ELECTROMAGNETIC ANALYSIS OF WIND TURBINE GROUNDING SYSTEMS

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ABSTRACT

Lightning has been reported to cause a large number of wind turbine failures and the grounding system of the wind turbine plays an important part in protection against this lightning damage. The design of the grounding system serves two main purposes. Firstly, the safety of personnel who are in the vicinity of the grounding system at the time of a lightning strike or power system fault must be ensured. Secondly, the lightning or power system currents must be dispersed into the ground while preventing large overvoltages.

In this paper the transient behaviour of wind turbine grounding systems are studied. The modelling and analysis capabilities of the general purpose program EMTP (Electro Magnetics Transient Program) have been investigated with necessary supporting calculations being developed. Simulation results are presented using both EMTP and a specialist grounding software, CDEGS (Current Distribution, Electromagnetic fields, Grounding and Soil structure analysis). Practical examples of grounding system designs are given.

1 INTRODUCTION

A windfarm, as any other electrical system, must be grounded to provide a low impedance connection between the electrical equipment and the general mass of the ground. The grounding system should ensure the effective operation of protective devices, provide a reference potential for electrical equipment and prevent excessive overvoltages and potential gradients that may cause damage to equipment or threaten human life.

Unlike conventional grounding systems that are relatively compact in size, the wide geographical area covered by a windfarm results in the windfarm grounding system spanning a considerable distance. This results in the inductive component of the grounding system impedance becoming large in relation to the resistive component. In addition, windfarms are often located in areas of high soil resistivity where a low impedance ground is difficult to obtain.

Standard methods to determine the impedance of a grounding system based on simple formula are unsuitable for windfarms owing to their distributed nature. This paper examines the use of computer modelling to assess the suitability of windfarm grounding systems for protection against power system faults and lightning strikes.

2 TYPICAL WINDFARM ELECTRICAL DESIGN AND GROUNDING REQUIREMENTS

A wind turbine typically contains an induction machine generator supplying a grounded star transformer winding at approximately 700V. The high voltage side of the local turbine transformer is wound in delta and is connected to the windfarm distribution cable. The windfarm cable system is then normally connected to a star transformer winding or equivalent at the windfarm substation. The star point is often grounded through a resistor to control the windfarm earth fault level.

A number of grounding requirements exist within a windfarm to protect both equipment and human life. The windfarm electrical protection, in the form of fuses or ground-fault relays require a certain fault current to operate. The lower the grounding system impedance of the windfarm, the more likely the protection is to operate since the prospective fault current will be higher and the easier it is to detect fault conditions.

Lightning strikes to a wind turbine will raise the local ground potential resulting in large differential voltages between the power cable phase conductors and armour/screen as well as the high voltage winding on the wind turbine transformer and the grounded case/low voltage winding. This differential voltage may be able to break down either the cable or transformer winding insulation and damage that piece of equipment. The lower the grounding impedance, the lower the voltage rise produced by the lightning strike leading to a lower likelihood of insulation breakdown.

An injection of current into the ground from either a lightning strike or a power system fault will result in potential gradients along the soil surface. The magnitudes of these potential gradients will depend partially on the grounding system impedance. As humans and livestock could be killed by excessive potential gradients, the ground impedance should be low enough to minimise the danger of lethal step and touch voltages.

3 RESPONSE OF A GROUNDING SYSTEM TO POWER SYSTEM FAULTS AND LIGHTNING CURRENT

Although the same grounding system is normally used for protection against both power system faults and lightning strikes, the response to either energisation source is dramatically different owing to the high frequency components contained in lightning current.

Lightning current is considered to have an average rise time of 5.5µs and a time to half value of 75µs with a peak current of 30kA [1]. This fast rise time results in high frequency components being injected into the grounding system. The grounding system inductance, significant in relation to the resistance for a large grounding system, causes these high frequency components to increase the total grounding impedance owing to the change in inductive reactance.

