indication of the material degradation, there is no doubt that they are intimately linked to the aging of machine insulation. Material degradation can be detected by non-destructive techniques (e.g., partial discharge measurements, change of tan δ) or by destructive techniques, such as by cutting small pieces of the insulating material and by putting them under the scrutiny of the scanning electron microscope (SEM). Wind generators are a modern subject of research, especially in view of the growing demands of electric energy worldwide and the problems facing the environment all over the globe. Wind turbines are a novel field of research regarding partial discharge diagnostics since they are subjected to a variety of aging factors, which are different from conventional turbines. In this respect, particular attention should be paid to the multi-factor stressing of insulation and their consequences on the partial discharges.

Key words: Partial discharges, Rotating machine insulation, Wind turbines
doi:10.1631/jzus.C1000256 **Document code:** A **CLC number:** TM8

1 Introduction

Partial discharges (PDs) play a significant role in influencing the lifetime of insulation (Kelen, 1967). The action of PDs causes deterioration of all kinds of insulation and, consequently, one should pay particular attention to these phenomena, both from the manufacturer's point of view and also from the utility's point of view (Bartnikas, 1987).

Although machine insulation is very hard, PD may also occur and cause deterioration. Much work has been done in this respect by various researchers regarding the means of PD detection and registration in machines (Kheirmand, 2002; Kheirmand *et al.*, 2004). Machine insulation can suffer serious damage (Zalis, 2000). To prevent such unwanted events, special care should be taken with respect to the type and the quality of insulation used, and also to the successful means of PD recording of even the smallest PD events.

Wind generators are a modern subject of research, especially in view of the growing demands of electric energy worldwide and the problems facing the environment all over the globe. Historically, there are several types of generators as potential candidates for wind applications. One type is the squirrel cage induction generator, which has been frequently applied commercially. A second popular type is the induction generator with a wound rotor, while a third is the current excited, synchronous generator. These types have been synchronized directly to the grid, providing a constant speed solution. It is not the purpose of this paper to thoroughly examine the various types of generators, nor is it the purpose to propose which one of these types is most suitable for the aforementioned applications. Insulating materials used for wind turbine generators are basically the same as for conventional generators, but they must be reliable and they must withstand a multitude of stresses without needing frequent maintenance or repair (Bruetsch and Weyl, 2002; Bruetsch, 2004).

Although considerable work has been published regarding wind turbine generators, less attention has been paid yet with respect to their possible insulation damage because of PD (ISET, 2005).

In the context of this paper, a review is offered regarding the PD role in wind turbine insulation and comments are made with respect to the ability of the users to successfully avoid further insulation damage. Particular attention is paid to the fact that even small PD may cause insulation deterioration and eventual degradation. It is our aim to show that PD is an important phenomenon, intimately related to the health of the insulation of such systems.

2 Partial discharges as a deterioration phenomenon

PD has generally a damaging effect on insulating materials and systems (Mason, 1978). PD is a phenomenon depending on the type of the applied voltage waveform (Böning, 1963), the value of the applied voltage, the developing electric stress in various parts of the stressed system, temperature, pressure, and operating conditions in general (Devins, 1984; Kelen and Danikas, 1995). PD is a complex phenomenon which may come from enclosed cavities in a solid insulating system, from air bubbles in a liquid insulant, or from enclosed particles. PD may develop in minute tubules and/or in very small channels (electrical trees) and can eventually reduce the lifetime of an insulation (Mason, 1978; Devins, 1984).

There are several methods of detection of PD, e.g., electrical (Kuffel *et al.*, 2000), optical (Bradwell, 1983), and acoustic (Gallagher and Pearmain, 1983). Such techniques contributed greatly not only in detecting the correct PD signals but also in attempting to relate the various parameters of PD with the corresponding insulation damage (Pearmain and Danikas, 1987).

PD has been observed in various kinds of insulating materials and systems irrespective of their mechanical and electrical properties (Tanaka *et al.*, 1993; Li *et al.*, 2009). In the case of machine insulation, previous work suggests that PD can be a dangerous phenomenon, especially if combined with other kinds of stresses such as mechanical and thermal. Work performed some years ago suggested that thermal and electrical stresses contribute to the lowering of dielectric strength of rotating machine insulation, and to the eventual shortening of its life (Danikas and Karlis, 2006a; 2006b; 2008). It is therefore important to attempt to find diagnostic tools appropriate for the correct prediction of the lifetime of such insulating systems.

