**Lightning Protection of Wind Turbine Blades – How Supersizing Has Created New Challenges for Nanodielectrics Research**

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**SUMMARY**

This article reviews the implications of super-sizing in lightning protection of wind turbine blades and how polymer nanocomposites, with improved electrical and thermal performance, may be used to mitigate consequent issues.

**INTRODUCTION**

The exploitation of wind as a useful source of power has a very long history, stretching back many thousands of years. Although simpler devices can be identified, vertical-axis windmills were used in the middle east around 200 BC followed, in the Middle Ages, by the development of horizontal axis windmills in Europe and around the Mediterranean. The first large machine for the generation of electricity using wind power was installed in the USA in 1888, with an output of 12 kW [1], leading to the progressive development of such concepts across the world. The oil crisis of 1973 inspired a new wave of interest in wind power, notably, in relation to grid-connected wind farms with, perhaps, the first large scale adoption of this concept occurring in California in the 1980s, where more than 16,000 machines were installed in this decade with a total generating capacity of about 1.7 GW [1]. In more recent times, Europe has played a leading role in exploiting wind power with, in 2010, the region accounting for just under 50% of the world’s onshore installations. Since this time, a rapid growth in the technology has occurred globally such that, by 2018, China had become the largest exploiter of onshore wind generation, with approaching one-third of the world’s installed capacity [2]. A major enabling factor in the growth in wind generation described above has been the dramatic increase in wind turbine (WT) ratings that have occurred over recent decades. In 1985, typical turbines had a rated capacity of 50 kW; in Europe, installed offshore WT were, in 2017, characterized by an average power output of 5.9 MW [3]. The next generation of WT is exemplified by GE’s Haliade-X offshore turbine, with capacities up to 14 MW [4]. This evolution has been facilitated by increases in turbine size, from rotor diameter of ~15 m in the mid-1980s [3] up to ~220 m in the case of Haliade-X [4]. This has been made possible by improvements in design, materials and manufacturing, which have led to the manufacture of WT blades (WTB) of increasing size. Indeed, Froese [5] reported that, on average, WTB lengths have increased by about 2 m per year between 2007 and 2017; the Haliade-X turbine employs blades that are 107 m in length. As in other areas such as aerospace and Formula 1, the production of such structures with the required specific properties has, necessarily, led to the widescale adoption of polymer-based composite materials.

In addition to increasing mechanical demands, the “super-sizing” of WT technology also has electrical implications. Inevitably such large structures also attract lightning strikes. Lightning stepped leaders originating from thunderclouds produce electric fields. Large vertical structures enhance these fields and upward moving leaders are initiated from the upper points of those structures. It is generally accepted that the taller the object, the higher the field enhancement which, in turn, makes the object more attractive to lightning [6], [7]. Although the height of turbines is primarily responsible for the attraction of lightning, WTs cannot be treated as stationary vertical objects. Rotating blades present time-space variable electric field enhancement, due to which the lightning tends to attach to different parts of the blades (see [8], [9]). Additionally, the surface charge accumulation (e.g. in the surface water droplets) is another issue, since it modifies the local electric field and may result in a different initiation point for the upward moving leader [9], [10]. Lightning is a complex phenomenon and additional information can be found in [6], [7], [11]. The key point is that lightning can inflict severe damage [12]–[16] unless WTBs are protected. The protection design depends on the material used and it needs to be adjusted for the carbon fiber reinforced polymers (CFRP) that will be utilized in the next generation of WTs.

This paper suggests that the electric engineering issues associated with lightning protection can be solved by a modification of the existing materials rather than through introduction of a totally new engineering design. This pathway is preferable not only from the cost saving point of view, but also because the blade design is primarily driven by mechanical requirements and it would be beneficial to decouple the system’s lightning protection design from those. A potential use of graphene nano-flakes, is proposed, to tailor the electric properties of the equipotential bonding (EB). Such polymer composites systems can deliver a combination of properties that might mitigate both heating issues and potential flashovers/breakdowns.

**LIGHTNING PROTECTION OF WIND TURBINE BLADES**

The common protection strategy is to divert the lightning current from the structural elements and so, lightning needs to be intercepted by receptors (metal bolts or rivets) along the surface of a WTB (Figure 1) and the lightning current diverted to the ground by, so-called, down-conductors (thick copper or aluminum cable, Figure 1).



