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Article

A Review of Current Issues in State-of-Art of Wind Farm Overvoltage Protection

Petar Sarajcev * and Ranko Goic

Mechanical Engineering and Naval Architecture, Department of Power Systems, Faculty of Electrical Engineering, University of Split, Ruđera Boškovića bb, HR-21000, Split, Croatia;
E-Mail: ranko.goic@fesb.hr

* Author to whom correspondence should be addressed; E-Mail: petar.sarajcev@fesb.hr;
Tel.: +385-21-305806; Fax: +385-21-463877.

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Abstract: This paper elaborates on several important outstanding issues in the state-of-art of overvoltage protection selection for modern wind farms. The lack of experience with this still-new technology, together with the inherent complexity of wind farm electrical systems, entails several unresolved issues pertinent to the topic of overvoltage protection, particularly in relation to lightning-initiated surges. Firstly, several aspects of the wind turbine lightning incidence, along with the issues related to the selection of lightning current parameters (pertinent to the wind farm overvoltage protection), are addressed in this paper. Secondly, several issues in the state-of-art models of the wind farm electrical systems—for the lightning surge analysis—are addressed and discussed. Here, a well-known ElectroMagnetic Transients Program (EMTP) software package is often employed, with all of its benefits and some limitations. Thirdly, the metal-oxide surge arrester energy capability and the issues related to the selection of the surge arrester rated energy—in relation to the direct lightning strikes to wind turbines—is addressed. Finally, some general considerations concerning the overvoltage protection selection for wind farm projects, particularly regarding the installation of the metal-oxide surge arresters, are provided as well.

Keywords: EMTP model; lightning; overvoltage protection; risk of failure; surge arresters; wind farm

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1. Introduction

Wind farms are probably the single most significant contributors to the production of "green" renewable electrical energy, with additional capacity increases planned for the near-future. They are often constructed with dozens to several tens of individual wind turbines of ever increasing power. Modern wind turbine generators are already in the several MWs range [1]. Wind turbines are often spread across several square kilometers, thus covering very large surface areas. They are also often mutually interconnected by buried medium voltage (MV) cable networks. Hence, an electrical grid is created for collecting the produced power from individual wind turbines and transmitting it to the high voltage electrical power system. This gives rise to the complex, mutually interconnected, electrical system.

Wind farms are often located in regions which might span across mountain ridges or in other areas of elevated ground, where the wind resource is significant [2]. However, these locations in-turn often coincide with high keraunic levels and additionally usually have relatively high soil resistivity (often in excess of thousand Ωm in some parts of the southern Europe). Due to the fact that wind turbines (WT) present very tall and isolated objects, exposed to direct lightning strikes, they present extremely vulnerable structures (from the LPS standpoint), and in fact tend to get struck by lightning very often [2–4]. Hence, high lightning strike incidence, combined with high soil resistivity, can have adverse effects on the performance of individual wind turbines and on the wind farm as a whole. This aspect will be addressed in the paper.

Lightning is a rather complex and stochastic natural phenomenon which still attracts interest from researchers around the world. The occurrence of lightning in wind farms is influenced by several different factors, such as the charge structure of the thunderclouds, the height of the cloud base, prevailing thunderstorm approach direction, geographical location, the altitude above the sea level, of the wind farm site, seasonal and even diurnal variations in lightning activity, topographical and orographical effects, *etc.* [5]. With respect to tall structures (such as wind turbines) lightning can be classified into two main types: upward- and downward-initiated. These two forms of lightning can be further subdivided into positive and negative polarity, respectively; the polarity being that of the charge transferred from the cloud to the ground. Significant differences exist between downward- and upward-initiated lightning strikes [5].

According to the research of Eriksson, among others, it could be argued that wind turbines—as tall objects reaching beyond 100 meters in height—experience upward initiated lightning strikes to some extent [6]. This has been corroborated with observations and measurements of lightning strikes on wind turbines, carried out at different wind farms throughout the World, e.g., [7–9]. Hence, this fact would necessitate describing the lightning current parameters (*i.e.*, the log-normal distribution) which is associated solely and particularly with strikes to wind turbines. The selection of proper/appropriate lightning current parameters (amplitude, front duration and wave duration) for the overvoltage protection analysis of wind farms is still a matter of ongoing research. Implications of these factors have been studied as well in, e.g., [10].

Furthermore, the problem of determining the lightning incidence of modern wind turbines is itself exacerbated by several peculiarities, some of them associated with tall structures in general [11], and some specific to wind turbines in particular [12]. One such peculiarity arises from the fact that the

blades in wind turbines rotate, which introduces new effects and complexity, specific to wind turbines, and not found in other tall structures. It has been speculated for some time that upward-moving wind turbine blades could initiate their own upward lightning [12]. However, this has not yet been confirmed. The upward-initiated lightning could have influence on the lightning incidence of wind turbines. This issue will be briefly addressed in this paper as well. A more detailed and in-depth analysis could be found in [10].

Another lightning-related issue could be prominent in the wind farms constructed on terrains having high soil resistivity. This is the lightning incidence of MV power cable networks associated with the wind farms. However, it could be stated that these potential problems have not attracted significant attention, probably due to the fact that, e.g., Germany, Spain and Denmark, as the main producers of wind power in Europe, do not experience these problems (because of generally low soil resistivity on their wind farm locations). Namely, the lightning strikes terminating on the ground surface could end-up on the MV cables and produce damage to their outer or even main insulation. In order for this to happen, the lightning needs to strike at some (close) distance from the cable route. This issue will be addressed briefly in the paper as well.

Overvoltage protection analysis and verification of the surge arrester efficiency, for the power system equipment, have often been tackled by means of the well known ElectroMagnetic Transients Program (EMTP) software package [13,14]. This platform has been, in fact, widely used since the 1980s—in conjunction with the increased usage of digital computers—in lightning and switching surge analysis of high voltage electrical power systems. The main concern in its application in the overvoltage protection analysis of wind farm electrical systems is the development and usage of appropriate system component models, along with their mutual interconnection and interaction, e.g., [13–16]. Hence, the main problems in lightning surge analysis of wind farms could be seen in the proper application of appropriate EMTP models for each of the individual components of the rather-complicated wind farm electrical system.

One such model is presented in [16]. According to [16], the EMTP model of a wind farm electrical system—for lightning surge studies—could be decomposed into the following main parts: (i) model of the lightning surge current; (ii) model of the lightning surge channel; (iii) model of the wind turbine, which includes models of wind turbine blades, tower and possibly other associated electrical equipment; (iv) model of the wind turbine grounding system; (v) model of the cable lines; (vi) surge arrester model, including the connecting leads; (vii) transformer model and (viii) models of other electrical equipment if needed, e.g., WT generator. It can be seen that there is a significant number of components, which need to be modeled for high frequencies, associated with lightning transient analysis. Furthermore, each of the above mentioned components have several individual and influential factors which determine their transient behavior, e.g., frequency dependence, non-linear behavior, *etc.*

Furthermore, wind farm topology and other factors influence its overvoltage protection selection [17]. On top of that, there are several different arrangements of wind turbine systems: generators producing power at the medium voltage level, e.g., 12 kV, thus removing the need for the step-up transformer; generators producing power at low voltage level, e.g., 600 V, thus having a step-up transformer, which could be located in the wind turbine tower base or in the adjacent housing. Consequently, all these aspects need to be accounted for when analyzing the overvoltage protection for a wind farm,

particularly from the viewpoint of the lightning-associated surges, e.g., [16,18,19]. A prominent feature of wind farm overvoltage protection is a so-called back-flow surge—initiated by the direct lightning strike to the wind turbine—which needs to be accounted for and appropriately addressed [16,17,19–25]. Additionally, the lack of experience with this rather new technology is another obstacle. Hence, several problems associated with these aspects of the lightning surge protection selection for wind farms will be addressed in the paper.