In the context of this review it is not possible to include every case of PD affecting all sorts of electrical machines. The authors will concentrate, as best as they can, only on the influence and diagnostics of PD in relation to the wind turbines/generators.

3 Partial discharges in wind generator insulation

PD is already a complex phenomenon even in rather uncomplicated laboratory arrangements (Suwarno *et al.*, 1996; Danikas, 2001). Typically, PDs can be detected by using electrical circuits consisting of a coupling capacitor in series or in parallel with the test object, an RLC impedance, an amplifier, and an oscilloscope (Gallagher and Pearmain, 1983; Kuffel and Zaengl, 1984). It is even more complicated, when one deals with PD in generator insulation because of the sheer length of the windings and the attenuation of the PD signals (Fort, 1990; Hutter, 1992; Gulski and Zielonka, 1996).

In Gulski *et al.* (1999), e.g., known patterns of phase resolved PD distributions were presented for 6 MW and 63 MW turbogenerators. Databases were constructed, helping the experimenter to distinguish between generators in good condition and those in unacceptable conditions. Furthermore, databases were constructed with the aim of distinguishing and identifying the source of the discharge in the insulation. On-line PD tests are possible by using capacitive or inductive couplers with the generator in regular operation. The difficulty with on-line testing is the interference one can receive from a noisy environment and/or the complexity of the propagation of the PD signals through the stator windings, which in turn may cause cross-talk between the phases. Gulski *et al.* (1999) pointed out that a remedy to the latter problem is the use of a spectrum analyzer to suppress external noise. By tuning the spectrum analyzer at an appropriate frequency (ranging from 10 to 100 MHz), one can remove the unwanted noise and display the PD on a 50 Hz time base. Such a technique can function.

However, it is a question whether it can respond suitably when many defects are present. Although the approach of Gulski *et al.* (1999) refers to turbogenerators, it can easily be seen that it can also apply to wind generators since the main principles are the authors' concerns. A similar approach to the PD question was developed by Hutter (1992), where on- and off-line PD measurements were made. As was pointed out, both narrow- and broad-band PD measurements are necessary in order to acquire data to create PD databases, which in turn will create a reliable statistical analysis. Off-line measurements have the advantage of a detailed study of possible PD from a variety of sources; it has, however, the disadvantage of not taking into account simultaneously applied thermal and mechanical stresses to the insulation. On-line measurements can give realistic results, but they suffer from a high level of interference, which at times may reach magnitudes as great as 500 times the real PD.

In wind generators, the insulating system is basically the same as for conventional generators, based on a form wound coil design in both vacuum pressure impregnation (VPI) and resin-rich (RR) technology. Wind generators are supposed to last 20 years, but problems may start appearing in the first five years in the gear box and the drive train bearings (Eriksson *et al.*, 2008; Kung, 2009; Zhou *et al.*, 2009). A good introduction to wind generators and their different types was offered in Eriksson *et al.* (2008), where the authors commented not only on the classical horizontal type wind turbines, which have the main rotor shaft and electrical generator at the top of a tower and must be pointed into the wind, but also on their vertical counterparts, i.e., the vertical-axis wind turbines (VAWTs), which have the main rotor shaft arranged vertically.