**Figure 1:** Typical cross-section and lightning protection system of a WTB.

The placement of the receptors is a complex engineering problem, which depends on the blade design, materials used, and operational conditions (e.g. rotational speed). It is addressed for each blade design using a combination of analytical, experimental and numerical methods [12], [16]–[19]. However, even with receptors and down-conductors in place, the blade can still be damaged by lightning. The key problem is the hollow structure of WTBs, which consists of both conducting and dielectric components. The WTB outer surface (skin, typically dielectric) is supported by a rigid structural beam (spar) which could be either a dielectric or a conductor (Figure 1).

To highlight the crucial role of material properties and internal connections within the lightning protection of a WTB, the system can be represented by a simplified equivalent circuit (see Figure 2). The current is injected to point “2” and its distribution within the blade structure is controlled by the time characteristics of the lightning pulse and by the values of self-inductances *L*, resistances *R* and a mutual inductance *M*, which are functions of the mechanical design. Smaller blades are commonly constructed using insulating materials such as glass-fiber composites. Glass fibers are good insulators, thus *Rspar* is rather large. No charge separation takes place inside the spar during lightning pulses and there is zero potential difference, *V12*. In this case, there is no issue associated with the protection of the spar. Of course, the induced electric field may still result in electron avalanches from the charges accumulated on the skin. Therefore, a major electrical protection issue, here, relates to the choice of the skin material and the distribution of receptors to eliminate internal breakdowns and only allow external skin surface flashovers.

However, as structural dimensions increase, so does the need for materials with improved mechanical characteristics, which has necessitated the adoption of CFRP composites in the WTB structure. While these materials provide the required mechanical properties, their electrical characteristics create problems in terms of lightning protection. CFRPs are moderate conductors, therefore *Rspar* values allow induced currents to propagate. Large lightning currents of the order of hundreds of kiloamperes and, foremost, extremely high rates of rise of current (*di/dt* up to 200 kA/µs [20]) in the down-conductor result in electric fields, associated charge separation and high potentials on conductive spars (e.g. voltage *V12* across 10 mm gaps between the spar and the down-conductor that can reach 10 MV [20], [21]). Under such conditions, damage is inflicted indirectly as a consequence of high voltage breakdown of the insulating material between the down-conductor and the floating CFRP spar caps. The larger the blades, the higher the potential difference between the spar and the down-conductor.



Figure 2. Simplified equivalent circuit of a WTB for predictions of the lightning current propagation.

A solution to prevent internal arcs would be electrically to bond the down-conductor with the CFRP structures, such that no significant potential difference would exist between these two elements. In terms of the equivalent circuit, points ‘1’ and ‘2’ are then connected with an equipotential bonding conductor *Reb*. Unfortunately, this would create another problem: the current through the spar is still controlled by the reactance and the resistances of the large elements (spar and down-conductor), so this configuration would result in the lightning current being shared between the CFRP spar and the down-conductor. As a result of the large current propagating through the bonding contacts, elevated temperatures are often observed at the joint interfaces, because of the large contact resistance, which leads to thermal degradation of the polymer matrix and delamination at the interfaces, with associated formation of voids. Sparks in these newly formed voids can cause further delamination and complete disintegration within the composite joint. Furthermore, CFRP components typically display high anisotropy, being characterized by markedly different properties parallel to the fiber direction and along the two orthogonal axes. The electrical conductivity along the fibers (longitudinal direction) can be up to 10,000 times larger than those in transverse and through-thickness directions [22]. Consequently, currents tend to penetrate only the thin top layer of CFRP composites which, in turn, leads to highly localized Joule heating close to contact surfaces. Such non-uniform distributions of the current density through the spar cross-section leads to large voltage variations between carbon fiber laminates and along the edges of the spar which, in turn, may result in sparks between the laminates and flashovers in the edges. Any attempt substantially to reduce currents in the bonding (and in the spar) by increasing *Reb* brings back the original issue: *V12* exceeds the breakdown strength. Clearly, the appropriate electric properties for the bonding need to be used, while at the same time the mechanical and chemical compatibilities of the bonding, the spar and the down-conductor need to be ensured. Although this is not a simple task, it could be achieved by modification of the conventional bonding materials.

