Wind Power Plant Split Factor For Safety Design

Parametric Analysis and Simplified Calculations

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Outline

- Purpose of the paper/presentation
- Overview of system modeled in software
- Effect of various inputs on split factor (based on software)
  - Feeder Length
  - Substation Grounding Resistance
  - WTG Grounding Resistance
  - Soil Resistivity
Outline

- Hand calculation methods
  - Overhead and underground systems
- Comparison to software results
- Effect of various multi-layered soil resistivity models
Purpose

- Goal of WTG grounding is to meet IEEE 80 touch and step voltages at WTGs and GSUs along collector circuits.
- Most software and hand calculations are insufficient for such a large interconnected system.
- Typical approach requires modeling the entire system or analyzing stand-alone WTGs, which requires a split factor.
Purpose

- Split Factor (SF) = Percent of current returning to the source through the local (WTG) ground versus the alternate paths (neutrals and adjacent WTG grounds)
- IEEE 80 (Annex C) is designed for substations, therefore split factor is not directly applicable to WTGs
  - Approach is similar however
Goals

- Determine an appropriate way to calculate split factor when analyzing a single WTG
- Examine the primary factors affecting the split factor and WTG ground performance
- Compare calculation method to more detailed system models
Initial Analysis

- Designed to represent realistic designs, but simplified to practical cases
- Over 10,000 cases analyzed with various combinations on inputs
  - Several factors were weeded out early on when determined they had minimal impact
Factors Considered & Effects

- Construction of collector circuits
  - Overhead (OH) design or underground cable with insulated neutral
    - Neutral grounded at each WTG
    - Behave nearly the same
  - Underground (UG) with external ground conductor adjacent to power cable
    - Results in much better split factor
Factors Considered & Effects

- Soil resistivity
  - Varied from 10 to 5000 ohm-m
  - Most analysis in uniform, but multi-layered is realistic
  - Typically the bottom layer has most impact
  - Soil resistivity drives WTG and system resistance
Factors Considered & Effects

- Fault position along feeder
  - Faults near substation grounding have some benefit of lower impedance
  - Far end only has one path back, so higher split factor
  - Almost all faults along middle of feeder have same split factor
Factors Considered & Effects

- Spacing of WTGs along collector circuit
  - The further the WTGs are apart, the higher the split factor (more resistance from one WTG to the next)
- Neutral conductor of collector circuit
  - Similar to spacing, the neutral conductor size and composition changes the resistance from WTG to the next
Factors Considered & Effects

- Others with minimal impact
  - Substation resistance
  - Distance to the substation
  - Number of collector circuits
  - Total collector circuit length

- All have a few percent or less impact
Split Factor versus Soil Resistivity

![Graph showing the relationship between split factor and soil resistivity. The graph plots split factor (%) versus soil resistivity (Ohm-meters). The blue line represents OH, and the red line represents UG. As soil resistivity increases, the split factor decreases.]
Factors Considered & Effects

![Graphs showing factors considered and their effects on WTG grounding.](image-url)
Final System Analyzed

- Fifteen (15) WTGs per feeder, spaced 1000 feet apart
- Analyzed only one feeder at a time
- Simple design on unfaulted WTG (but more extensive on faulted one (to maximize SF))
- Ground conductor is bare #1/0 AWG (Copper UG, ACSR OH)
Final System Analyzed

- OH has no pole grounds (WTG grounds provide greater than 4 grounds per mile)
- Home run (longer segment of conductor with no WTG’s connected between substation and first WTG) is ignored
Final System Analyzed

Substation Grounding System

Collector Circuit

WTG Ground (Unfaulted)

Faulted WTG Ground
Simplified Method

- System is essentially a ladder network of resistances, similar to methods in IEEE 80
- General approach:
  - Determine resistance of WTG ground and neutral conductor (between each WTG)
  - Determine equivalent impedance of entire collector system
  - Calculate split factor
Simplified Method

- The factors needed to calculate this equivalent impedance are:
  - $Z_{\text{span}}$ – Determined from the length and conductor properties of a span
  - $R_{\text{turbine}}$ – The impedance of a WTG stand-alone grounding system
  - $R_{\text{conductor}}$ – Resistance of the bare conductor in a span (underground only)
Simplified Method – Overhead

- Overhead is simplest:
  - Equivalent
    - Middle of Circuit
    - End of Circuit
  \[ Z_{ColOH} = \frac{Z_{Span}}{2} + \sqrt{Z_{Span} \times R_{WTG}} \]
  \[ Z_{ColOH} = Z_{Span} + \sqrt{Z_{Span} \times R_{WTG}} \]
  - Split Factor
    \[ SF = \frac{Z_{Col}}{R_{WTG} + Z_{Col}} \]
Simplified Method – Underground

- Underground (continuous ground) adds an additional factor:
  - **Equivalent** $Z_{ColUG} = \frac{Z_{Span}}{2} + \sqrt{Z_{Span} \times \left( \frac{1}{R_{WTG}} + \frac{1}{Z_{Con}} \right)^{-1}}$
  - Middle of Circuit

$$SF = Z_{Col} / (R_{WTG} + Z_{Col})$$
Comparisons of Results

- Compared results calculated in software and by the simplified method at WTGs along the collector circuit
- Used three simple uniform soil resistivity models
- Looked at overhead (or underground with insulated neutral) and underground with external ground
Comparison – Overhead

- Very good match, particularly in low resistivity soils
- In high resistivity soils, simplified method may slightly underestimate split factor
  - Particularly true near the end of collector
  - Slight margin (safety factor) should be added if simplified approach is used
Comparison – Overhead
Comparison – Underground

- Better match than overhead, leaning conservative
- In low resistivity soils, simplified method may slightly overestimate split factor
- Adding a slight safety factor still justifiable in high resistivity soils
Effects of Multi-layer Soil Uniform Soil

- 100 ohm-m uniform
  - Base case – relatively consistent SF along collector
Effects of Multi-layer Soil
Shallow High $\rho$ over Low $\rho$

- 100 ohm-m (3 feet) over 10 ohm-m
  - Similar to uniform 10 ohm-m uniform
Effects of Multi-layer Soil Thick High $\rho$ over Low $\rho$

- 300 ohm-m (50 feet) over 10 ohm-m
  - Top layer dominates SF, but SF is less uniform along the feeder. Values similar to 100 ohm-m average)
Effects of Multi-layer Soil
Shallow Low $\rho$ over High $\rho$

- 10 ohm-m (3 feet) over 300 ohm-m
  - Similar characteristic and values to equivalent 100 ohm-m uniform resistivity (bottom layer has impact)
Effects of Multi-layer Soil Thick Low $\rho$ over High $\rho$

- 10 ohm-m (50 feet) over 300 ohm-m
  - Similar to uniform 30 ohm-m soil – bottom layer has some impact, but relatively minimal
Conclusions

- SF is consistent along the collector except the very ends (primarily far end)
- SF is lower on UG collector with continuous ground than OH collectors (or UG with insulated neutral)
- SF is lower in high resistivity soil (where most useful)
- Length of collector, number of collector circuits, and substation resistance don’t affect SF significantly for typical designs
- Hand calculation methods presented match well with detailed analysis for SF and GPR
Questions?

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