Eriksson *et al.* (2008) commented on the advantages and disadvantages of the respective types of wind turbines without, however, making any reference to their PD behavior. Methods proposed to detect PD in such systems, include the measurement of PD inception voltage and the recording of the corresponding magnitudes of PD (Eriksson *et al.*, 2008; Kung, 2009; Zhou *et al.*, 2009), for at least two different parts of the whole system (this means the wind generator plus the electrical power system involved), as well as their corresponding trends in a period of time. Such a method, although it may give valuable information about the general tendency of the whole electrical system, it is based only on two main quantities, namely the PD inception voltage and the largest PD magnitude. Particular emphasis was given to PD analysis in Dean (2009), where emphasis was given again to the pulse height analysis of PD. The author paid attention not only to electrical stresses but also to thermal degradation and, if the wind generator functions off shore, to chemical attack. Chemical attack can be perceived as chemical reactions due to PDs, i.e., chemical changes in the insulation itself. More generally, chemical attack may be due to PD action and may be combined with other degrading factors, such as humidity and temperature. The history of previous failures should be taken into account and also any evidence of unusual power surges or transient events. PD measurements must be related to some visual and/or chemical diagnostic techniques, such as scanning electron microscope (SEM) or energy dispersive X-ray (EDX) coupled with elemental analysis on selected regions and volumes down to about 1 cm^3. PD studies of the insulation of such generators must be coupled with identification of the composition of possible solid by-products. Needless to say, if need be, other types of by-products can be assessed with gas chromatography. Visual inspection of the windings was also suggested by Warren and Stone (1998), where PD testing at regular intervals was recommended (once or twice per year depending on the type of the machine). Off-line testing, however, has some disadvantages. PD sites, for example, in such a test, may behave erratically when the machine is off-line, making trending from test to test inconsistent, which means that there is no consistent tendency from test to test. Large PD may unexpectedly come from locations not normally experiencing high voltages. Conversely, on-line testing according to Warren and Stone (1998), may be performed by using sensors (high voltage capacitors with a capacitance of 80 pF, radio frequency current transformers (RFCTs) installed on the ground leads from surge capacitors, and antenna-like devices called stator slot couplers (SSCs) installed under the stator wedges or between the top and bottom coils). The problem with on-line testing, as has been noted in other publications, is the interference from other electrical equipment and/or other power tool operations (Kheirmand, 2002;

Kheirmand *et al.*, 2004). Such sources may cause confusion for the operator. Methods to overcome this problem have been proposed; the most common is to use two sensors per phase in a bridge-like formation to balance out noise or use the different pulse shape characteristics between PD and noise.

The problem of PD identification and elimination of noise for motors and generators at 4160 V and above, was tackled in Paoletti and Golubev (1999a; 1999b), where, apart from the already known pulse height analysis methods and diagrams, it was indicated that repeated starts, stops, and thermal loading swings, may cause excessive stress on the end-turn windings. This in turn will further cause small cracks and voids to the insulation at the point where the winding extends from the iron core. Such damage may at times go unnoticed. Paoletti and Golubev (1999a; 1999b) emphasized the differentiation between positive PD and negative PD, the former being more a characteristic of voids in the slot between insulation and iron, whereas the latter a characteristic of voids at the inner copper/insulation interface. Particular emphasis was given to the external noise. In that, the authors did not suggest a different proposal from other researchers (i.e., elimination of cyclical noise, elimination of cross-coupled pulses, and recording of signals only from sensors, rejection of pulses with width different from that of PD pulses). Other researchers (Kemp and Zhou, 1996) suggested that attention should be paid to the earthing of the machine frame, since any flaw in the earthing path can give rise to excessive coupling wave components. Furthermore, the calibration of the PD detecting equipment should be done in such a way, to emulate real PD pulses. Such observations are particularly relevant for on-line condition monitoring of wind generators. In this respect, Zhou *et al.* (1996) gave a good insight as to a possible solution to the problem of interference. For PD detection the authors used a high voltage and high frequency current capacitor over different frequency bands. The advantages of such a system consist in the ability of distinguishing true PD from interference, especially in industrial environments. There are also other techniques, which can distinguish between true PD and interference signals. A relevant method, proposed in Kashisha *et al.* (2009), is based on a combination of the discrete wavelet transform (DWT) and the time-of-arrival method, to de-noise PD. This combination method helps in discriminating signals arriving at the same time at the PD detector, from real PD arriving at different times.

A further method of distinguishing real PD from noise was proposed in Patsch and Benzerouk (2003), where not only the positive and negative PD pulses were recorded but also the time difference between the times of the highest positive and the highest negative PD. The time difference can be used to separate noise signals from discharge pulses.

Note that, as a general comment on all the above, with a PD acquisition system, if one wants the PD data to be trendable (i.e., to show a certain trend, so that one can extract some useful conclusions regarding the state of the wind generator insulation), a machine has to be tested under the same conditions (load, temperature, voltage). Such an assumption is possible when dealing with laboratory conditions, but it is illusory when dealing with generators subjected to frequent load cycles. A method of rectifying this is the frequent monitoring of the generator in question (Stone *et al.*, 1996).