An effective strategy to eliminate breakdowns, evenly spread the current and, thereby, eliminate these adverse effects would be through tailoring the CFPR composite so as to increase the through-thickness electrical conductivity. In this respect, nano-filled polymer systems (polymer nanocomposites) might play an important role in the wind energy sector.

**POLYMER NANOCOMPOSITES IN WIND TURBINE APPLICATIONS**

The inclusion of particulate fillers within polymeric matrices has commonly been used to modify bulk properties or reduce cost, according to the desired requirements. Fillers with at least one nanometric dimension (< 100 nm), so called nanofillers, have attracted considerable scientific/engineering interest over recent decades [23], since the use of such systems can lead to property enhancements not attainable in other ways. Such effects are commonly ascribed to the large interfacial area that characterizes these systems and, as such, should depend on the size and geometry of the particulate phase and the local interactions that occur between the nanofiller and the surrounding matrix. Particulate, quasi-spherical entities; fibrous or tubular (1-dimensional, 1D) structures; and platelets or layered (2-dimensional, 2D) nanomaterials exhibit a variety of surface/volume ratios, geometrical aspect ratios and different tendencies to agglomerate [24] (Figure 3).



**Figure 3**: Types of nanoparticle geometries and the respective attributes

Polymer nanocomposites have recently begun to be considered for use in WTB where the use of nanofillers has been demonstrated to enhance mechanical performance and extend the lifetime of WT components [25]. Apart from the mechanical reinforcements of polymer matrices, fillers for electrical and thermal conduction enhancements have also been investigated, due to their potential in various applications such as in electronics, antistatic devices, etc. [26]. As a general rule, the conductivity of an (insulating) polymeric matrix containing electrically conductive fillers follows a percolation behavior [27], according to which, the composite’s conductivity sharply increases at a certain, critical filler volume fraction – the *percolation threshold* (Figure 4). In large-scale industrial applications such as WT, the key is to achieve electrical percolation at the lowest possible filler content to minimize risks of adverse effects on mechanical performance. Even though the electrical and thermal percolation behaviors greatly differ from each other [28], there is a common parameter leading to substantial electrical and thermal improvements at low filler contents: the nanoparticle geometrical aspect ratio. As such, properly selected nanofillers have the potential to lead to affordable nanocomposites displaying low electrical percolation threshold and enhanced thermal conductivity, which could be utilized either as structural adhesives, or CFRP matrices in WTB as a means of mitigating resistive heating phenomena [29] and improving lightning protection [30].



**Figure 4:** Electrical percolation threshold in polymer composites and the effect of filler aspect ratio

***Electrically and/or Thermally Conductive Nanofillers***

A number of different electrically and/or thermally conductive fillers can be considered for the development of nanocomposite polymers with the desired performance (see Figure 5). Some of these are briefly discussed here.



**Figure 5**: Classification of electrical and/or thermal enhancements in polymers

An obvious strategy for conductivity enhancements in polymers would be through the addition of metallic particles; several studies have investigated percolation effects in such systems, with various degrees of success being reported [31]. Nevertheless, the use of metallic nanoparticles in this context is not widespread, due to issues such as: thermal expansion mismatch with the matrix and eventual crack formation; increased cost; flammability; toxicity. In contrast, adding carbon-based nanofillers to polymers is a widespread industrial practice; for example, carbon black has long been used in the production of semi-conducting shields in power cables [32] and, consequently, it has been considered as a potential candidate for improving the interlaminar mechanical and thermal performance of CFRP components [33]. However, its low aspect ratio typically results in large percolation thresholds (~16 vol%), poor thermal conductivity values and deteriorated mechanical performance. Nevertheless, research interest in carbon-based nanofillers was invigorated by the development of carbon nanotubes (CNT) [34] and graphene [35] which, being 1D and 2D nanostructures, respectively, can be characterized by high geometrical aspect ratios.

