An Overview of Wind Plant Design Standards and Common Nomenclature and Available Resources to the Power Engineer

IEEE PES Wind Plant Collector System Design Working Group

Session: Wind Plant Collector Design 4.0

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• Past Experience
  – Westinghouse/ABB – 15 Years
    • Power system planning studies – worldwide
  – Engineering Manager for Electric Cooperative
  – Director of engineering – PDA-Consulting firm
  – Senior Consultant – S&C Electric Co.
  – Currently – Principal – ESC Engineering, Inc.

• Key points
  – Past member - NFPA 70E Standard Committee
  – Registered PE in 30 states
  – Over 40 technical papers and articles
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1 - Reactive Power Compensation for Wind Power Plants

• Abstract—This technical paper provides the basic guidelines for the application of reactive compensation systems to be used as part of a wind power plant. A brief history of wind plant reactive compensation system is discussed, then the fundamental needs of why reactive compensation is required. The paper will then provide some alternatives for reactive compensation, how to size the reactive compensation, and finally some of the principles on how different compensation devices work.
1 - Reactive Power Compensation for Wind Power Plants

- Requirements
  - Power Factor Requirement
  - Dynamic Voltage Support Requirements
  - Low Voltage Ride-Through Requirements
  - High Voltage Ride-Through Requirements

- Wind Plant Analysis
  - Load Flow, Short Circuit, Harmonics

- Wind Plant Details
  - Wind turbine generators (WTGs)
  - WPP - Collector System
  - Point of interconnection (POI)
  - Transmission line, if applicable
1 - Reactive Power Compensation for Wind Power Plants

- Wind turbine generators (WTGs).
  - Type & number
  - Power factor capability, control modes available (i.e., power factor, voltage, or reactive power).
  - SCADA dynamic response times,
  - VRT capability.
  - Step-up transformer details (MVA, percent impedance, X/R ratio, and available taps).

- WPP - Collector System
  - Collector cable schedules, including cable types, sizes, and lengths.
  - If applicable, details of collector substation transformer(s) (MVA, percent impedance, X/R ratio, and available taps)
1 - Reactive Power Compensation for Wind Power Plants

- Point of interconnection (POI).
  - Short-circuit levels & X/R ratios at the POI.
  - Control mode(s) at the POI; (i.e. voltage control, power factor control, constant susceptance control) along with the acceptable tolerances, dead bands, slopes, or other measures of dynamic response for these items.
  - Location of turbines relative to the POI.

- Transmission line, if applicable
  - Distance from the collector substation transformer to the POI.
  - Data (R, L, C)
1 - Reactive Power Compensation for Wind Power Plants

- Types of Reactive Power Compensation
  - Mechanically-Switched Shunt Capacitors
  - Mechanically-Switched Shunt and Regulated Reactors
  - Static Var Compensator
  - WTGs
- Choice of reactive power compensation
1 - Reactive Power Compensation for Wind Power Plants

- Voltage ride-through
  - During-fault behavior
  - Post-fault recovery

Fig. 3. Voltage ride-through of a wind power plant with induction machines without any additional ride-through measures as a function of the short circuit ratio.
2 - Wind Power Plant Collector System Design Considerations

• *Abstract*—This paper presents a summary of the most important design considerations for wind power plants. Various considerations, including feeder topology, collector design, interconnect and NESC/NEC requirements, and design engineering studies are discussed.
2 - Wind Power Plant Collector System Design Considerations

- Feeder Topology
- Collector Design
- Substation Design
2 - Wind Power Plant Collector System Design Considerations

- NESC and NEC considerations for wind power plants
- Turbine step-up transformer application
  - Transformer Type
  - Winding Connection
  - Transformer Protection and Switchgear
  - Transformer Primary Terminals
  - Transformer Impedance
  - Transformer Rating

Figure 3 – Transformer predicted insulation life as a function of kVA rating for a 1.5 MW WTG application operating at 0.95 power factor in an actual wind and ambient temperature regime.
2 - Wind Power Plant Collector System Design Considerations

