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Analysis of the Impact of Tower Footing Impedance on the Low Voltage Ride Through Capability of DFIG-Based Wind Systems

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Introduction

This work seeks to integrate the results of technical research into engineering curriculum, thereby closing the divide between research and teaching. The investigation of tower footing impedance and its influence on LVRT capability will serve as a practical case study for students, enhancing their comprehension of wind energy systems. Preliminary research was done to analyze the educational impact, utilizing the material in classroom settings as a quality assessment performance indicator to test students' ability to apply relevant technical codes and standards in engineering design.

Single line to ground (SLG) faults in transmission lines are often caused by an insulator flashover [1]. At the point where the SLG occurs, zero-sequence current flows back to the ground of the power system. On a grounded system, a fault in a steel tower or grounded wood pole automatically includes the footing impedance in the fault circuit [2]. Hence, the flow of the zero-sequence current is greatly influenced by the line's zero-sequence impedance, the arc resistance, and the tower footing impedance (TFI); so, the resultant fault current may be quite smaller than the computed one when ignoring any of these resistances. Fault impedance, Z_F, can be categorized using three criteria as follows; bolted fault when $Z_F=0$, arcing fault when Z_F includes the arcing resistance and finally the transmission-line insulator flashover when Z_F includes the arc resistance, transmission tower resistance and the tower footing resistance. Fault duration, material behavior during prolonged fault durations, local temperature and air pressure, conductor diameter, and surface condition of the faulty component are some other factors which may impact fault impedance [3]. The simplified circuit diagram in Figure 1 illustrates that during fault incidences, fault impedance influences the computation of the fault current, i_{res}, drawn from a renewable energy resource (RES) system and the voltage at the RES terminals, v_{res}, as follows:

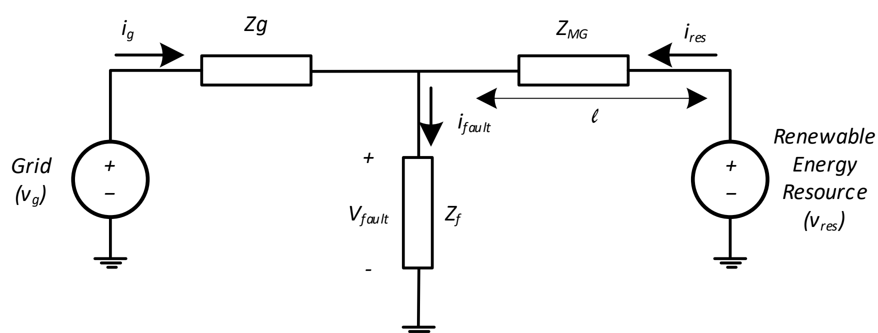

Figure 1. Simplified circuit schematic of the power system and RES connection during a fault incidence.

$$\begin{aligned}
\vec{\imath}_{fault} &= \vec{\imath}_{res} + \vec{\imath}_g \\
\vec{v}_{res} &= \vec{v}_{MG} + \vec{v}_{fault} \\
\vec{v}_{res} &= Z_{MG}\vec{\imath}_{res} + Z_f(\vec{\imath}_{res} + \vec{\imath}_g) \\
\vec{\imath}_{res} &= \frac{\vec{v}_{res} - Z_f\vec{\imath}_g}{Z_{MG} + Z_f}
\end{aligned} \quad (1)$$

Where v_g is Thevenin equivalent voltage of the utility grid, i_g is the grid current, i_{fault} is the fault current, Z_g is Thevenin equivalent impedance of the system connecting the utility grid until the point of the fault, Z_{MG} is Thevenin equivalent impedance of the microgrid (MG) connecting the RES until the point of the fault.

As seen by the i_{res} equation, increasing the tower footing resistance, which in turn increases the fault impedance, reduces the numerator while increasing the denominator, resulting in a large drop in the fault current drawn from the RES. However, when the transmission-line towers are connected with overhead shield wires next to the substation, the effective TFI is significantly lower since they are connected in parallel [4]. Therefore, to provide a sufficient impedance in the fault circuit, it is recommended to electrically separate the shield wire from the towers and the station ground mat and just to keep one tower per circuit to be connected to the ground mat to release and left charges and static electricity to the ground [4].