Carbon nanotubes exhibit extremely high aspect ratios and consequently, when suitably dispersed, can lead to composite systems that are characterized by very low percolation threshold values. Typically, the related literature considers 1D nanomaterials as superior to other particle geometries in terms of percolation performance [36] and, consequently, CNT-based coatings have been considered as potential candidates for lightning protection of the fiber laminated components used in WT [37]. However, fibrous materials – as in the case of asbestos – are known to be potentially hazardous and, consequently, CNT exposure might lead to a series of health conditions such as lung interstitial fibrosis, lung tumorigenesis, etc. [38]. In view of such concerns, exposure to 1D materials should be restricted and, therefore, their industrial use may be limited by safety concerns.

The nanometric equivalent of graphite, the 2D graphene, complies with the geometrical characteristics needed for low percolation thresholds, is characterized by low cost and is a non-hazardous nano-structure [39]. Thus, graphene-based nanomaterials could be a cost-effective alternative to CNT. Consequently, graphene thin films have been considered for use in lightning protection of CFRP composites used in WT applications [40].

While the above has concentrated on the aim of enhancing electrical conductivity, increasing thermal conductivity could also be beneficial. As such, another potential option would be the exploitation of thermally conductive but electrically insulating nanomaterials, which could be used in components where conduction of electrical current should be avoided. The most common nanoparticles used in this area are the (typically spherical) metal oxides, such as aluminum oxide (Al2O3) and zinc oxide (ZnO), or metal nitrides such as aluminum nitride (AlN) or boron nitride (BN); with the latter exhibiting both 1D and 2D habits. Such materials have been reviewed in [41]. Highly ordered polymers exhibiting high intrinsic thermal conductivity might constitute another option, an example being, tailored epoxy resins displaying a molecular structure sufficient for the formation of highly ordered mesophases (typically stacked aromatic rings) that suppress phonon scattering [42]. Indeed, various epoxy resins and/or hardeners exist that lead to material systems characterized by thermal conductivity values between 0.2 W/mK and 1 W/mK [43]. However, such high molecular weight structures are usually characterized by processability issues (e.g., high viscosity). Lately, ultra-high molecular weight polyethylene (UHMWPE) flakes have been used successfully as a filler to increase the thermal conductivity of compatible polymers, such as ethylene/(vinyl acetate) (EVA) and low density polyethylene (LDPE) [44]. Despite apparent compatibility issues, related studies have suggested that the use of polyethylene with epoxy resins may, nevertheless, be plausible [45]. However, further research is required here.

***Graphene Oxide-based Epoxy Systems***

Since the objectives, here, primarily relate to the dissipation of accumulated charges and damaging currents resulting from lightning strikes and, only secondarily, to heat dissipation, graphene was examined in detail in a series of recent studies. 2-D graphene sheets can be found stacked together in naturally layered graphite, such that a key prerequisite for the exploitation of graphene’s potential is successful layer separation within the polymer matrix.

Large scale production of graphene for industrial purposes requires scalable synthesis methods with high yields and relatively low cost. Amongst the existing methods, synthesis of the readily exfoliated graphene oxide (GO) offers many advantages, including increased compatibility with epoxy resins, a characteristic that stems from the oxygen-containing groups introduced onto the GO surface. However, somewhat contrarily, the very same functional groups that enhance matrix compatibility, and thereby promote dispersion, can severely degrade electrical and thermal properties compared with pristine graphene. Thus, GO is commonly subjected to further treatment steps to reduce it chemically or thermally into so-called reduced graphene oxide (rGO). The latter resembles a product that is more closely related to idealized graphene, albeit displaying increased degrees of structural and chemical defects, as well as being prone to re-stacking phenomena. In order to overcome the latter effects, further functionalization may be used (see Figure 6).

From the above, it is evident that control of the surface chemistry of GO flakes is of utmost importance if both matrix compatibility and intrinsic filler properties are to be optimized. As such, we describe the treatment of graphite to form GO with various surface chemistries of variable molecular arrangements and/or reactivities with the epoxy matrix [46] and, specifically, consider this in term of three steps:

* Synthesis of GO via a traditional acid/oxidant-based route [47]
* Synthesis of GO via an alternative (mild) acid/oxidant-based route [48], [49]
* Further functionalization to improve matrix compatibility [50]

The respective GO fillers were incorporated into an epoxy resin designed for, and widely used in, structural fiber reinforced composites for wind energy applications but, clearly, as in areas such as nanodielectrics, the surface functionalizing moiety can be tailored to suit the matrix polymer and application of interest. Details on each case, separately, are described below and are summarized, altogether, in Figure 7.