Metal-oxide (MO) surge arresters provide the crucial means of surge protection for wind farm equipment, both from switching and lightning overvoltages. The main concern in wind farm overvoltage protection comes from the lightning overvoltages, which are the consequences of the direct lightning strikes on the associated wind turbines [17,21]. Transient behavior of the electrical micro-system of the wind turbine could have significant influence onto its overvoltage protection selection. Hence, very detailed models of the wind farms (including detailed models of the WT internal elements)—as briefly mentioned above—are needed to facilitate the numerical verification of the MO surge arrester capabilities in protecting the wind farm electrical equipment.

Furthermore, the energy capability of the MO surge arresters depends both on the switching and lightning overvoltages. It could be argued that the energy capability required of MV surge arresters installed in wind farms often stems from the lightning surges, unlike with the surge arresters installed in typical MV distribution networks (where switching surges could dominate), e.g., [15,21,26]. Hence, a selection of energy capability, in regards to the lightning overvoltages, for the wind farm MO surge arresters is of particular importance. A statistical approach could be employed in determining the MO surge arrester lightning surge energy capabilities [15,27]. This aspect will be addressed in the paper as well.

The paper itself is organized in the following manner. In Section 2, the issues pertinent to the lightning incidence of modern wind turbines is addressed and discussed. Section 3 addresses several issues present in the various models of the wind farm electrical systems and their usage in the lightning-related analysis. Here, particular emphasis is given to the peculiarities related to the application of the EMTP software package in the numerical simulations of wind farm lightning surges. In Section 4, the issues related to the selection of the MO surge arresters for wind farm projects are addressed, with particular emphasis on their needed energy capability (in regards to the lightning surges). Finally, in the Conclusions and Discussion section of the paper, some general considerations about overvoltage protection selection for wind farm projects, and its analysis, are provided.

2. Issues Related to Lightning Incidence of Wind Farms

Some important issues related to the lightning incidence of wind turbines will be addressed hereafter. The issues pertinent to the lightning-initiated damage of underground MV power cables, associated with wind farm projects, will also be briefly addressed here as well.

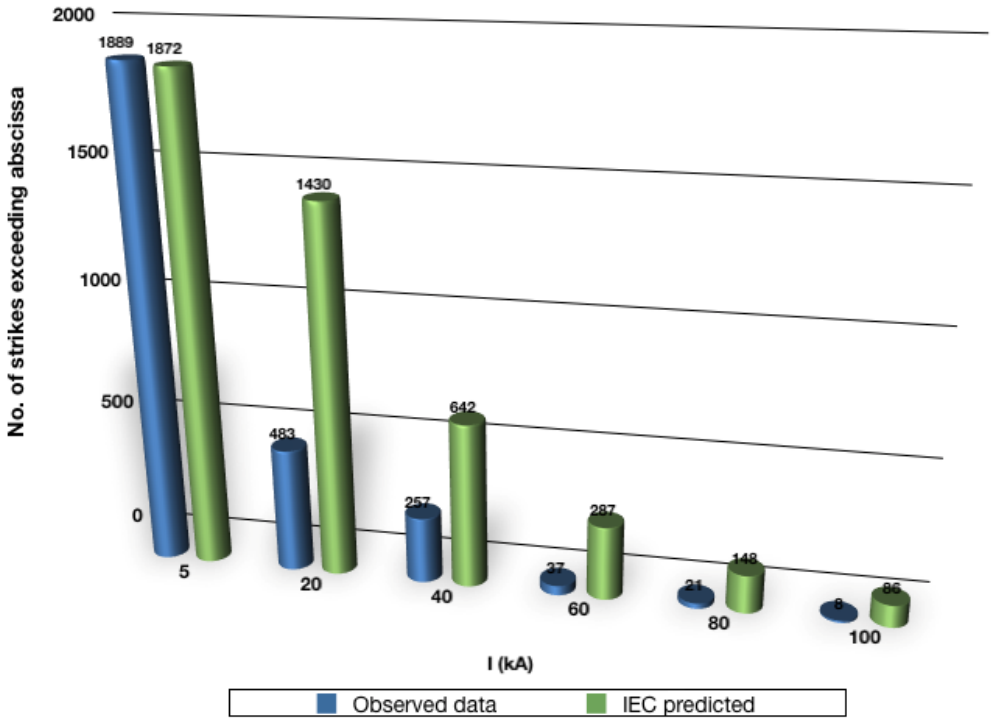
2.1. Lightning Incidence of Wind Turbines

Modern wind turbines generally reach heights (tower height up to the hub plus one blade length) in the 120 m to 170 m range. It needs to be pointed out that the latest WTs on the market now reach heights in excess of 170 m, with possible trends of extending this even further, e.g., [28]. This

"growth" of the WTs is fuelled by the intense demand for ever increasing power output from the installed generators. According to Eriksson's research on data gathered from tall, free-standing structures, among others, this would mean that the WTs will experience upward-initiated lightning strikes to some extent [6]. Hence, when assessing the lightning incidence of modern wind turbines one should account for both, upward- and downward-initiated lightning strikes, e.g., [10].

In order to put things into perspective, Figure 1 depicts the actual measurement data, gathered from real wind farms, and compared with data obtained by the IEC TR61400-24:2002 [4]. This Figure, obtained from the data presented in [8], represents a cumulative distribution of lightning strikes exceeding different current amplitudes, and incident on wind turbines. It is clear from Figure 1 that there is a discrepancy between the IEC predicted values and the actual measurement data, particularly in the high-amplitude region [8]. Although TR61400-24:2002 has been superseded by the official release of the IEC standard 61400-24:2010 [29], this comparison still holds valuable information.

Figure 1. Comparison of lightning current amplitudes obtained from IEC prediction and those actually observed on the wind turbines.



Due to the significant number of upward-initiated lightning strikes seen in WTs, there is a clear tendency that the statistical distribution of lightning current amplitudes—pertinent to the WT incidence—will be associated with lower median values, as has been already observed from several wind farm measurements [7–9]. It is also known that the median current amplitudes associated with upward-initiated lightning have values in the range between 8 kA and 12 kA [5]. On the other hand, it is generally accepted that a downward negative lightning is often associated with amplitudes having a median value of around 30 kA [30]. This latter value is often used in lightning-related analyses of high voltage (overhead) transmission lines. Hence, as has been noted in the Introduction, it would seem necessary to derive the unique set of parameters of the appropriate log-normal distribution, specifically

tailored for the lightning incidence of wind turbines, which would account for both, the upward- and downward-initiated lightning strikes (and their relative proportion; see also the Figure 1). Furthermore, other lightning current parameters (front duration or steepness, wave duration, charge transferred, *etc.*), associated with WT incidence, should be derived from measurements carried out on actual wind farms. They would certainly differ from those provided for the HV transmission lines. However, both the IEC TR61400-24:2002 [4] as well as the current IEC 61400-24:2010 [29] apparently neglect to fully consider these implications.

One final remark is in order, which pertains to the latest measurement results obtained from a wind park in Japan [7]. Observations of lightning incidence reported in [7] reveal the fact that approximately 30% of lightning strokes end-up simultaneously on two or more wind turbines in the wind park. This might influence the subsequently derived lightning current parameters as well.