Nevertheless, while the data for line zero-sequence impedance is accessible, this is not the case for the arc and footing resistances. However, there are several widely used techniques for determining arc resistance [5-7], the resistance of the tower grounding system, which will provide substantial resistance, is based on the transmission line design and geographic location. Therefore, to choose the right setting for protective relays to maintain the power system stability, it is important to determine a realistic upper limit for the footing impedance and which lines will offer significant resistance, particularly with the integration of RESs. Further, high fault currents may result from system faults close to generating stations in large, grounded power systems, which are more serious than those a few miles or less from the generating station, because fault current rapidly decreases as fault distance from the source grows.

Moreover, a crucial factor in maintaining power system stability is the Low Voltage Ride Through (LVRT) capability during system transients, as well as the capacity of RES to remain connected and stable during brief intervals of low voltage in the grid, which is essential for averting cascading failures and facilitating system recovery [8-12]. The impact of TFI on the LVRT capability must therefore be investigated immediately to choose the best protection settings which guarantee system stability, an area that has not received enough attention in the literature to yet.

The current study focuses on how the doubly fed induction generator (DFIG) responds to the change in TFI during faults, as it is one of the most common generators used in wind farms, a popular RES, and because its stator and grid-side converter (GSC) are directly connected to the grid, DFIG-based wind turbines (WT) are particularly susceptible to utility grid disruptions. Consequently, to maintain LVRT functionality after a system failure and improve power system stability, several internal and external devices, as well as control and protection methodologies, have been proposed in the literature [13-15]. These solutions encompass both exterior LVRT techniques, like protection-based techniques, FACTS-based techniques, and hybrid approaches, and interior LVRT techniques, which is mostly based on control strategies. All these devices or techniques add to the cost and complexity of the wind farm's installation, necessitating a comprehensive optimization process to identify the most appropriate LVRT system for wind energy applications and region as well. Consequently, the design, selection, or implementation of an appropriate LVRT technique for wind turbines requires an understanding of all aspects influencing the wind energy system, including TFI.

The primary goal of this study is to conduct a qualitative investigation into the impact that TFI has on the LVRT capability, and hence the power system and WF stability, during short-term severe voltage dips and this is due to the fact that this subject has not been extensively investigated in the research.

Significant insights and suggestions for improving the power system's LVRT capabilities in an economical and effective way could be provided by the investigation.

Further, the analysis of the impact of tower footing impedance on the LVRT capability of DFIG-based wind systems is not only crucial for advancing the field of electrical engineering but also holds significant educational value as it can be effectively integrated into both undergraduate and graduate engineering curricula. By incorporating this material into classroom instruction, students can gain practical insights into real-world applications of theoretical concepts, thereby enhancing their learning experience.

The following is the organizational scheme of the article's following sections: Section 2 discusses the factors affecting the TFI, Section 3 provides synopsis of the effect of tower footing impedance on the grid during single-line-to-ground fault. In Section 4, a conclusion has been drawn and provide suggestions for further studies.

Factors Affecting Tower Footing Impedance

- ***Soil Resistivity and Grounding System***

Although it is commonly assumed that the transmission line tower is completely grounded, in reality, every tower grounding system has a measurable impedance which might be range from 5 ohms to 300 ohms and in direct proportion to the soil resistivity. The following equation is taken from the EPRI Redbook and applies to a single ground rod of length (L) and cross section area (a); it is used to determine the impedance of the rod [4].

$$R = \frac{\rho}{2\pi L}\left(\ln\left(\frac{4L}{a}\right) - 1\right) \tag{2}$$

It can be concluded from Equation (2) that soil resistivity will have a substantial impact on the ground resistance. Further, grounding techniques for transmission towers vary among utilities and sometimes even between structures. As a result, the impedance of the tower footing is a crucial factor for insulation coordination, and studies indicate that a specified footing impedance needs to be achieved for each tower for the transmission system to perform its function effectively. By measuring the actual footing impedance during installation and inserting more rods as needed, the required resistance value can be reached [16].