**Figure 6**: (a) Graphite-based products; typical chemical structures of: (b) single sheet of graphite (graphene), (c) GO and (d) rGO

***Conventional Synthesis of GO***

The most common approach to the preparation of GO involves oxidation of graphite by exposure to a strong oxidant (potassium permanganate, KMnO4) dissolved in an acidic medium composed of a sulfuric/phosphoric acid mixture. Since the resulting oxygen-based groups that decorate the GO surface are relatively volatile, a possible alternative to GO reduction is a high-temperature *in-situ* post-curing treatment of the epoxy/GO nanocomposite, as a means of reducing the GO when already incorporated into the cured epoxy. Analysis of respective GO-filled epoxy systems before and after such post-curing has therefore been undertaken in order to demonstrate any distinguishable effects stemming from GO reduction. It was revealed [47] that while the presence of reactive functionalities on the GO surfaces leads to covalent bonding with the epoxy matrix, filler contents as low as 2 wt.% are sufficient to perturb the curing process and reduce the glass transition temperature (*Tg*) by more than 10 oC compared with the unfilled resin. During subsequent post-curing (>100 oC), it was shown that further crosslinking reactions associated with the GO occurred, which led to increased filler/matrix interfacial interactions and modified mechanical performance. Despite this, the final *Tg* was still lower than that of the equivalent, post-cured, unfilled epoxy and charge transport was only slightly enhanced. It is also noteworthy that the GO required dispersion within an appropriate polar solvent which, from a technological perspective, might be disadvantageous on numerous grounds.

***Targeted Synthesis: Moderately oxidized GO (mGO)***

While a number of strategies may be envisaged for alternative synthesis approaches, here, we describe a successful one, where the synthesis of moderately oxidized GO (mGO) was undertaken via oxidation using a mild oxidant (chromium trioxide, CrO3) in a sulfuric acid environment [48]. To assess the value of the above synthetic route, the mGO was compared with GO produced via the traditional methodology described above and with a commercial, low-oxygen graphitic product, edge-oxidized GO (eGO) [51]. Characterization of the three different graphene-based systems via analytical methods revealed that the mGO, as envisaged, is characterized by a moderate level of oxidation and reduced carbon defect content. The obtained mGO surface chemistry was beneficial in terms of:

* Maintaining epoxy compatibility (as opposed to eGO)
* Ensuring no adverse interactions with the crosslinking of the matrix (as opposed to GO)
* Not compromising mechanical performance (as opposed to eGO)
* Allowing low electrical percolation threshold and enhanced thermal conductivity (as opposed to both eGO and GO).

Specifically, the achieved percolation thresholds were ~1 wt.% with mGO and ~10 wt.% with eGO, while the maximum achieved electrical conductivity was in both cases >10-8 S/cm. The achieved thermal conductivity increase compared with the unfilled epoxy was ~200% (at 16 wt.% mGO). A 30 wt.% of eGO was required to achieve an increase of ~150%. An extensive review revealed that mGO typically displays similar and comparable performance achievements with those reported in the literature [46], [48], albeit via a simplified and less costly production method. It is worth mentioning that the mGO, did not require solvent-assisted dispersion, thus the preparation of epoxy-based composites could be performed directly, using readily scalable, high-speed mixing.

This work therefore established that alternative acidic-oxidant synthesis routes can result in desired chemical characteristics and electrical/thermal properties combined with ease of synthesis and processing, thereby opening up the potential for technological deployment in applications such as CFRP-based WTB.



**Figure 7:** Summary of graphene structure/property relations in GO/epoxy-based nanocomposites

***Functionalization of mGO: Varying the surface chemistry***

The ability to vary the number and nature of the reactive sites on GO provides the potential of further surface chemistry tailoring. Here, we illustrate this through the grafting of amino-terminated moieties of various molecular structures onto the surface of mGO, to generate functionalized graphene oxide (fGO). Specifically, the mGO was treated with two bifunctional agents of different molar masses (termed d230/fGO and d4000/fGO for short and long surfactants, respectively) and a short trifunctional agent, t440/fGO [50]. The functionalization process was an additional step after the production of mGO and the grafting process was shown to be successful via a range of relevant analytical methods. The preparation of epoxy composites was, again, performed via scalable high-speed mixing. Incorporation of the abovementioned three fGO systems into the epoxy resin resulted in slightly perturbed crosslinking reactions, due to the presence of the grafted amino-moieties, an effect that was pronounced with short surfactants. However, the surface treatment was revealed to result in improved platelet distribution and reduced platelet stacking, with the longest surfactant displaying the most promising results. The consequences of grafting included a reduction in the percolation threshold (to just 0.5 wt.% with the use of the longest reagent) and a slight increase in the maximum achieved electrical conductivity. However, the thermal conductivity of the fGO-containing systems was found to be adversely affected at low filler contents.