Furthermore, as a concrete example of the influence of the upward-initiated lightning strikes on the lighting incidence of wind turbines, let us examine the modern WT having a total height of 170 m (tower height plus one blade length). Let us, thus, compare the lighting incidence of this WT (situated on flat ground) computed by implementing the IEC standard [29], in combination with Anderson's approximation [30], and the analysis presented in [10] (which accounts for the upward-initiated lighting strikes). The WT is situated in the region described with a ground flash density of 4 strikes/(km^2·year). Annually expected number of lightning strikes to this WT, according to the IEC recommendation, could be estimated with the following expression [29]:

$$N_{IEC} = N_g \cdot C_d \cdot (9\pi \cdot H^2) \cdot 10^{-6} \cdot P_{down}(I) \tag{1}$$

where N_g—ground flash density, strikes/(km^2·year); H—WT height, m; C_d—orographic coefficient which is equal to one for WTs situated on flat ground; $P_{down}(I)$—Anderson's approximation to the cumulative probability distribution function of the log-normal distribution for the (negative) downward lightning current amplitudes, e.g., [30]:

$$P_{down}(I) = \frac{1}{1 + \left(\frac{I}{31}\right)^{2.6}} \tag{2}$$

On the other hand, the approach presented in [10] provides the following expression for the estimation of WT lighting incidence (combined negative upward- and downward-initiated lightning strikes):

$$N_{EMP} = 0.9 \cdot N_g \cdot 24 \cdot H^{2.05} \cdot 10^{-8} \cdot \left[p_u \cdot P_{up}(I) + (100 - p_u) \cdot P_{down}(I)\right] \tag{3}$$

with:

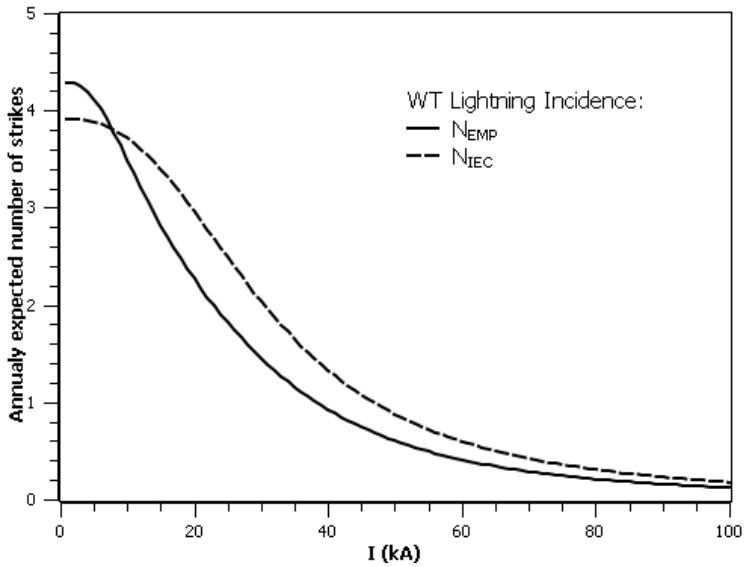
$$p_u = 52.8 \cdot \ln(H) - 230 \ (\%) \tag{4}$$

representing the percentage of upward-initiated lightning strikes as a function of WT height. The expression (4) has been derived by Eriksson on the basis of the measurement results gathered from different free-standing structures and is valid up to the height of *ca.* 500 m, [6]. The following approximation to the cumulative probability distribution function of the log-normal distribution for the upward-initiated lightning current amplitudes could be employed [10]:

$$P_{up}(I) = \frac{1}{1+\left(\frac{I}{12}\right)^{2.7}} \tag{5}$$

However, it should be mentioned that the expression (5) was originally derived for the amplitudes of the subsequent (negative) downward lightning strokes [30]. As an approximation, it could be employed for the upward-initiated lighting strikes as well [10]. Hence, in accordance with the expression (4), approximately 40% of all lightning strikes to this WT would be upward-initiated lightning. The obtained computational results, providing the WT lightning incidence, are presented in the Figure 2.

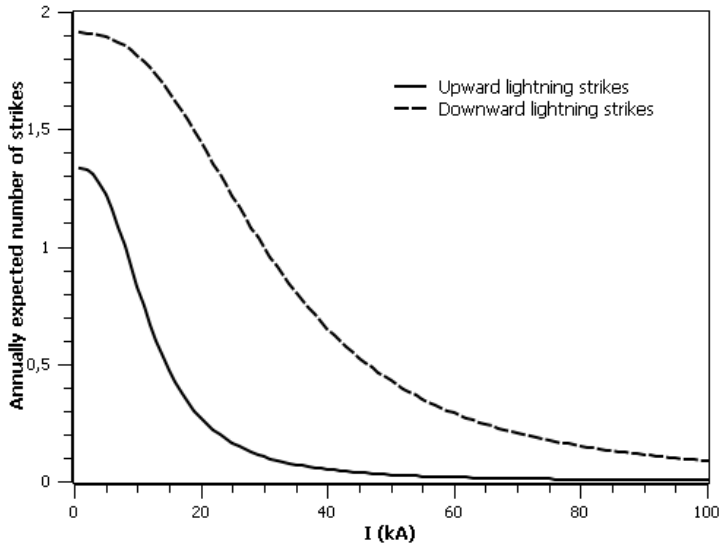
Figure 2. Comparison between wind turbine lightning incidence obtained from the IEC 61400-24 [30] and the analysis presented in [10].



According to the data from the Figure 2 it is clear that the number of lightning strikes to this WT, predicted with the analysis presented in [10] and IEC 61400-24 [29] are somewhat different, which has been already confirmed in Figure 1. Analysis presented in [10] predicts a larger number of lighting strikes on this WT, having low current amplitudes (below some 10 kA), then the relevant IEC standard. On the other hand, IEC predicts a larger number of lightning strikes having medium-to-high current amplitudes (above some 10 kA). According to both Figures 1 and 2, there is a tendency which suggests that the current IEC 61400-24 [29] somewhat exaggerates the WT lightning incidence in favor of the high-amplitude lightning currents. This would have repercussions on other subsequently carried out lightning-related analysis, including the selection procedure for wind farm surge arresters.

Let us finally examine the relative proportion of upward- and downward-initiated lightning strikes to this WT. This has been carried out in accordance with the empirical equation (3), with expression (4), and with the introduction of the above described input data. Subsequently obtained computation results are graphically displayed in Figure 3. It is quite clear from this figure that the annual expected number of upward-initiated lightning strikes exceeding a current amplitude of some 50 kA is extremely small.

Figure 3. Lightning incidence of the wind turbine in respect to the upward- and downward-initiated lightning strikes.



2.2. Lightning Incidence of MV Cables

The situation where wind farm locations are accompanied by high soil resistivity of the terrain (e.g., some parts of the Southern Europe) they provide favorable conditions for lightning-initiated damage of the associated wind farm MV cable networks. This is due to the fact that soil ionization and subsequent propagation of lightning currents through the soil is considerably affected by the soil resistivity. In highly-resistive soils, lightning currents could propagate for considerable distances in the ground, terminating at the buried cables. This could in turn produce damage to their outer insulation (*i.e.*, cable jacket). Two methods for the estimation of the lighting incidence of buried cable lines are presented and compared in [31]. They have been applied to wind farm cable networks.

If the lightning strike penetrates the cable jacket, the subsequent lightning current in the cable screen gives rise to the impressed electric force along the inner surface of the screen, thus creating the resultant (traveling wave) voltage difference between the screen and the phase conductor (*i.e.*, voltage stress of the main cable insulation). If this voltage difference exceeds the insulation strength of the cable (*i.e.*, BIL of the cable insulation), damage to the main cable insulation is an obvious result. At the point of damage to the cable main insulation, a new pair of traveling waves is established, which now emanate in both cable directions. These traveling waves are now formed on the cable screen and on the phase conductors. Due to the fact that cable screen has significantly higher surge impedance then the phase conductor, traveling waves on the cable screen and phase conductor will experience different attenuation and propagation effects, e.g., [31]. Hence, a traveling voltage difference between the cable screen and a phase conductor (hence, across the cable main insulation) will start to form from the point of the last insulation breakdown. This overvoltage will increase with the traveling wave propagation distance along the cable. Consequently, it might increase in excess of the main cable insulation strength (*i.e.*, cable BIL), thus causing additional/subsequent insulation breakdown (damage). Several of these subsequent insulation breakdowns could happen, owing to several different influential factors, e.g., cable design, lightning current amplitude, soil resistivity, *etc.*

It needs to be highlighted here that, due to the shielding effect of wind turbines, not all cables in the wind farm could be struck by lightning. However, parts of the cable network in-between the distantly positioned wind turbines and particularly the cables connecting the (parts of) wind farm to the MV/HV transformer station are certainly exposed to lightning strikes. According to the analysis presented in [31], it is expected that a characteristic wind farm cable network of, e.g., 20 km buried in 2000 Ωm soil (implementing ground level lightning current distribution) will experience approximately 1.7 lightning strikes every year. This is, statistically speaking, certainly not an insignificant number. In terms of the number of lightning strikes per 100 km of cable per year, this would mean that between 8 and 9 strikes could be expected [31]. Finally, it needs to be pointed out here that not all of these lightning strikes will damage the cables, but some cable damage due to lightning could be expected during the normal life span of the wind farm cable network.