- ***Considerations for Shield Wires***

By allowing a portion of the fault current to flow through several parallel routes between the shield wire and neighboring tower grounds, shield wires can reduce the TFI and thus affect the overall fault impedance. It is crucial to note that the transmission line design may practically contain shield wires on the entire line, intermittently, or continuously. Because the TFI is greatly decreased when a transmission line with shield wires is equipped with a continuous and grounded shield wire, the fault current to ground can propagate through the shield wire to adjacent towers, as shown in Figure 3. As a result, when a transmission line with shield wires experiences a fault, most of the fault current may be directed to the towers that are in close proximity to the affected structure and follow every path back to the ground.

If the insulation on the shield wires successfully stops the flashover from reaching nearby towers, then the maximum TFI on segmented lines can be the same as on a single tower. Hence, at any given location in a system, TFI can be such that it causes the X_T/R ratio to be low. As a result, the actual fault current could be much lower than the expected value, which is usually calculated ignoring fault resistance.

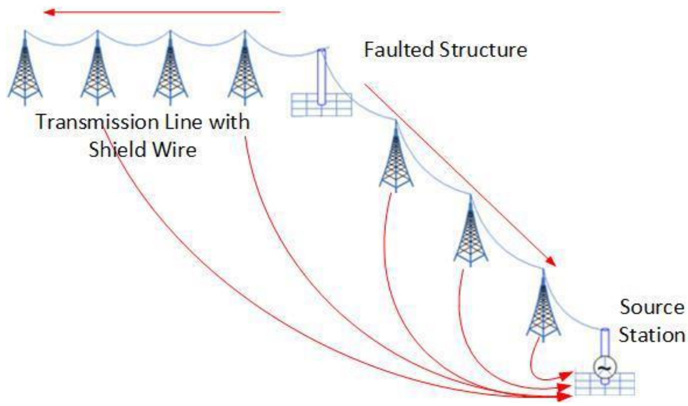

Figure 3: Distribution of fault current on transmission line segments

For instance, Fig. 4 illustrates a simplified diagram of the ladder network and the transmission line grounding system of interest. Z_G denotes the ground impedance of the stand-alone tower, while $Z_{shield\text{-}wire}$ is equivalent to the impedance of the shield wire between towers.

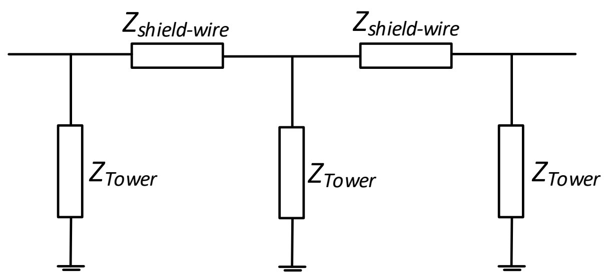

Figure 4. Ladder Network of the transmission line during fault

The overall impedance (Z_{total}) seen by the system at the fault location can be determined using [17], as
follows:

$$Z_{\text{total}} = \frac{Z_{\text{shield-wire}}}{2} + \sqrt{Z_{\text{shield-wire}} * Z_{\text{Tower}}} \tag{3}$$

After the equivalent impedance of the system under fault has been determined, the fault current split factor (SF) which determine how much current will flow through the fault path can be determined as:

$$SF = \frac{Z_{\text{total}}}{Z_{\text{total}} + Z_{\text{Tower}}} \tag{4}$$

Therefore, the SF can be reduced as the impedance of a span decreases, which in turn results in a decrease in ground fault current in the grounding system under analysis. This can be achieved by either decreasing the distance between towers or increasing the size of the shield wire.