From the above account of the effect of different GO material processing protocols on the macroscopic properties of epoxy/GO composites, it would appear that achieving some universal panacea in which all aspects of the performance of such systems are simultaneously improved is difficult to achieve. Rather, we suggest, some compromise should be sought according to the application of interest, in which the impact of particular material characteristics on overall system performance is explored and materials are designed to bring maximal technological benefits.

**IMPACT OF GO ON WIND TURBINE BLADE PERFORMANCE**

***Unidirectional (UD) CFRP case***

To this end, the effects of including GO on the lightning protection performance of a medium size WTB was examined, which was represented using the simplified structures shown in Figure 8, (dimensions taken from [52]). In the analyzed structure, unidirectional (UD) CFRP composites with either neat or GO-filled epoxy have been assigned to both spar and EB components with fiber direction 1 being aligned with the blade longitudinal axis. The distribution of current density was evaluated for the first positive stroke, having time parameters equal to 19 µs and 485 µs, and a peak current of 100 kA [21], [52]. (UD CFRP is often used for spars due to simple manufacturing procedure and low cost [25], [53]).

In this analysis, the peak value of the lightning current was halved and only half of the blade (i.e. one shell) was modelled, on symmetry grounds, since previous studies have shown that the lightning current splits equally between the upper and lower shell due to their similar geometry (Figure 1) and impedance [21]. To model the lightning current flow in the blade structure, a previously published modelling approach [52] was used. The material properties were taken from [54], [55]. The lightning current is injected at the blade tip (*x* = 40 m, Figure 8) and splits at the EB, gradually propagating through the spar. Although the current spreads over the 5 m section of the EB, it tends to concentrate densely at the EB outer edge close to the down-conductor (EB interface), which is the most problematic region where sparks are most often observed.



**Figure 8:** Top view and cross-section depicting the internal components inside a WTB. CFRP principal directions: 1 (longitudinal), 2 (transverse) and 3 (through-thickness). The component dimensions (down-conductor, spar, EB-BIAX) are show on the 2-3 sectional view. The majority of the damage is observed at the entry edge of EB (*x* = 40 m) due to excessive Joule heating and at the end of EB (*x* = 35 m) due to breakdown of the insulation gap between down-conductor and spar, as indicated on 1-2 sectional view. Section *x* = 40 m is used in Figures 9,10,12,13.

Part of the EB section around the EB/down-conductor interface at the tip is shown in Figure 9. The increase in through-thickness conductivity due to GO addition, appears to be moderate (threefold increase). Nevertheless, even such an increase results in current spreading evenly through the EB cross section, reducing the peak current density at the top layer by 50%, and the associated Joule heat by a factor of 2.



**Figure 9:** Cross-section current distribution at the EB/down-conductor interface at the tip (*x* = 40 m): (a) UD CFRP with neat epoxy and (b) UD CFRP with GO-filled epoxy. Modelling approach from [52] was used.

The addition of GO into the epoxy also affects the peak temperature in the EB where, a drop from 200 oC to 120 oC (see Figure 10) is observed, rendering such a simple design fit for purpose. Note that the temperature distribution around a thin (~ 50 μm) surface layer in the GO-filled epoxy EB is much smoother (Figure 10b) compared to the neat epoxy EB (Figure 10a). This makes thermal strain and the associated interfacial debonding less likely.

Overall, the introduction of GO into the epoxy in EB presents clear benefits that, combined with a simple design and low-cost manufacturing, outweigh any additional complications related to the introduction of nanoparticles into such components.