Several general measures have been proposed, by various researchers, in order to mitigate this unfavorable situation for lightning-endangered cable networks, which could be equally-well applied to wind farm cable networks, e.g., [32–35]. According to the aforementioned references and furthermore in line with the established practices regarding the cable construction, the measures for protecting the underground cables from lighting could be classified as follows [31]: (i) use of cables having special construction elements to mitigate the lightning damage; (ii) installation of additional grounding (*i.e.*, shielding) wires above or in the vicinity of cables; (iii) routing the cables through specially constructed metal pipes; and (iv) applying the MV metal-oxide surge arresters along the cable route. Some of these measures are rather expensive, while others might not be adequate for some applications. Discussion of these various measures and their applicability to wind farm projects is provided in [31].

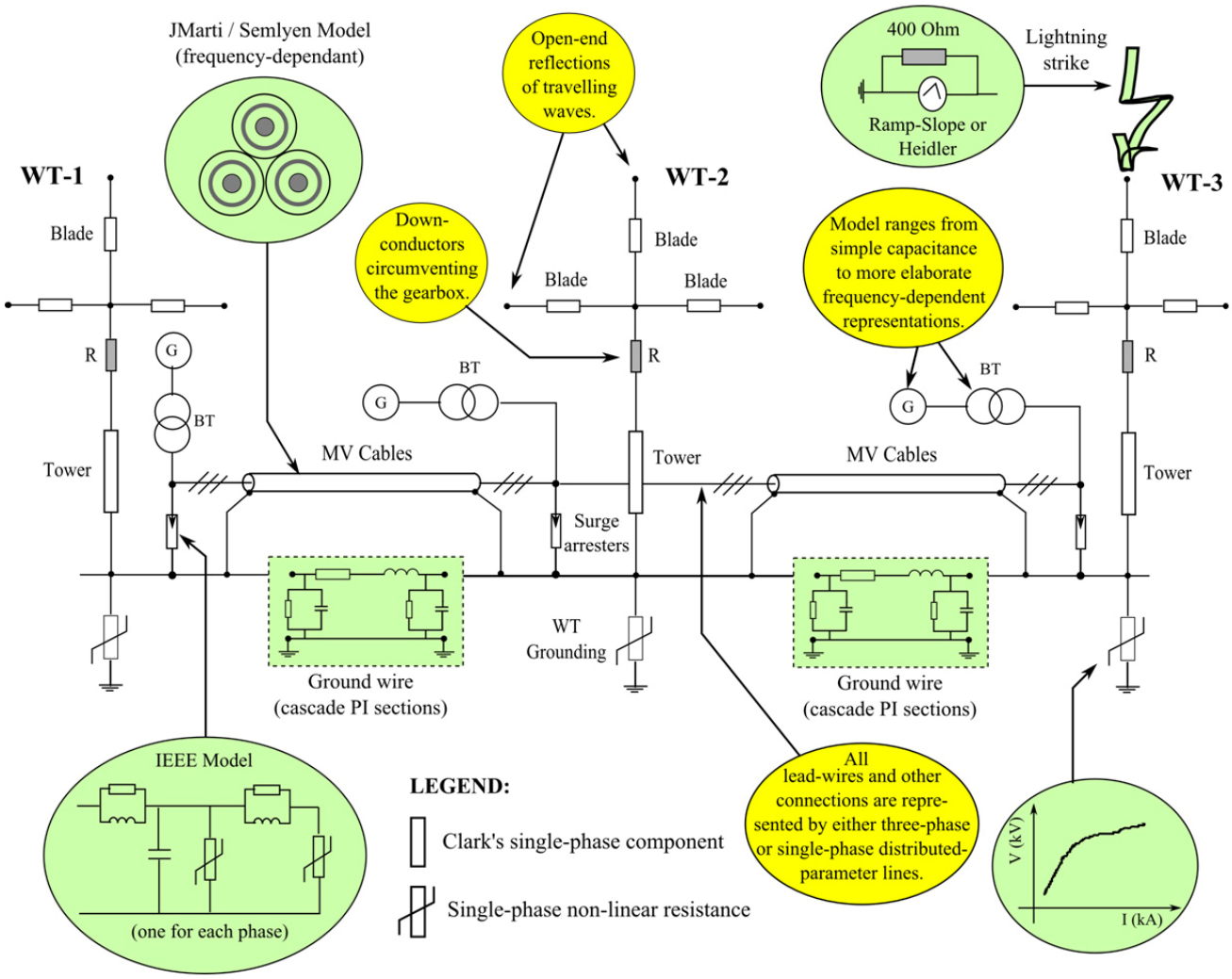
3. Issues Related to EMTP Models of Wind Farm Components

It has been already mentioned that the wind farm electrical system is complex. The data needed for these models are sometimes difficult to obtain; the reason for this is that it often consists of several different components, each needed to be appropriately modeled for the lightning surge analysis [15,16,21,36–41]. Moreover, wind farm component models are often frequency-dependent, non-linear or otherwise involve proprietary data belonging to the manufacturers. On the other hand, some wind farm component models are inherently complicated due to the nature of the associated phenomenon, such as for example the model of the wind turbine grounding system.

It has been said in the Introduction that the EMTP model of the wind farm electrical system consists of several different parts [16]: (i) model of the lightning surge current; (ii) model of the lightning surge channel; (iii) model of the wind turbine, which includes models of wind turbine blades, tower and possibly other associated electrical equipment inside the wind turbine (*i.e.*, lightning down-conductors); (iv) model of the wind turbine grounding system; (v) model of the medium voltage cable lines; (vi) surge arrester model, including the connecting leads; (vii) transformer model and (viii) models of other electrical equipment if needed (such as the WT generator).

As an example, Figure 4 depicts an EMTP model for the section of the wind farm which consists of three wind turbines connected with MV cables, e.g., [16]. Elements from Figure 4 are implemented in the EMTP software package using the appropriate models. Labels introduced in the Figure 4 have following meaning: G—wind turbine generator, BT—three-phase step-up transformer, R—surge impedance/resistance of lightning down-conductors circumventing the gearbox, if present.

Figure 4. Graphical depiction of the EMTP model for the section of the wind farm electrical system.



Three-phase components were employed, where appropriate, *i.e.*, MV cables, connecting leads, *etc.* Hence, this EMTP wind farm model incorporates a combination of three-phase and single-phase representations of various wind farm electrical components; some of those are frequency-dependant, while others are non-linear. More details could be found in, e.g., [16]. More general and in-depth treatment of various electrical power-system components can be found in, e.g., [15,37].

Several most important aspects of the EMTP models for the mentioned wind farm electrical components will be addressed hereafter. Firstly, the EMTP software package—which is almost universally applied to the wind farm lightning-initiated transient analysis—has some limitations, which should be borne in mind. One important limitation has been pointed out by Ametani, for example, is concerned with the TEM mode of lightning surge propagation [41]. Namely, it is a well-known but often "forgotten" fact that the EMTP software package is based on the circuit theory approach—assuming the TEM mode of wave propagation—where the parameters of a circuit need to be provided for the simulation. However, there are some phenomena that include non-TEM mode of wave propagation, which would not be tackled by the circuit approach [41].