- Design Engineering Studies
  - Load Flow Studies
  - Short Circuit Analysis
  - Harmonics Analysis
  - Temporary Overvoltage And Insulation Coordination Studies
  - TRV Analysis For Circuit Breakers
  - Grounding Studies
  - Arc Flash Assessment Studies
  - Other Special Studies
Abstract-- Proper insulation coordination is critical to achieving expected life from wind plant equipment. The collector systems of large wind plants require the application of surge arresters to protect the equipment insulation from transient overvoltages. The application of surge arresters is constrained by maximum operating and temporary overvoltage levels. This paper provides a tutorial description of the process of selecting and applying surge arresters to wind plant medium voltage collector systems, with emphasis on the peculiar properties of this application.
3 - Wind Power Plant Grounding, Overvoltage Protection, and Insulation Coordination

- **Wind Plant Voltage Environment**
  - Continuous Operating Voltage
  - Temporary Overvoltages (TOV)
    - Ground Faults
    - Loss of Ground Reference
    - Self-Excitation
    - Transformer Saturation Interaction
    - Ferroresonance
    - Switching Transients
    - Lightning Transients
3 - Wind Power Plant Grounding, Overvoltage Protection, and Insulation Coordination

- Insulation Coordination
  - Surge Arrester Characteristics
  - Arrester Installation Considerations
    - Arrester Lead Length
    - Separation Effects
    - Open End Reflection Voltages
  - Insulation Coordination Steps

![Graph](https://via.placeholder.com/150)

*Figure 2 – Increase of TOV due to feeder capacitance for an isolated feeder cable with a ground fault applied.*
3 - Wind Power Plant Grounding, Overvoltage Protection, and Insulation Coordination

- Mitigation of TOV
  - Grounding Transformer Application
    - Zig-Zag Grounding Transformer
    - Wye-Delta Grounding Transformer
    - Wye-Broken Delta Grounding Transformers
  - Transfer Tripping
  - High-Speed Grounding Switches
  - Do Nothing – Accept Failures

- System Grounding at the Substation

- Apparatus Grounding
  - Collector Substation
  - Wind Turbine Generator
4 - Characteristics of Wind Turbine Generators for Wind Power Plants

• *Abstract*—This paper presents a summary of the most important characteristics of wind turbine generators applied in modern wind power plants. Various wind turbine generator designs, based on classification by machine type and speed control capabilities, are discussed along with their operational characteristics, voltage, reactive power, or power factor control capabilities, voltage ride-through characteristics, behavior during short circuits, and reactive power capabilities.
4 - Characteristics of Wind Turbine Generators for Wind Power Plants

- Turbine Characteristics
  - Five types
- Voltage, Reactive Power, and Power Factor Control Capabilities
- Reactive Power Capabilities
- Voltage Ride-through
- WTG Behavior During Grid Short Circuits

Figure 8: Reactive Power Capabilities of a 2 MW Type 5 WTG
4 - Characteristics of Wind Turbine Generators for Wind Power Plants

– Type 1 WTG

The Type 1 WTG is implemented with a squirrel-cage induction generator (SCIG) and is connected to the step-up transformer directly.

– Type 2 WTG

In Type 2 turbines, wound rotor induction generators are connected directly to the WTG step-up transformer in a fashion similar to Type 1 with regards to the machines stator circuit, include a variable resistor in the rotor circuit.
– Type 3 WTG
Type 3 turbine, known commonly as the Doubly Fed Induction Generator (DFIG) or Doubly Fed Asynchronous Generator (DFAG), adds a variable frequency ac excitation (instead of simply resistance) to the rotor circuit.

– Type 4 WTG
Type 4 turbine offers a great deal of flexibility in design and operation as the output of the rotating machine is a full-scale back-to-back frequency converter.

– Type 5 WTG
Type 5 turbines consist of a typical WTG variable-speed drive train connected to a torque/speed converter coupled with a synchronous generator.
• Abstract—This paper presents basic guidelines on design considerations for wind power plant substation and collector system based on redundancy, reliability, and economics. Design considerations, although similar to utility substation and underground or overhead distribution systems, often include aspects not normally considered for those systems. This paper will highlight design considerations unique to wind power plant design comparing economic and reliability benefits among available design options. Power loss analysis in a typical wind power plant is explained. Finally, an overall economic analysis to be considered when designing a new wind power plant is presented.
5 - Wind Power Plant Substation and Collector System Redundancy, Reliability, and Economics

• Design Philosophy And Engineering Considerations
  – Design Philosophy & Design Considerations
• Substation Design
• Collector System Design
• Wind Power Plant Loss Consideration
  – Collector System Losses
  – WTG Step-up Transformer Losses
  – Feeder And Substation Grounding Transformer Losses
  – Collector and/or Interconnect Substation Transformer Losses
  – Reactive Power Compensation System Losses
  – Forced Loss of Energy Production
• Overall Economic Evaluation of Wind Power Plant
• Availability/Reliability Considerations for Wind Power Plants
Table I. Cost/Reliability Comparison for different Bus Configurations.