**Figure 10:** Cross-section temperature distribution at the EB/down-conductor interface at the tip (*x* = 40 m): (a) UD CFRP with neat epoxy and (b) UD CFRP with GO-filled epoxy. Modelling approach from [52] was used.

***Biaxial (BIAX) CFRP case***

Apart from the thermal performance, the addition of GO also reduces the electric field in the air at the edges of the spars, thereby reducing the probability of streamer formations inside the blades (see Figure 11b). Taking into account potential electric stress concentration, CFRP containing neat epoxy may experience breakdown, whereas GO-filled epoxy leads to a reduction of ~20% in the electric field. Nevertheless, higher electric field values are reached under the subsequent short stroke due to its steep rate of rise of current (*di/dt*), which may exceed the breakdown strength of the insulation gap between the down-conductor and the spar. The correlations between voltage and the current variations (*di/dt*) can be explained by the equivalent circuit in Figure 2. Low frequency components of the lightning current are taken by the down-conductor because resistances *Reb* << *Rdc* << *Rspar*, whereas high current lightning pulses are mainly propagating through the spar because reactances *Xdc* >> *Xspar* >> *Rspar*. Therefore, the current split between the spar and the down-conductor for the steep rate-of-rise of current (*di/dt*) is a function of the reactances *X*, i.e the rate (*di/dt*). This current goes through the EB (resistor) with the voltage drop *V12*= *Ispar*(*t*)·*Reb*. The *Ispar*(*t*) is determined by the reactance (i.e., structural features of the blade), thus in order to drop *V12* below the breakdown value the *Reb*needs to be reduced.

A potential solution to this is to increase the transverse conductivity of the EB. CFRP materials can be made more isotropic in the in-plane directions, by utilizing multi-layered composites with different fiber orientations. An example of such components are the commercially available BIAX products [52], [56], [57]. As expected, the lower resistance reduces the field by a factor of 100 (Figure 11c compared with 11b), since the conductivity of BIAX CFRP is two orders of magnitude higher than UD CFRP.



**Figure 11:** (a) Location of high electric field (*x* = 35 m); Transverse electric field (*Ey*) distribution for (b) UD CFRP EB and (c) BIAX CFRP EB.

While BIAX CFRP eliminates flashovers, the significantly higher current density (Figure 12a compared to Figure 9a) leads to higher temperatures (Figure 13a compared to Figure 10a).



**Figure 12:** Cross-section current distribution at the EB – down-conductor (BIAX) interface at the tip (*x* = 40 m): (a) CFRP with neat epoxy and (b) CFRP with GO-epoxy. Modelling approach from [52] was used.

The major difference, here, is the concentration of the current towards the outer edge of the EB which, in turn, leads to excessive Joule heating and higher temperatures at this edge. The addition of GO rectifies this via evenly distributed current within the EB (Figure 12b), thereby, reducing the temperature rise (Figure 13b).



**Figure 13:** Cross-section temperature distribution at the EB – down-conductor (BIAX) interface at the tip (*x* = 40 m): (a) CFRP with neat epoxy and (b) CFRP with GO-filled epoxy. Modelling approach [52] was used.

The versatility of nanoparticles such as GO in tailoring electrical and thermal properties is therefore demonstrated, by the fact that such systems can be readily used in various fiber layups, under equivalent manufacturing processes, depending on the component of interest.

**CONCLUSIONS**

Wind energy is at the forefront of the sector’s transition to a greener future. While this is being driven by the exploitation of more locations, it is apparent that for the move to ever larger and more powerful components, the deployment of polymer engineering and nanocomposites is crucial. However, the development of units with power outputs above 10 MW requires the use of WTB that are more than 100 m in length, with consequent increases in tip velocities and an increased propensity to be struck by lightning. Conventional EB designs can be readily used in conjunction with GO-filled epoxy composites, since the addition of GO does not significantly change the total current going through the EB and the spar. The current density is evenly distributed so that the temperature rise in hot spots is significantly reduced by the introduction of GO-filled epoxies. Furthermore, the increased conductivity of CFRP results in smaller potential drops in the EB, reduces surface electric fields and eliminates surface flashover discharges. Those combined thermal and electrical effects of GO-filled epoxies on the system performance renders such systems a promising and cost-effective alternative to other types of EB materials (e.g., metal foil mesh, etc.).

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A person wearing a suit and glasses

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