3.1. WT Grounding System

The single most important obstacle in applying the EMTP software package to wind farm lightning surge analysis is concerned with the appropriate modeling of the grounding systems for high frequencies and transients, which is a rather complicated matter that needs special treatment and attention. It is compounded by the fact that a non-linear soil ionization phenomenon often accompanies dissipation of large lightning surge currents through the grounding systems of small or modest surface area, such as those of wind turbines. Hence, soil ionization features prominently in lightning surge analysis and subsequently derived models of the TW grounding systems should account for it. Due to the inherent difficulty in analysing grounding system behavior under lightning strikes, various authors have resorted to different approaches, whose complexity varies significantly, from basic ones to quite elaborate ones, e.g., [15,16,41–43]. Table 1 provides a general comparison between different possible approaches in the transient grounding system analysis, with some of their merits and demerits [43].

Table 1. Comparison of different approaches for EMTP modeling the transient grounding system behavior.

General	**Grounding System Models**			
Complexity	**Electric Circuit**	**TLM**	**Electromagnetic**	**Hybrid**
Math. apparatus	Simple	Simple	Complicated	Fairly complicated
Comprehension	Very easy	Easy	Difficult	Fairly difficult
Solution procedure	Simple; Easy to include soil ionization; Can not predict wave propagation	Simple; Can include soil ionization; Can predict wave propagation	Complicated; Difficult to include soil ionization; Can predict wave propagation	Complicated; Difficult to include soil ionization; Gene-rally can predict wave propagation
CPU usage	Small	Small	Large	Fairly large
Accuracy	Least accurate	Fairly accurate	Most accurate	Fairly accurate
EMTP integration	Very easy	Easy	Very difficult	Difficult

It should be mentioned that the electric circuit and transmission-line models (TLM) could be rather easily incorporated into the EMTP software package, while the electromagnetic model could not. Hybrid models vary significantly, both in complexity and accuracy, as well as in the difficulty with which they could be incorporated into the EMTP solution procedure. Introduction of the soil ionization phenomenon is easier for some models than others [43].

A wind turbine grounding system can, during its transient state, exhibit either inductive or capacitive behavior, depending on the soil properties, geometry of the grounding system and the shape of the lightning surge current. The inductive behavior is undesirable, due to the fact that the impulse impedance of the system is larger than its low-frequency resistance (*i.e.*, the impulse coefficient is larger than unity) [44]. It is rather difficult to deduce, without the aid of a sophisticated time-consuming numerical analysis, what the behavior of the WT grounding would be, given a set of particular input parameters. On top of that, the above mentioned transient behavior changes with respect to several different influential factors (e.g., seasonal variations in soil resistivity, lightning current waveshape, *etc.*).

This complicates the derivation of the simpler and less sophisticated WT grounding models that could be acceptable for the lightning associated transient analysis. For instance, this was the reason behind the Japanese recommendation that the EHV transmission line towers (in the backflashover analysis) should be modeled as simple resistances [45].

Notwithstanding that, the problem of taking into account the transient behavior of the steel-reinforced concrete foundation of the WT—in modeling its grounding system—is not satisfactorily solved, *i.e.*, in such a manner that the model could be appropriately incorporated into the EMTP software package. Hence, there is still no general consensus regarding the adequate EMTP-type models of the WT grounding. One possible approach, which seems promising in this regard—although still not generally applicable—is presented in, e.g., [46].

3.2. WT Tower and Blades

Another matter altogether—also related to the EMTP models of wind farm components—is associated with the appropriate model of the WT tower and its blades. Nowadays, blades have special receptors for lightning attachment and conductors (as part of the LPS system) for conducting the lightning current to the WT grounding system. Furthermore, blades are made of material that is conductive when wet (fiberglass reinforced plastic). The EMTP-type models for these components, appropriate for the lightning surge analysis, are not readily obtainable. One possible approach to modeling the WT tower—which heavily rests on the existing models of the HV transmission line towers—is presented in [39]. Here tower and blades are represented as simple constant-value and distributed-parameter transmission lines (*i.e.*, the so-called Clark components in EMTP). Another possible approach is provided in, e.g., [40]. However, frequency-dependence of the tower as well as lightning surge attenuation on the tower and blades is not accounted for in these simple models. Here, again, there is no general consensus regarding the appropriate model of the WT tower and its blades.

A possible solution to this problem could be seen in following the paths set out in obtaining the models for the EHV and UHV transmission line towers (which include both frequency-dependence and surge attenuation), e.g., [45,47,48]. This, however, necessitates sophisticated, e.g., finite-difference time-domain (FDTD) models of complete wind turbines, compounded with the detailed experimental measurements carried-out on scale models, e.g., [47,48].

3.3. Step-Up Transformer and WT Internal Components

Yet another matter—which is ubiquitous in general power system lightning surge analysis—refers to the analysis of lightning transients transferred through the three-phase transformers. The EMTP model of the three-phase transformers for this (lightning associated high-frequency) analysis is rather well-known; although obtaining all of the data needed for its construction could be rather difficult, e.g., [15]. This is due to the fact that the internal design (and geometry) of the transformer must be known in detail, or the sophisticated measurements have to be performed on the transformer, in order to construct its high-frequency model, e.g., [15]. However, manufacturers of the wind turbines' step-up transformers consider this information proprietary, which makes it difficult for the overvoltage protection designer to accurately predict its transient behavior. Hence, it would be useful if the

manufacturers could provide the appropriate transformer models (for their own WT step-up transformers), which would be suitable for lightning surge analysis.

Furthermore, there are several uncertainties associated with modeling the wind turbine internal components, including the wind turbine generator, shaft bearings, low-voltage cables positioned vertically, *etc.*, [16,37,38]. Some of the difficulties encountered here arise again from the manufacturers' proprietary concerns, while others emanate from the general complexity of the matters at hand. Particular difficulties are associated with modeling of the main-shaft bearing and its lightning protection system, which must in-turn prevent lightning flashovers on lubricants (and electrical/thermal damage to the bearings). A recent, rather extensive and sophisticated, investigation into these issues is presented in [49]. According to this research, transient behavior of the main-shaft bearings could be modeled with an appropriate capacitance.

3.4. Three-Phase Single-Core MV Cables

There are also obstacles with modeling single-core three-phase MV cables in the EMTP software package. Although the EMTP employs very sophisticated frequency-dependent distributed parameter cable models (e.g., so-called JMarti or Semlyen models), it cannot readily accept all of the cable data needed for the rigorous simulation, [15]. Namely, the semiconductive layers below and above the main cable insulation could not be taken into account readily in the EMTP. Hence, a special procedure is devised in order to alleviate this problem, e.g., [15,50].

Notwithstanding that, it can be rather difficult to provide sufficiently accurate input parameters for cable system; due to the uncertainties in the geometrical data provided by the manufacturers (they usually provide guaranteed data but not necessarily the actual measures). Additionally, small geometrical distances involved in the cable data, with addition of complicated cable design—core, main insulation with semiconductive layers below and above it, screen of different designs (solid, stranded conductors, tapes), and outer sheath—complicate matters even further. Small variations in cable parameters, as well as neglecting the semiconductive layers, can have noticeable effects on the cable transient behavior [15].

3.5. Lightning Current and Channel

Finally, there are issues related to the selection of the EMTP models for the lightning strike. It is comprised of the ideal current source, which is analytically described by some of the following functions: double-exponential function, ramp-slope function, Heidler function, *etc.* [15,36,45]. The usage of the double-exponential function as a lightning current is nowadays considered discredited, while the Heidler function is often recommended. However, some researchers recommend using the Ramp-slope function instead of the Heidler function, e.g., [45]. Lightning channel is represented by the simple resistance, which is equal to the channel surge impedance, the value of which is often provided from the range between 400 Ω and 2000 Ω [15,16,45]. It is often recommended to adopt the lower value of the lightning channel impedance for lightning currents having high values, and *vice versa*. This resistance is connected in parallel to the above mentioned ideal current source.

It has been shown by several researchers that by using different lightning current waveforms (additionally in combination with different lighting channel surge impedances), different transient

overvoltages on the equipment could be expected, e.g., [15]. This should be borne in mind while carrying-out numerical simulations.