Synopsis of the Effect of Tower Footing Impedance on the Grid during Single-Line-to-Ground Fault

To assess the impact of the TFI on WF operation during a grid fault and to determine the most effective LVRT enhancing method or standard to be used, the power system shown in Figure 5 is simulated using Matlab/Simulink for various TFI values, and the violation of the LVRT standard is recorded in each case.

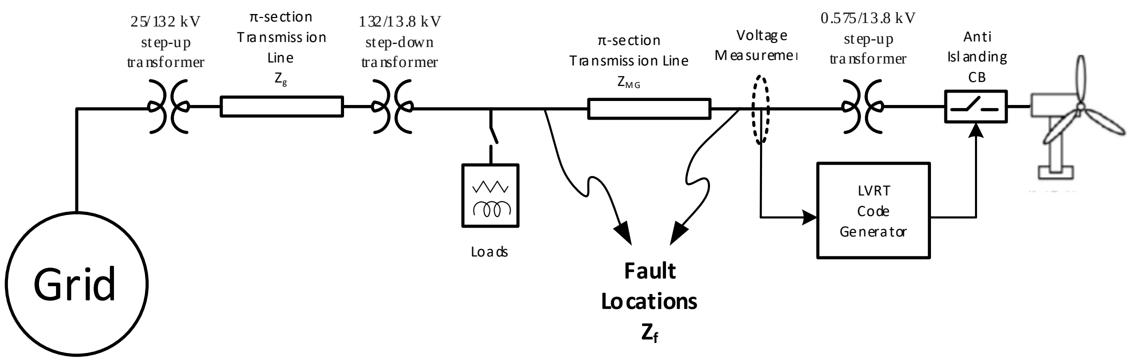

Figure 5. The simplified model used in Matlab/Simulink to assess system under study.

A 25 kV, 60 Hz power plant with a 25/132 kV step-up transformer powers the power system. A 20 MVA wind farm is then connected to the grid using a 13.8 kV transmission line and a 132/13.8 kV transformer. The grid and WF, which has a 0.575/13.8 kV step-up transformer, are providing 30 MVA loads which are located at the 13.8 kV level.

If a single-phase to ground bolted fault, $Z_{af} = 0$, occurs at phase (a) just in front of the WF's transformer, i.e $l = 0$ and $Z_{mg} \approx 0$, the positive, negative, and zero sequence components of the WF's fault currents are all equal and can be calculated using the symmetrical component concept using Equation (1) and replacing the subscript (res) with (wf) as follows:

$$\left|\vec{\imath}_{wf1}\right| = \left|\vec{\imath}_{wf2}\right| = \left|\vec{\imath}_{wfo}\right| = \frac{\left|\vec{v}_{wf} - Z_{af}\vec{\imath}_{g}\right|_{pre-fault}}{Z_{mg1} + Z_{mg2} + Z_{mgo} + 3Z_{af}} \quad (3)$$

As a result, it is also possible to calculate the current that is drawn during phase (a) of the WF when replacing the three components $Z_{mg1} = Z_{mg2} = Z_{mgo} = 0$ as follows:

$$\left|\vec{\imath}_{wf_a}\right| = \left|\vec{\imath}_{wf1}\right| + \left|\vec{\imath}_{wf2}\right| + \left|\vec{\imath}_{wfo}\right| = \frac{3\left|\vec{v}_{wf} - Z_{af}\vec{\imath}_{g}\right|_{pre-fault}}{3Z_{af}} = \frac{\left|\vec{v}_{wf} - Z_{af}\vec{\imath}_{g}\right|_{pre-fault}}{Z_{af}} \quad (4)$$

During the SLG bolted fault and that the TFI is not taken into consideration, $Z_F = 0$ and TFI=0, at phase (a) at the 5th second, Figure 6 depicts the impact of such a fault on the WF's voltage for all three phases. The stability of the system is guaranteed by comparing the RMS values of the three phase voltages with the USA's LVRT standard, as shown in the figure. It can be seen from the figure that phase (a) voltage dropped below the LVRT safety threshold, isolating the WF, due to the extremely small fault impedance and its close proximity to the WF. The anti-islanding circuit breaker tripped, shutting down the system.