<table>
<thead>
<tr>
<th>Bus Type</th>
<th>Cost</th>
<th>Reliability</th>
<th>HV</th>
<th>MV</th>
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<tbody>
<tr>
<td>Single</td>
<td>46.7%</td>
<td>Low</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Sectionalized</td>
<td>57.0%</td>
<td>Low</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Main &amp; Transfer</td>
<td>66.8%</td>
<td>Low</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ring</td>
<td>53.3%</td>
<td>Medium</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Breaker-and-a-Half</td>
<td>73.8%</td>
<td>High</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Double Breaker – Double Bus</td>
<td>100%</td>
<td>High</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
6 - Arc-Flash Hazard in Wind Power Plants

• *Abstract*— The topic of this paper is the arc-flash hazard in Wind Power Plants (WPP). A brief introduction of the concept of arc flash is followed by the presentation of a methodology to perform an arc-flash hazard analysis on a WPP collector system. Issues such as faults being fed by multiple sources, as well as the modeling of the fault current of the wind turbine generator are addressed. The paper concludes with two examples using the presented methodology.
6 - Arc-Flash Hazard in Wind Power Plants

• Arc-flash Hazard
  – General Description Of Arc-flash Hazard
  – Arc-flash Models
  – Arc-flash Concerns Specific To Wind Plants
  – Arc-flash Hazard Protection
  – Protection Boundary
  – Protection Equipment
    • Protection Equipment
    • Circuit Breakers
    • Protective Relays
    • Ground Fault Sensors
6 - Arc-Flash Hazard in Wind Power Plants

- Arc-flash Incident Energy Calculations
  - Equipment Setups
  - Short-circuit Study
    - Collect The System And Installation Data
    - Calculate Arcing Fault Currents
    - Fault Currents Fed From Multiple Sources
  - Coordination Study
    - Determine The Fault Clearing Times
    - Clearing Times For Faults With Multiple Sources
- Arc-flash Hazard Study
- Examples
6 - Arc-Flash Hazard in Wind Power Plants
7 - Design and Application of Cables and Overhead Lines in Wind Power Plants

• Abstract-- This paper presents a summary of the most important considerations for wind power plant collection system underground and overhead cable designs. Various considerations, including conductor selection, soil thermal properties, installation methods, splicing, concentric grounding, and NESC/NEC requirements are discussed.
7 - Design and Application of Cables and Overhead Lines in Wind Power Plants

- Underground Medium Voltage Cable And Construction
  - Cable Selection
  - Commonly Used Cables In WPP
    • EPR
    • TR-XLPE
  - Cable Properties
  - Cable Splicing: Underground / Above Ground Splice Boxes/Sectionalizing Cabinets
    • Cable Splicing
    • “Cold” Shrink Splice
    • “Heat” Shrink Splice
  - Direct Burial (Plowing/Trenching) Vs. Duct Bank
7 - Design and Application of Cables and Overhead Lines in Wind Power Plants

- Cable Neutral (Concentric)
  - Sizing Of Cable Neutral (Or Shield)
  - Single/Multi Point Grounding And Cross-bonding
- Calculation Of Cable Ampacity
  - Soil Considerations
  - Calculating Cable Losses
  - Circuit Configuration/Spacing
- Overhead Construction
  - Design Considerations
  - Transition From Underground Sections
Abstract—Wind power plants use power transformers to step plant output from the medium voltage of the collector system to the HV or EHV transmission system voltage. This paper discusses the application of these transformers with regard to the selection of winding configuration, MVA rating, impedance, loss evaluation, on-load tapchanger requirements, and redundancy.
8 - Power Transformer Application for Wind Plant Substations