This effect means that the grounding system resistance is not valid in the determination of the voltages expected to result from a lightning strike since the inductive reactance is not accounted for. Power system faults where the frequency of the injected current is much lower than that in a lightning wave may also see some effect of the grounding system inductance although this will not be as exaggerated at this 50/60Hz.

4 USE OF ELECTROMAGNETIC FIELD MODELLING TO ASSESS THE RESPONSE OF AN GROUNDING SYSTEM

The fact that the grounding resistance, a commonly measured and calculated value, cannot be used to calculate the response of large grounding systems means that other approaches must be investigated. Such approaches include the use of electromagnetic field theory to model grounding systems and calculate their response to both low and high frequency excitation. Large grounding systems in soils of varying resistivity with current injection from a power system fault or a lightning strike can then be examined.

Two commercial software packages, EMTP and CDEGS, have been used to apply electromagnetic models to windfarm grounding systems. Both programs can simulate the response of a windfarm grounding system to low frequency, high frequency and transient current injections.

CDEGS is designed to analyse the response of a grounding system under both high and low frequency excitations. To analyse the response of the grounding system to a time domain transient, a fourier transform must be carried out to obtain the frequency spectrum. Once the grounding system response to these frequencies has been computed, an inverse fourier transform can be used to obtain the time domain response of the grounding system to this transient. This approach is detailed by Dawalibi [2]. CDEGS calculations involve an accurate representation of a grounding systems by the use of elementary segments. Various electromagnetic algorithms describe the electromagnetic fields in the surrounding area, complex mathematical expressions being translated in an effective computational algorithm.

Transmission line models, are widely used to effectively simulate grounding system behaviour especially when examining high transient conditions. By extending the capabilities of EMTP, the response of a grounding system to transient phenomena can be computed using transmission line models. The software package is able to model an extensive grounding systems. It is used by modelling the grounding system using a lumped parameter model with high shunt conductance or a frequency dependant distributed parameter transmission line model. The mutual coupling between grounding system components is accounted for by treating them as different phases of a transmission line. The application of both of these two models of grounding systems is based on numerical methods. The trapezoidal rule of integration is used, due to stability and accuracy properties.

5 TYPICAL WINDFARM GROUNDING SYSTEM

The grounding of a single wind turbine is normally achieved by placing a ring electrode around the foundation and bonding it through the foundation to the turbine tower. The foundation reinforcement bar is also connected directly or via the turbine tower to the ring electrode and will be effective in acting as an ground electrode since the surrounding concrete can be considered to have a resistivity equal to that of the surrounding soil [3]. However, it is normally ignored to provide a worst case analysis of the grounding system.

Vertical rods or strip electrodes (horizontal electrodes) are often used in conjunction with this ring electrode to achieve a certain value of ground resistance. A resistance of 10Ω or less (before it is connected to any other system) is stated in the appropriate British Standard [4] as being suitable for lightning protection purposes and a similar value can be found in other international standards/recommendations.

The individual wind turbine grounds are usually connected by the metallic screen or armour of the main power cable running between the turbines. This has the effect of reducing the overall site ground impedance to a low value, often 1-2Ω. Where the windfarm is sited in an area of high soil resistivity, each turbine ground may be connected by a strip electrode in addition to the connection provided by the power cable screen/armour.

6 SAFETY CRITERIA AND EQUIPMENT OVERVOLTAGE RATINGS

Criteria to ensure the safety of humans during power system faults are well defined in various standards and should be applied by the designer of an grounding system. Similar criteria to assess the hazard to humans during lightning strikes are not as well defined but can be inferred from the IEC standard detailing the effects of current on the human body [5].

The vulnerability of equipment to lightning overvoltages should be established for a particular grounding system design. A 33kV/700V transformer may, for example, have a rated lightning withstand voltage of 170kV [6] and it is possible to assess the likelihood of a lightning strike producing an overvoltage above this level. This can be performed for all electrical equipment installed on a windfarm including power cables, transformers, circuit breakers, surge arresters etc.