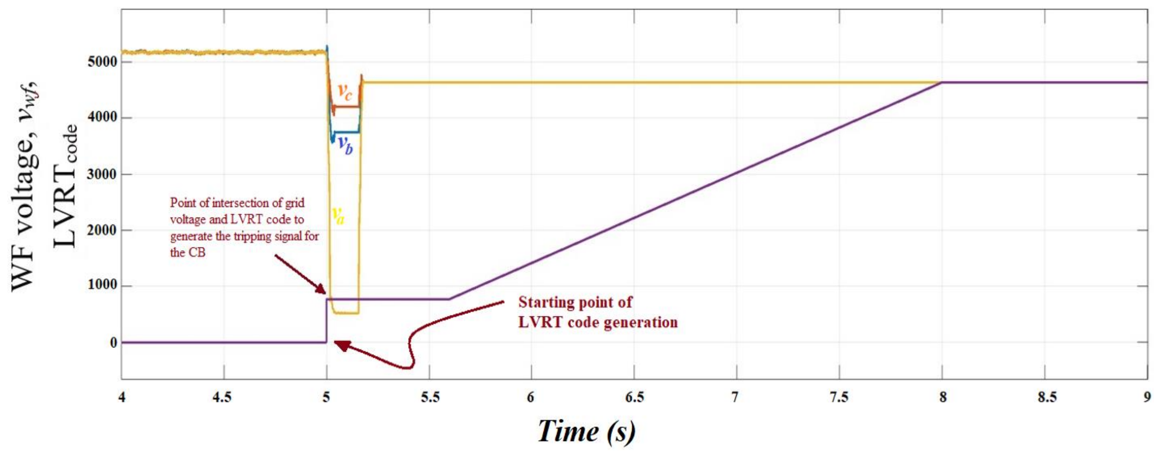

Figure 6. WF's three phase voltages and LVRT standard during SLG bolted fault at phase (a) at the 5th second when TFI=0.

However, incorporating TFI implies that the fault possesses significant impedance, $Z_{af} \gg 0$, in this case, leading to a substantial reduction in fault current and a modest decrease in fault voltage, thereby satisfying the LVRT code criteria as shown in Figure 7. Consequently, the wind farm's protective mechanism will not activate, enabling it to maintain its connection to the grid and ensuring the power system stability. However, this will not be the case during a prolonged fault duration of several seconds, as the phase voltage may fall below the 90% threshold necessary to meet the LVRT criteria, and hence activating the protection mechanism. Therefore, to uphold an adequate impedance level in the fault circuit, it is advisable to disconnect the tower's shield wire from both the towers and the WF's grounding mat to prevent a substantial decrease in fault impedance due to the parallel connectivity of transmission-line shield wires and to guarantee that only one tower per circuit is linked to the ground mat for the dissipation of static charges. Therefore, selecting the appropriate LVRT settings or code for a certain area is largely dependent on the fault characteristics and TFI of the region.