4. Issues Related to the MO Surge Arrester Selection

The MO surge arresters provide means of protecting wind farms from lightning (and switching) transients, although—due to their significant exposure to lightning strikes—the lightning-associated transient effects dominate. It can be stated that the MO surge arrester selection procedure is in itself a compromise in satisfying several mutually exclusive criteria, e.g., [51]. The selection of surge arresters for wind farms (at the MV level) having unfavorable conditions (high keraunic levels combined with high soil resistivity) should be treated as a special application, due to their emphasized exposure to direct lightning strikes.

Furthermore, surge arrester selection is concerned, not only with selecting the arrester electrical data, but with its installation (*i.e.*, positioning) within the wind turbine, thus assuring the satisfactory protective distances, e.g., [51,52]. Additionally, wind farm surge arresters need careful consideration on the part of the selection of their energy capability, particularly in relation to the lightning transients. All these aspects will be briefly discussed hereafter.

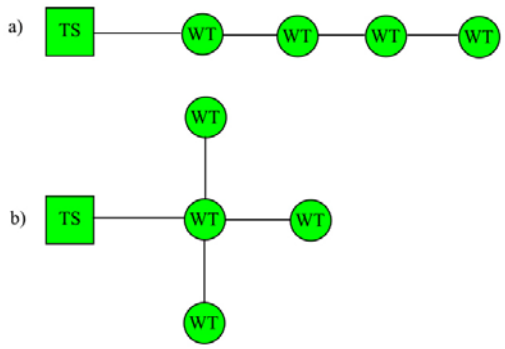
4.1. Wind Farm Topology

It has been mentioned in the Introduction that the main source of lightning-initiated overvoltages on electrical equipment (MV level) in wind farms comes from the so-called back-surge phenomenon, associated with direct lightning strikes on WTs, e.g., [16–20]. Namely, in the instance of the lightning strike on the WT, a transient overvoltage rise of the WT grounding produces a back-surge, which travels—through the connected MO surge arrester—from the WT grounding system to the phase conductors of the associated equipment. This means that the surge arrester in fact "brings" the overvoltage from the WT grounding onto the phase conductors (at the WT which has been struck by lightning). Subsequently, this transient overvoltage propagates, by means of phase conductors, through the wind farm electrical system, and dissipates to ground through the surge arresters installed at other WTs (see Figure 4), [16,17,19–25].

The topology of the wind farm electrical system bears significant influence on the obtained transient overvoltages in different parts of the wind farm, as well as the number and disposition of surge arresters. It is interesting to note that surge propagation in a wind farm electrical system is dominantly governed by the wind turbine arrangement rather than by the distance between the WTs. The cascade connection of WTs in the wind farm results in larger overvoltages on electrical equipment of the associated WTs (those which have not been struck by lightning). Hence, the parallel arrangement of WTs would seem favorable in this regard [17]. On the other hand, in high-resistivity soils, where any single WT grounding resistance could be rather high, a cascade arrangement might be preferable.

Figure 5 provides two simple possible examples of the wind farm topology: (a) cascade connection and (b) parallel connection (*i.e.*, star configuration) of WTs (where label TS represents a MV/HV transformer station). It should be noted here that the actual wind farm topology, in wind farms having dozens of WTs, is usually a combination of the aforementioned configurations.

Figure 5. Graphical depiction of the: (**a**) cascade and (**b**) parallel (*i.e.*, star configuration) wind farm topology.



The final determination of the wind farm arrangement/topology depends on numerous different influential factors (overvoltage protection being only one of them), such as for example: the topology of the terrain at the wind farm location, costs associated with MV cable networks, position of the transformer station (TS) in regards to the wind farm site, *etc.*

4.2. Selection of Surge Arrester Electrical Data

Selection of the surge arrester electrical data is based on a well-established procedure, e.g., [51–53]. There is nothing significantly contentious in this regard, even when applied to wind farm projects. However, proper application of the selection procedure itself is of a major importance. In that regard, different possible temporary overvoltages (TOV) should be considered and scrutinized when selecting surge arrester electrical data, particularly regarding those emanating from earth faults (while having accounted for the type of the system grounding, *i.e.*, solidly grounded, resistance grounded, reactance grounded or even isolated). Furthermore, TOVs resulting from the load rejection, loss of system ground reference, WT generator self-excitation and step-up transformer saturation interaction should be accounted for as well, e.g., [26]. Sometimes, even the combination of TOVs (*i.e.*, ground fault with Ferranti effect) should be also accounted for, depending on the concrete wind farm project.

Finally, it should be borne in mind that surge arresters do not protect wind farm electrical equipment from TOVs. On the contrary, they need to be able to withstand these TOVs. However, due to the fact that TOVs define the surge arrester electrical data, they will influence the selected arrester's protective levels, and therefore (indirectly) affect the overvoltage protection of the wind farm electrical equipment.

4.3. Surge Arrester Installation

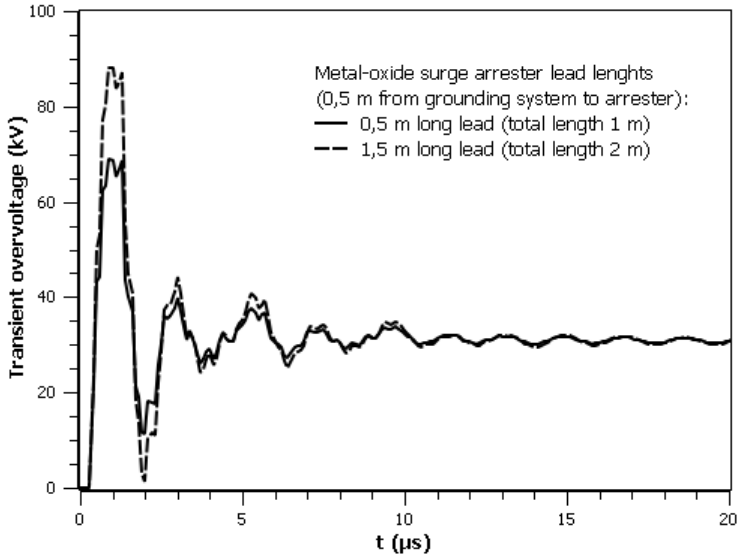
It is sometimes the case, where the wind turbine generator features its own step-up transformer—which is in-turn positioned at the tower base—that the space available for the additional electrical equipment (e.g., MV switchgear, surge arresters, *etc.*) in the tower base is significantly constrained, e.g., [54]. In cases where the step-up transformer is positioned in the nearby housing, these problems are eliminated, but additional ones are then introduced, e.g., [19]. Furthermore, step-up transformers positioned at the tower base are often the dry-type transformers, which are vulnerable to overvoltage stresses (*i.e.*, the non-self-restoring insulation).

Particular consideration should be paid to the length of the arrester connecting leads. The surge arrester should be positioned as close as possible to the step-up transformer, installed in the vicinity to the ground (grounding system) and connected with as short as possible (and possibly straight) low-inductivity conductors. This is often not technically feasible, due to the fact that the surge arrester needs to be installed in the, e.g., MV (sometimes gas insulated) switchgear compartment (due to the mentioned problems with space availability at the WT tower base), e.g., [54]. Here, the length of the electrical connections between surge arresters and step-up transformer, as well as the length of the arrester's own leads, influence the effectiveness of the obtained overvoltage protection (in relation to the lightning surges which are the consequence of the direct lightning strike to this WT). The transient behavior of the MV switchgear micro-system could have significant impact onto the effectiveness of the installed surge arresters in protecting the step-up transformer.