- Winding Connections
  - Ground Source Requirements
  - Winding Configuration Alternatives
- Transformer MVA Rating
- Transformer Impedance
- Transformer Loss Evaluation
- Load Tapchanger Applications
- Multi-transformer Applications
  - Practical Constraints
  - MV Collector System “Reach”
  - Availability And Reliability
  - Constraints On Contingency Operation
Abstract - This paper presents a summary of the most important protection and coordination considerations for wind power plants. Short-circuit characteristics of both aggregate wind plant and individual wind turbine generators, as well as general interconnection protection requirements are discussed. Many factors such as security, reliability, and safety are considered for proper conservative protection of the wind power plant and individual turbines.
9 - Wind Plant Collector System Fault Protection and Coordination

- Wind Power Plant Short-circuit Modeling
  - Short-circuit Contributions of WTGs
    - Type 1
    - Type 2
    - Type 3
    - Type 4
  - Wind Plant Modeling
9 - Wind Plant Collector System Fault Protection and Coordination

- Wind Power Plant Zones of Protection
- WPP Interconnection Coordination
- WPP Protection
  - WPP Substation Transformer
  - WPP Substation Bus
  - WPP Collector Protection
  - WPP Capacitor Banks
  - WTG Step-up Transformer
  - WPP WTG
10 - Wind Power Plant Testing and Commissioning

- Abstract—Complete testing and commissioning of the wind plant collector system is a critical step to ensure all equipment and systems are in proper working order prior to system energization and operation. In addition a comprehensive test agenda will ensure baseline data is available for comparing with future test data obtained during normally scheduled maintenance outages. This paper provides a thorough description and methodology for complete testing and commissioning of the wind plant medium voltage collector system and the equipment internal to the wind turbine itself.
10 - Wind Power Plant Testing and Commissioning

- **WPP Collection System**
  - Ground Grid Resistance Testing
    - IEEE 81
  - Underground Medium-voltage Collector Cable Systems
    - IEEE Standards 141 And 400-acceptance And Maintenance Tests
  - Overhead Medium-voltage Collector Systems
    - Sag/Tension, Etc.
  - Fiber Optic Cables

- **Wind Turbine**
  - Generator
  - Pad-mount Transformer Testing
  - SECONDARY (Low Voltage) CABLES

- **Matching Specification, Reviewing Test Reports, and Testing for Acceptance**
10 - Wind Power Plant Testing and Commissioning

- Substation
  - Main Transformer
  - Grounding Transformers
  - Switchgear / Feeder Breakers
  - Disconnects
  - Voltage & Current Transformers
  - Arresters
  - Capacitor Banks
  - Reactors
  - Station Service Power
  - Station Batteries
  - Control Wiring
  - Protection Relays
  - DSTATCOMM
11 - Wind Power Plant SCADA and Controls

• *Abstract*—This paper discusses the range of application for SCADA and control systems in a wind power plant, the most important SCADA and control system considerations, and contractual requirements for SCADA and control systems.
11 - Wind Power Plant SCADA and Controls

- Wind Turbine Controls
  - Nacelle Mounted Anemometer and Wind Vane
  - Sensors
    - Rotor Speed Sensor
    - Electric Power Sensor
    - Pitch Position Sensors
    - Vibration Sensors
    - Oil Level And Temperature Indicators
    - Hydraulic Pressure Sensors
  - Operator Switches
  - Pitch and Yaw
  - Generator
  - Closed Loop Design
  - Supervisory
  - Safety
11 - Wind Power Plant SCADA and Controls

• Plant SCADA
  – OEM SCADA
  – Third-party SCADA

• Plant Control
  – Voltage And Power Factor Regulation
  – Capacitor/Reactor Banks And Dynamic Var Devices
  – Ramp Rate Control
  – Frequency Droop Control
  – Power Curtailment
  – Auxiliary (I.E. Battery Banks, Alarms Etc)

• Security And Reliability Compliance
  – Remedial Action Scheme (RAS)
  – Protection System Relaying (PSR)
  – Data Telemetry
  – NERC Reliability Standards
  – IEC Standards
12 - Harmonics and Resonance Issues in Wind Power Plants

• Abstract—This paper presents a summary of the most important issues with respect to harmonics and resonances within wind power plants. An introduction is given to provide an overview of the various power quality related issues encountered when designing, commissioning, or operating a wind power plant, as well as typical characteristics of the components associated with wind power plants. The many variables, which influence harmonics and resonance in wind power plants, will be described with respect to analysis methods, avoidance, mitigation, and compliance with IEEE Std 519-1992 recommended practices.
12 - Harmonics and Resonance Issues in Wind Power Plants