All the above is related to the view expressed by Ramesh Babu and Jithesh (2008), where it is stated that grid failure and frequent tripping are two of the major causes that can adversely affect the windmill operation. Sudden frequent failure of the grid can result in frequent stoppages of the windmill, which can affect the transmission system. Also, high fluctuated voltages from the grid can be passed into the generator, resulting in generator failure. The frequent stoppage of windmills resulting from sudden frequent failure of the grid or frequent change and irrelevant wind turbulence can result in mechanical damage to the wind turbines, especially to the transmission system. Further, if the machine is suddenly stopped at full load, there is a possibility of damage to the transmission, generator windings, brake pads, etc. In other words, the wind generator is subjected to random events, which in turn may cause damage to its insulation.

A critical point to be noted is that it is difficult, if not impossible, to talk about acceptable limits for any type of PD. Internal PD can appear from a few hundred to thousands of pC. If the PD magnitudes reach tens of thousands of pC, then the situation may become uncontrollable. External PD, such as those causing surface tracking, may appear at a few tens of thousands of pC, and can cause only minimal damage to the insulation. As was reported in Bradwell (1983), the rate of change of the maximum PD magnitude may be a better indicator than the absolute PD magnitude. However, even in this case, the sources of PD have to be identified and located. The problem of innocuous PD for machine insulation has been dealt with in Danikas and Nelson (1993) and Danikas and Tanaka (1994), where it was pointed out that small enclosed cavities and small PD can indeed cause long-term deterioration.

This point needs some further comments: the magnitude of PD that may endanger the lifetime of a machine insulation is for some researchers in the range of 2000 to 5000 pC (Kurtz and Lyles, 1979), whereas for others it lies above 10 000 pC (Miller *et al.*, 1982; Wilson *et al.*, 1985). This brings again the point that regular control of the insulation has to be performed, if we want to know the exact state of the insulation. Moreover, other PD parameters, such as the dynamic inception voltage and the dynamic extinction voltage, can be taken into account, if one wants a more complete diagnostic picture of the insulation (Kim and Nelson, 1992). In a conventional discharge inception (or extinction) measurement, the root mean square (rms) voltage at which discharges appear (or finally disappear) is recorded while the voltage slowly ramps. The dynamic inception (or extinction) voltage corresponds to phase angles at which discharges start to appear (or finally disappear) in the phase angle distribution (Nelson *et al.*, 2000).

Wind generators are subjected to a number of stresses, which may be simultaneous. A factor to bear in mind is the salinity of the sea, especially for wind generators functioning off shore. Numerous publications have stressed the importance of environmental stresses, particularly in outdoor insulators (Gorur, 1991; Danikas, 1995; 1999). The fact that machine insulation is stressed at both electrical and environmental stresses is relatively new. Certainly, other requirements are imposed for outdoor insulators and others should be considered for wind generator insulation.

4 Discussion

Although in general, large PD causes insulation failure in machines, attention has to be paid also to small PD. The reason behind this is, as mentioned in Bruning (1984), sudden failures of large generators occurred after they passed the usual tests and only after a few months in service. This points to some phenomena, possibly related to PD, not hitherto detected, and consequently related to some small PD, not easily detected (or, in case we do not like the term ‘PD’, some charging phenomena).

It has to be emphasized that, although PD is an important aspect of insulation failure, it is by no means the unique cause of failure. In this respect, PD may come from a variety of synergistic stresses (Christodoulou *et al.*, 1998). PD phenomena tend to become even more serious when they are combined with stresses of other types (e.g., thermal, mechanical), some of which have a cumulative effect on the insulation. In fact, the problem of PD in machine insulation, is to be considered with the more general problem of combined stressing on electrical equipment. Although several aging models have been proposed, none of them has a general application to all kinds of insulation. It should be remembered what a pioneer in the field of electrical insulation wrote, “One should approach the multi-stressing of insulation not with a generalized model but bearing in mind the specificities of each situation” (Kelen, 1976; 1990; 1995).