Hence, let us consider a following simple and typical example, e.g., see Figure 4. The MO surge arresters (U_n = 10 kV, U_r = 12.5 kV, I_n = 10 kA) are installed in the typical WT tower base, near the step-up transformer (HV transformer side). They are modeled according to the IEEE recommendation, e.g., [16], see also Figure 4. The grounding of the WT equals 30 Ω (e.g., soil resistivity of 2000 Ωm at the wind farm site), and is modeled as a non-linear resistance, see Figure 4. Four WTs are connected in series (*i.e.*, cascade connection) through a 400 m long three-phase single-core MV cables, forming an isolated portion of the wind farm. Cables are modeled with frequency-dependent distributed parameters, e.g., [16]. Lightning current with a 60 kA and 1/75 μs ramp-slope shape strikes the top of the last WT in this string/cascade. Lightning channel has a surge impedance of 400 Ω. Surge arrester leads are here modeled with 1 μH/m inductances.

Figure 6 provides a transient overvoltage at the phase conductors of the step-up transformer (HV transformer side), considering two different surge arrester lead lengths. It could be seen from the Figure 6 that the physical and electrical distances between the surge arrester position and the protected equipment, as well as its connection to the grounding system, has significant influence on the obtained transient overvoltages.

Figure 6. Influence of the arrester leads on the obtained transient overvoltages at the protected equipment.



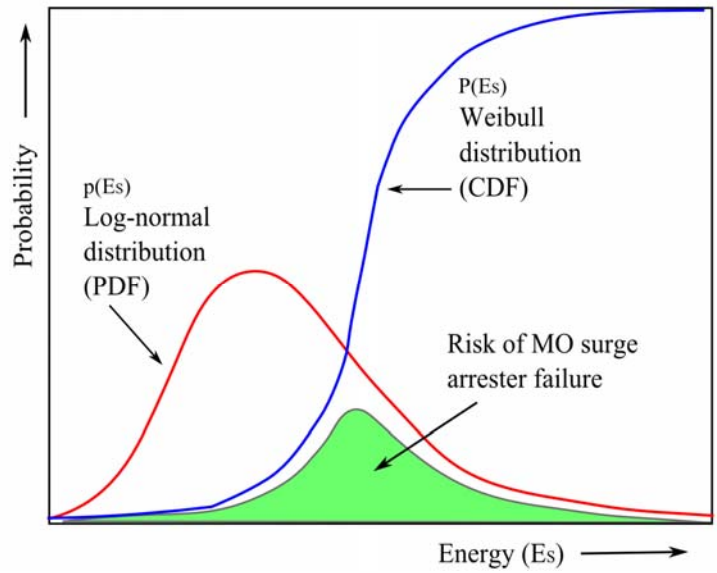
Furthermore, it could be argued that the proper EMTP models of the various MV switchgear components (compartments) are not readily known. Moreover, they could be rather difficult to procure due to the manufacturer's proprietary concerns. These effects have been neglected in the above provided analysis. However, the exact geometry of the switchgear compartment could be of importance here (*i.e.*, its transient behavior during lightning-associated transients), in addition to the actual disposition of the surge arresters.

4.4. Surge Arrester Energy Capability

The selection of the MO surge arresters for wind farm projects which are constructed on terrain with high soil resistivity (sometimes in excess of 2000 Ωm) and accompanied with high kearunic levels, is a formidable task. Particularly the needed energy capability of the surge arresters, in these unfavorable conditions (under the scenario of the direct lightning strike to the WT), could be significant. This rather extreme WT lightning exposure, combined with the rather high costs associated with equipment damage, necessitates sophisticated methodology in determining the MO surge arrester capabilities.

The analysis of the MO surge arrester energy capability—regarding the direct lightning strikes to WTs—could be seen in the application of the EMTP software package in conjunction with the statistical approach to the MO surge arrester energy absorption capability, e.g., [15,27,54–60]. This analysis in-turn stems from the statistical determination of the MO surge arrester risk of failure analysis, due to the excessive lightning energy absorption. The main concept behind the statistical approach to the MO surge arrester risk of failure is graphically depicted in Figure 7.

Figure 7. Graphical illustration of the statistical approach to the MO surge arrester risk of failure analysis.



According to the Figure 7, the risk of arrester failure is obtained from the probabilities associated with two statistically independent events: (1) arrester will fail due to some amount of absorbed energy, described by $P(E_S)$; and (2) that amount of energy will be dissipated through the arrester during the lightning strike, depicted with $p(E_S)$. The probability of the first mentioned event is analytically

derived from the Weibull distribution, while the probability of the second one is obtained from the log-normal distribution [27,55–58].

The probability of the MO surge arrester failure is provided by the cumulative distribution function (CDF), $P(E_S)$ in Figure 7, which in fact introduces the probability that the surge arrester will fail while absorbing the energy E_S in (kJ).

The cumulative distribution function of the arrester failure could be obtained from the Weibull distribution [15,27]:

$$P(E_S) = 1 - 0.5^{(Z/4+1)^5} \tag{6}$$

with:

$$Z = \frac{E_S / E_R - 2.5}{0.375} \tag{7}$$

where E_R is the rated energy capability of the MO surge arrester, as supplied by the manufacturer, provided in (kJ):

$$E_R = w_c \cdot U_c \tag{8}$$

In Equation (8), w_c is the arrester rated energy capability, kJ/kV and U_c is the arrester continuous operating voltage, kV; they are readily obtainable from the manufacturer's data sheets. The rated energy capability is assumed to have zero probability of failure and is located at four standard deviations below the mean value, according to [27]. It should be mentioned here that the behavior of the MO surge arresters, in regards to the lightning-associated energy stresses, is still not well understood, e.g., [15,27,59].

On the other hand, the probability that the energy stress E_S will occur, as a consequence of the direct lightning strike to the wind turbine, is provided by the probability density function (PDF), $p(E_S)$ in Figure 7. This PDF is modeled on the assumption of the log-normal distribution of energy E_S, with the following expression [55,58]:

$$p(E_S) = \frac{\exp\left[-\frac{(\ln(E_S) - \lambda)^2}{2 \cdot \beta^2}\right]}{\sqrt{2\pi} \cdot E_S \cdot \beta} \tag{9}$$

where λ and β are the parameters of the introduced distribution, *i.e.*, the expected value and the standard deviation of $\ln(E_S)$, respectively. These two parameters could be derived from the expected value and variance (or standard deviation) of the energy stress, E_S, using respectively the following general relations [55,58]:

$$\beta^2 = \ln\left[1 + \frac{V(E_S)}{E^2(E_S)}\right] \tag{10}$$

$$\lambda = \ln[E(E_S)] - \frac{1}{2} \cdot \beta^2 \tag{11}$$

where $V(E_S)$ and $E(E_S)$ are the variance and the expected value of the energy stress E_S, respectively. They could be in turn obtained from the following expressions [55,58]:

$$V(E_S) = \int_0^\infty \left[g(I) - E(E_S) \right]^2 \cdot p(I) \cdot \mathrm{d}I \tag{12}$$

$$E(E_S) = \int_0^\infty g(I) \cdot p(I) \cdot \mathrm{d}I \tag{13}$$

where the newly introduced function $g(I)$ describes the MO surge arrester absorbed energy *versus* lightning stroke current amplitude, and is obtained from the EMTP simulations (*i.e.*, $g(I) = E_S$). This function is unique for each specific MO surge arrester and further depends on the wind farm topology, wind turbine geometry, grounding of the wind turbine and other influential factors, contained within the EMTP model of the wind farm.

The joint probability of MO surge arrester experiencing the energy absorption level E_S—from the direct lightning strike to the wind turbine, having current amplitude I (kA)—and at the same time not being able to withstand it, indicates the probability of arrester failure at that energy level. It needs to be accentuated that these two occurrences are treated as statistically independent events. Hence, the risk of surge arrester failure is obtained from the following expression [27,53,55,58]:

$$R = \int_0^\infty P(E_S) \cdot p(E_S) \cdot \mathrm{d}E_S \tag{14}$$

Finally, the PDF, $p(E_S)$, introduced above is computed from the MO surge arrester absorbed energy results—obtained from the EMTP wind farm simulations—for various amplitudes of lightning stroke currents I (kA). This procedure has been elaborately described in [58].