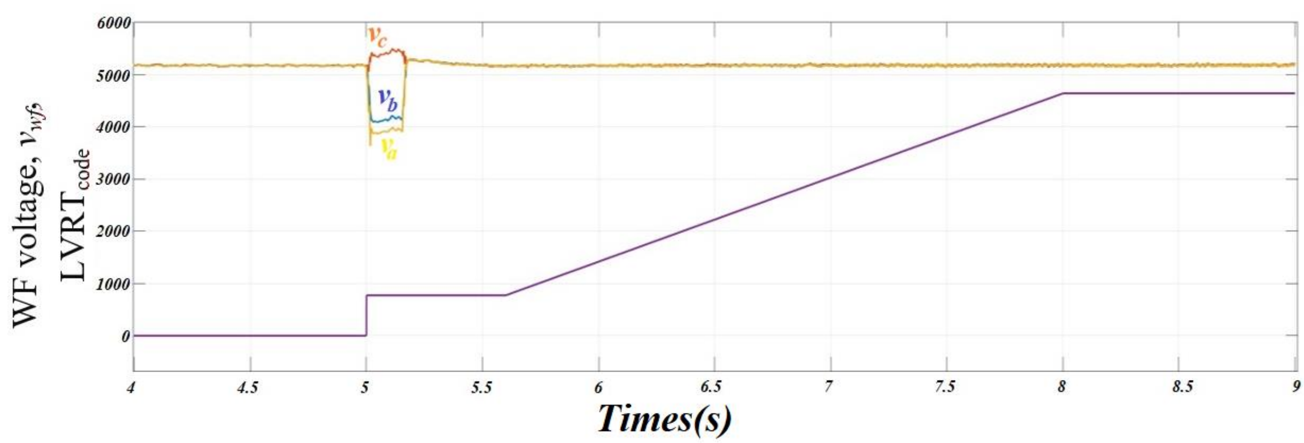

Figure 7. WF's three phase voltages and LVRT standard during SLG bolted fault at phase (a) at the 5th second when considering TFI (TFI≫0).

Bridging Theory and Practice in the Classroom

To bring the analysis of tower footing impedance and its impact on LVRT capability to life in the classroom, an interactive learning module was designed that combines theoretical instruction with hands-on activities. This module was implemented in an undergraduate electrical engineering course and included the following elements:

- ***Interactive Lectures***: Students were introduced to the fundamental concepts through engaging lectures that incorporated multimedia presentations, real-world case studies, and interactive discussions. These lectures aimed to build a strong theoretical foundation while highlighting the practical significance of the research.
- ***Simulation-Based Learning***: Using Matlab/Simulink software, students were tasked with modeling DFIG-based wind systems and analyzing the effects of varying tower footing impedance on LVRT capability. This hands-on approach allowed students to visualize the impact of different parameters and gain a deeper understanding of the underlying principles.
- ***Assessment and Feedback***: To evaluate the effectiveness of the module, students were assessed through project presentations. Additionally, feedback was collected through discussions to gauge student engagement and learning outcomes.

The results of this educational initiative were overwhelmingly positive. Students reported a stronger ability to apply theoretical concepts to practical scenarios. The hands-on, interactive nature of the module was particularly praised for making the learning experience more engaging and impactful.

Conclusion

The research presents case studies and simulations of the impact of tower footing impedance using Matlab/Simulink which can benefit both undergraduate and graduate students, and early career engineers in ensuring the dependable integration of renewable energy sources into the power grid in an economic and efficient way. From a technical point of view, the impedance created by the shield wire and the tower footing impedance can substantially influence transmission line protection mechanism. This study investigates the impact of TFI on the LVRT capabilities of renewable energy systems to meet grid standards during failures. The goal is to better understand how faults respond to different tower impedances to choose the most cost-effective and appropriate LVRT enhancing solution. It is found the impedance of tower footings greatly affects LVRT capability, since high impedance can result in less pronounced voltage sags, enabling the wind farm to maintain power supply, while a decrease in the impedance leads to more severe voltage dips, perhaps causing complete shutdown of the WF. Consequently, it is advisable to ensure sufficient TFI by isolating the tower's shield wire from both the towers and the WF's grounding mat, as this can significantly diminish short circuit currents and comply with the LVRT code requirements. Furthermore, it is critical to account for the impedance of the transmission line linking the point of common coupling to the wind farm when establishing the proper LVRT settings or code for a specific region and to enable the correct computation of fault currents during system failure.

Further, from an educational point o view, the integration of the analysis of tower footing impedance on LVRT capability into engineering education has proven to be highly beneficial. The study conducted in an undergraduate course demonstrated that students gained a more profound understanding of the subject and were able to apply their knowledge effectively.

Moving forward, further research could explore the long-term impact of such educational interventions and expand the study to include graduate-level courses. By continuing to bridge the gap between research and education, we can better prepare the next generation of engineers to tackle real-world challenges.

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