Furthermore, based only on PD measurements, this may not reveal all possible parameters concerning degrading machine insulation. This is the point raised in Martinez-Tarifa (2005), where the author, although he performed PD measurements on windings, also performed analyses by means of dielectric spectroscopy. Martinez-Tarifa (2005) presented data with which the author showed that dielectric high frequency conductance grows with aging time, insisting that this parameter gives more information regarding the state of the insulation. Such arguments are correct and they point to the fact that PD measurements are not the only and unique tool to diagnose the state of an insulation. To further stress this point, one can also refer to previous work on high-frequency methods for determining winding faults in electrical machines (electrical motors and windmill generators), where frequency dependencies of the winding admittance or transfer function are used to determine the consequences that have short circuit faults on windings (Florkowski and Furgal, 2004; 2005). Deformations and displacements of windings are recorded as changes in the transfer function and in admittance frequency related graphs. Moreover, more techniques were proposed regarding the in-service monitoring of the aging of stator windings in motors. Such techniques are based on detecting small variations of the turn-to-turn capacitances due to the dielectric aging (Werynski *et al.*, 2006; Perisse *et al.*, 2007). These techniques are adequate for large machines as well as for low-voltage machines fed by adjustable speed drives.

One may also say that, although the present paper refers to wind turbine generators, it also often refers to other types of generators. This is not necessarily a weak point of the paper, since the PD problems regarding the generators are more or less common in all types.

A peculiarity of the wind generators is that they start rather frequently, depending on the weather conditions. This peculiarity may mechanically stress the generator, given the different coefficients of expansion of the insulation, and copper and iron parts within it. Such frequent starts may also induce magnetic forces by the flow of large magnitudes of starting currents and large accelerating torque values, which in turn may add to the mechanical stress. Such effects contribute not only to the shortening of the lifetime of the wind generator, but also to the possible generation of more and larger PD. One should emphasize this point, since it is known that PD can be generated not only by electrical stresses but also by a combination of other aging factors (Brancato, 1992).

Contamination by water, airborne dust, and wear metals is of particular concern for wind turbines. Off-shore wind turbines would have a higher failure rate compared to on-shore installations due to the rough ambience at open sea. Many wind turbines are connected to weak power systems where unbalanced load distributions are not corrected for many months (Muljadi *et al.*, 1999).

This persistence or lingering of an unbalanced condition poses serious problems to the induction generator. Unbalanced operation of induction and synchronous machines has been the source of heating problems and reduced efficiency. Unbalanced loads represent many single-phase loads, which are common in rural and residential applications. Unbalanced loading at the point of common coupling (PCC) can cause unbalanced voltage drop across the transmission line, which will result in unbalanced voltages at PCC.

While the unbalanced phase voltage is small, large negative sequence currents can result due to low negative sequence impedance of an induction generator. These large currents eventually can cause unbalanced heating (hot spots) in the machine windings, which can potentially lead to failure. Conversely, the larger diameter of the direct drive synchronous generator and greater length of its stator and rotor windings, compared to the induction generator, are associated with the difficulty of adequately sealing windings on larger machines against external agents, and could statistically increase the probability of winding defects.

This paper concentrates mainly on the deteriorating effects of PD no matter where they come from. No special consideration has been given to the problems arising from pulse-width modulation (PWM) converters directly connected to the rotor winding. However, high repetitive voltage spikes with fast rise time produced by insulated gate bipolar transistors (IGBTs), may cause particular stresses on both the winding insulating system and the bearing insulation (Gao and Chen, 2007). Dinkhauser and Fuchs (2009) ascribed turn-to-turn faults to the converter. Principal reasons are high switching voltages and high-frequency harmonics of the converter, which lead to additional losses in the coils and a higher thermal stress caused by these losses. The danger of the turn-to-turn fault is the high induced current in the short circuited turns, which have nearly no resistance if they are very close in the winding distribution. This high current causes more insulation degradation and more turn-to-turn faults. Such considerations are not taken into account here but they will be the subject of a future paper.

5 Conclusions

In this paper a review on PD was given regarding wind turbine insulation. The general approach concerning this insulation is not that different from the diagnostic techniques in other types of machine insulation. The peculiarity of wind turbines is that they have frequent starts and, in this way, they may stress even more their insulating parts. Wind turbine insulation is a good example of insulation subjected to a multitude of stresses.

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