7 EXAMPLE OF WINDFARM GROUNDING

7.1 Single Turbine

The grounding arrangement of a wind turbine situated on the Greek island on Lemnos, as shown in Figure 1, can be used as an example of grounding system behaviour during lightning strikes, or power system frequency faults.

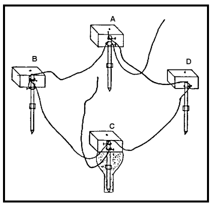

Figure 1 - Grounding Arrangement at Lemnos

Generally, the response of a small grounding system such as the one described, will be as if it was purely resistive. However, if long strip electrodes are used to reduce the grounding system impedance, the relatively high inductance means that the performance of the system subject to a lightning strike containing many high frequency components cannot be clearly defined.

The computed ground resistance of the arrangement described is 5.8Ω when the grounding system is situated in 100Ωm soil (a low soil resistivity). An energisation current of 1kA at 50Hz results in a maximum voltage of 5.8kV as expected. Similarly, the injection of a 5.5/70μs lightning wave with a peak current of 30kA results in a peak voltage of 174kV, the value expected for a purely resistive grounding system.

When a 50m long conductor is attached to the turbine base, the resistance is now calculated as 1.2Ω. The same injection of 30kA peak lightning current as before results, however, in a peak voltage of 54kV. This would suggest a grounding resistance of 1.8Ω. The reality is that this difference is caused by the high inductive reactance seen by the high frequency components of the lightning wave. This has been produced by the inductance present in such a distributed grounding system.

If the 50m electrode had been split into four 12.5m sections and attached to the four corners of the grounding system a lower ratio of inductance to resistance is achieved. The resistance of this arrangement is 0.98Ω and the peak lightning voltage is 29kV, the value expected when injecting the current into a pure resistance. By using four short strip electrodes as opposed to one long strip electrode, the grounding design has been improved. This is shown in Figure 2.

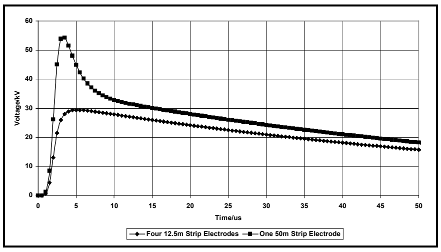

Figure 2 - Effect of short strip electrodes (lower plot) in comparison to longer lengths (upper plot) on reducing the maximum lightning voltage rise

7.2 Two Turbines Connected With Strip Electrode

The computation for a single wind turbine grounded with a 50m strip electrode showed the effect that the electrode inductance has on the response to an injection of lightning current. As a result, the use of the earthing system resistance to estimate the GPR at a point following a lightning strike is inaccurate. As a further example of this consider a system in 1000Ωm resistivity soil consisting of two turbine bases identical to the one used in 7.1 situated a distance of 100m apart with the grounding systems connected by strip electrode as shown in Figure 3. The computed resistance of the network is 18.59Ω and the maximum voltage rise for an injection of 1A at 50Hz is 18.59V.

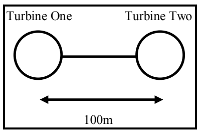

Figure 3 - Turbine Layout (not to scale)

An injection of a lightning current with peak current of 30kA results in a maximum voltage of 868kV at the injection point. This can be compared to a voltage of 558kV that would be expected if the same current has been injected into the 18.59Ω resistance. The voltage waveform produced at the base of the first wind turbine is shown in Figure 4 along with the waveform expected had the injected current flowed into a pure resistance. Note that the inductance increases the peak voltage and changes the time to peak.

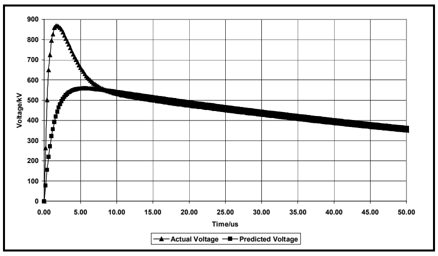

Figure 4 - Predicted voltage waveform following lightning current injection into the measured resistance (lower plot) compared with computed result taking system inductance into account (upper plot)

If the windfarm substation is assumed to be at a remote point and the high voltage system is grounded there, an overvoltage of 868kV will be present between the high voltage transformer winding and the locally grounded case/low voltage winding possibly leading to damage. The ground potential at the second wind turbine, 100m away will also rise due to the injection of lightning current and is shown in Figure 5.