Here, partial results, which have been obtained in [58], are reproduced for convenience. Namely, the estimated MO surge arrester risk of failure, computed for a part of the wind farm composed of three WTs interconnected in series (*i.e.*, cascade connection), is provided (e.g., see Figure 4). It is generally not likely that a single WT will become isolated from the rest of the wind farm and then stricken by lightning. This would, of course, produce the largest dissipated energy through the arrester, although this scenario might be exaggerated. It would seem more probable that the group of two or three (or even more) WTs might end-up being isolated from the rest of the wind farm, and one of them at the same time being struck by lightning. The larger the number of WTs in this isolated group the lower will be the energy dissipated by any single MO surge arrester, due to the fact that they assist each other in dissipating the lightning-produced energy. Hence, a compromise of sorts could be achieved by selecting, for example, three WTs as has been done here. Surge arresters having three different rated energies are considered in four different scenarios. The risk of failure is due to the direct lightning strike (1/75 μs or 1/150 μs waveshape) hitting one of the WTs, [58], having a 10 Ω or 30 Ω grounding resistance. The reader is advised to consult [58] for more information. Concrete results, reproduced from [58], are presented in Table 2.

Table 2. Risk of failure obtained for the MO surge arresters installed at the wind turbine stricken by lightning.

Scenario	MO Surge Arrester Risk of Failure		
	w_r = 2 kJ/kV	w_r = 4 kJ/kV	w_r = 6 kJ/kV
R_{DC} = 10 Ω 1/75 μs	0.50%	0.02%	0.00%
R_{DC} = 10 Ω 1/150 μs	6.14%	0.52%	0.08%
R_{DC} = 30 Ω 1/75 μs	0.97%	0.03%	0.01%
R_{DC} = 30 Ω 1/150 μs	11.56%	0.96%	0.13%

It can be seen for the Table 2 that the MO surge arresters having a rated energy of 2 kJ/kV have an 11.56% probability of failure. Surge arresters having higher energy level, such as those with 4 kJ/kV or even 6 kJ/kV, would be more favorable here, as can be nicely observed from Table 2. Additionally, it is obvious from the Table 2 that the larger WT grounding resistance brings with it more severe lightning energy stress on the installed surge arresters. Nevertheless, once the risk of wind farm surge arrester failure could be estimated, the costs associated with this risk (*i.e.*, the costs associated with the equipment damage, augmented by the costs of the undelivered electrical energy and other associated costs) could be minimized in a separate procedure. This procedure should in-turn provide means for the selection of the optimal MO surge arrester parameters for the concrete wind farm site.

On the other hand, the previously mentioned constraints—associated with the availability of the space at the WT tower base—might introduce difficulties in the selection of the MO surge arresters, regarding their energy capability (*i.e.*, the MO surge arrester rated energy capability), e.g., [54]. Namely, it is a known fact that the MO surge arresters, which are intended for installation in the MV switchgear compartment/cubicle, have low energy capabilities (they could not be as robust as the surge arrester for free-standing indoor application). These surge arresters, from various providers, are without exception of line discharge class 1 and, thus, consequently have a rather low energy capability. This is due to their slim design, which is of-course expected when one considers the fact that the energy capability of the MO surge arrester is proportional to the cross-sectional surface area of the ZnO discs. Hence, regarding the needed energy capability of the surge arresters, there is sometimes a need—at wind farm sites with high keraunic levels accompanied with high soil resistivity—for two of these class 1 surge arresters to be installed for each phase (at some of the WTs in the wind farm). This results in additional problems, associated with the performance and installation of parallel MO surge arresters, and often necessitates manufacturers' approval, e.g., [51].

From the presented analysis, it is rather obvious that significant undertakings, on the part of the wind farm designer, are expected and required in order to accommodate at least some of these above mentioned issues. Hence, sophisticated numerical models of the wind farm electrical systems—often constructed in the EMTP software package—provide useful tool in this regard, particularly in combination with the above presented statistical methodologies.

5. Conclusions and Discussion

The installation of the MO surge arresters (at MV wind farm level) is associated with several peculiarities which accompany wind farm projects, some of which have been introduced above. The lightning incidence at WTs is rather high and the associated energy stress on surge arresters (in direct lightning strikes to WTs) could be considerable. A sophisticated EMTP model of the wind farm electrical system should feature prominently in any analysis, as well as in the associated analyses of wind farm transient overvoltages. These analyses should include an estimation of the lightning incidence of WTs, modeling the impulse impedance of the WT grounding, defining the electrical layout of the wind farm and accounting for other influential factors (e.g., surge arrester installation including its connecting leads, MV switchgear, transformer, three-phase MV cables, *etc.*). However, it is evident from the above mentioned facts that this analysis is still limited by several unresolved issues. This could be of particular importance for the wind farms located in regions with high keraunic levels accompanied by high soil resistivity.

Generally speaking, the selection of the energy capability of the MO surge arresters (at MV wind farm level) depends on both switching and lightning overvoltages. However, it could be argued that the required wind farm surge arrester energy capability is significantly influenced by the lightning overvoltages, to which the wind turbines are heavily exposed. At the same time, sometimes it is not possible to fully optimize the surge arrester installation (due to the mentioned confinement issues). The trade-of between the arrester position and its energy capability features prominently here, due to the fact that those arresters intended for the installation into the MV switchgear compartments sometimes cannot satisfy the imposed energy requirements. On the other hand, those surge arresters (for indoor application) that could satisfy the imposed energy requirements usually cannot (are not intended to) be mounted into the MV switchgear cubicles. Hence, it would certainly be helpful if the manufacturers of the MV metal-oxide surge arresters—which are meant for the installation into the MV switchgear cubicles—could provide a wider selection of arresters having higher rated energy values (*i.e.*, higher line discharge classes).

Nowadays, it is quite evident that the major source of overvoltage stress on WT equipment (MV level) comes from the so-called back-surge phenomenon, which is associated with direct lightning strikes on the wind turbine (blades or even the nacelle). The surge arresters, installed at this stricken WT bring transient overvoltage from the WT grounding onto the phase conductors; this overvoltage subsequently propagates through the wind farm electrical network. Those WTs which are positioned at the electrical ends of the wind farm system have the most adverse conditions (regarding the lightning overvoltages) and need special treatment, both in the design of their grounding system, as well as in designing their overvoltage protection, *i.e.*, MV metal-oxide surge arrester selection.

Notwithstanding that, the topology of the wind farm electrical system features prominently in the distribution of the lightning-associated overvoltages, which propagate through the system. Namely, the surge on the lightning stricken WT decreases with lower grounding resistance, but the surge propagation to the distant WTs in the wind farm remains nearly unchanged. In fact, it is the topology of the wind farm that dominantly determines the surge propagation, not the distance between the wind turbines. Hence, the parallel connection of WTs presents a somewhat favorable arrangement, in contrast to the cascade connection, regarding the lightning surge propagation through the wind farm.

This should be, if possible, taken into account during the design phase of the wind farm projects (*i.e.*, planning the layout and interconnection of their MV cable/electrical systems).

Finally, experiences gathered from past wind farm projects, constructed throughout the World (particularly those on the seacoast of Japan), are being continually incorporated into new project developments. This is beneficial, particularly if seen from the standpoint of somewhat reduced availability of favorable new wind farm locations. This trend will probably increase in the future, due to the fact that the best wind farm locations get occupied first, thus producing adverse overvoltage protection conditions for newer wind farm projects. This can be combated by introducing effective overvoltage protection measures, inherited from the experience on past projects and fortified by extensive engineering scrutiny. Moreover, new wind turbine designs have introduced extensive measures to protect crucial equipment from lightning-generated overvoltages, for example: lightning receptors incorporated into the blades, as well as other LPS elements introduced into different WT parts, particularly blades and nacelle, such as the low-inductance down-conductors circumventing crucial parts of the WT (e.g., generator and gearbox if present), low-voltage SPD equipment, *etc.* All these measures have favorable influence in controlling the lightning-generated overvoltages and are helpful in acquiring the effective overall wind turbine overvoltage protection system.

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