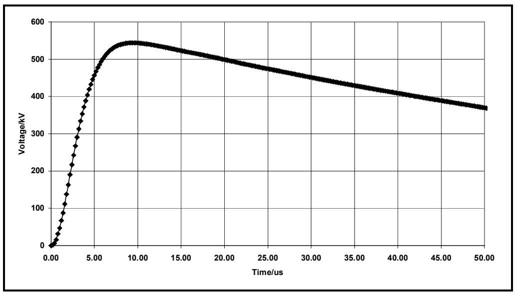

Figure 5 - Voltage at turbine two (remote from the injection point)

Even though the second turbine is 100m away from the first, a peak voltage of over 500kV is still developed at the local ground, a value that would again potentially damage the transformer and other equipment. The slower time to peak and smoother waveform than that seen at turbine one is another consequence of the relatively high level of inductive reactance present in the system.

7.3 Five Turbines Connected With Strip Electrode

Modern wind turbines are rated at 1MW and are situated a considerable distance apart, often hundreds of metres, when installed on a windfarm. Consider five such turbines with a 6.5m radius ring electrode at the base, separated by 400m and situated in 500Ωm soil. The individual turbine ground electrodes are to be joined by the armour of a power cable but must, firstly be given a ground resistance of 10Ω to meet the relevant British Standard. Two strip electrodes of 35m are joined to opposite sides of the turbine grounding systems to achieve this 10Ω resistance and the overall windfarm impedance at 50Hz is calculated to be 1.9Ω.

This arrangement of grounding system, although adhering to the British Standard, is not normal with most windfarm grounding system designers choosing to run strip electrode the full distance between two turbines. The addition of this extra strip electrode to run from one turbine base to the next would result in a extra 1.3km of electrode being needed for the whole windfarm. This would have the result of reducing the overall windfarm impedance at 50Hz to 0.9Ω but the effect on the lightning performance of the grounding system is less clear.

The plot of the voltage resulting from an injection of 30kA peak lightning current to the middle wind turbine of the five is shown in Figure 6 for both cases. The peak lightning voltage is the same in both cases but the voltage decays at a higher speed in the case of the turbines joined by strip electrodes. If one of the goals of the grounding system is to reduce peak overvoltages, the 1.3km of extra strip electrode used could be better employed locally to the wind turbine resulting in a system with a lower inductive reactance during a lightning strike.

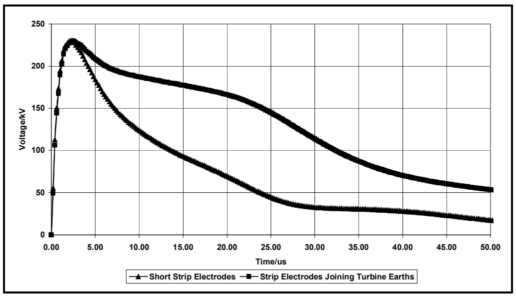

Figure 6 - Voltages at injection point of a wind turbine connected to short pieces of strip electrode or to the adjacent turbines with strip electrode

The small oscillations seen in Figure 6 are caused by travelling waves propagating back and forth along the grounding electrodes and are common in any large grounding system.

8 CONCLUSIONS

Owing to the complex and distributed nature of a windfarm grounding system it is preferable to obtain the grounding design partially through the use of computational software. A windfarm grounding system must be designed to take account of human safety, power system protection and equipment overvoltage ratings.

Examples have been given that show how such computational software based on electromagnetic field theory can be used to analyse a windfarm grounding system design. In particular, the difference in response of the grounding system to a power system fault and lightning fault has been examined.

9 ACKNOWLEDGEMENTS

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10 REFERENCES

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