- Resonance and Frequency Considerations
  - Frequency Scan Analysis
  - Source Characteristics Of Wind Turbine Generators
  - Source Characteristics Of Utility Interconnection
    - Ambient Voltage Distortion
    - Transmission System Harmonic Impedance
    - Representation Of Reactive Compensation Equipment
12 - Harmonics and Resonance Issues in Wind Power Plants

- Compliance with Power Quality Standards
- Harmonic Filter Overview

HARMONIC CURRENT LIMITS AT A WPP INTERCONNECTION

Example Wind Power Plant
Primary Current IL
102.8 MVA
345 kV
172.0 Amps

IEEE 519 (1992) Table 10-5 -- Current Distortion Limits for General Transmission Systems >161kV

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<th>2.0%</th>
<th>1.0%</th>
<th>0.75%</th>
<th>0.3%</th>
<th>0.15%</th>
<th>2.5%</th>
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<td>Limits (Primary Current Amps)</td>
<td>3.4</td>
<td>1.7</td>
<td>1.3</td>
<td>0.5</td>
<td>0.3</td>
<td>4.3</td>
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</table>

Harmonic Voltage Distortion (THD %)

Limit = 1.5 %
13 - Terms and Abbreviations Used in Wind Power Plant Collector System Design and Operation

• Abstract — Every industry has its terms and abbreviations (T&A). The wind power plant is no different. This paper is the first of its kind for this technical series on collector systems for wind power plants to provide some of the more significant T&A that are used. Future versions of this add more detail and may bring in new T&A as the technology develops.
13 - Terms and Abbreviations Used in Wind Power Plant Collector System Design and Operation

- Wind Power Plant Acronyms
- Terms and Definitions
## 13 - Terms and Abbreviations Used in Wind Power Plant Collector System Design and Operation

### Wind Power Plant Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
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<tr>
<td>ACE</td>
<td>Area Control Error</td>
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<tr>
<td>ACSR</td>
<td>Aluminum cable steel reinforced</td>
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<tr>
<td>AEP</td>
<td>Annual Energy Production</td>
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<tr>
<td>AGC</td>
<td>Automatic Generation Control</td>
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<tr>
<td>AMT</td>
<td>Alternative Minimum Tax</td>
</tr>
<tr>
<td>ANPR</td>
<td>Advance Notice of Proposal Rulemaking</td>
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<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
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<tr>
<td>ASI</td>
<td>Above Sea Level</td>
</tr>
<tr>
<td>ASOS</td>
<td>Automated Surface Observing System</td>
</tr>
<tr>
<td>ATC</td>
<td>Available Transfer Capability</td>
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<tr>
<td>AVR</td>
<td>Automatic Voltage Regulator</td>
</tr>
<tr>
<td>BA</td>
<td>Balancing Area</td>
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<tr>
<td>BIL</td>
<td>Basic Insulation Level</td>
</tr>
<tr>
<td>BOP</td>
<td>Balance of Plant</td>
</tr>
<tr>
<td>BWEC</td>
<td>Bats &amp; Wind Energy Cooperative</td>
</tr>
<tr>
<td>CAIR</td>
<td>Clean Air Interstate Rate</td>
</tr>
<tr>
<td>CAMR</td>
<td>Clean Air Mercury RLe</td>
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<tr>
<td>CAPX</td>
<td>Capital Expenditures</td>
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<tr>
<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
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<tr>
<td>CF</td>
<td>Capacity Factor</td>
</tr>
<tr>
<td>CIP</td>
<td>Critical Infrastructure Protection</td>
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<tr>
<td>CLR</td>
<td>Current Limiting Reactor</td>
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<tr>
<td>COD</td>
<td>Commercial Operation Date</td>
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<tr>
<td>CP</td>
<td>Cumulative Probability</td>
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<td>CP95%</td>
<td>CP 95% Level</td>
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<tr>
<td>CPC</td>
<td>Certificate of Public Convenience</td>
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<tr>
<td>CREZ</td>
<td>Competitive Renewable Energy Zone</td>
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<tr>
<td>CT</td>
<td>Combustion Turbine</td>
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<td>Ct</td>
<td>Thrust Coefficient</td>
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<td>DEP</td>
<td>Diurnal Energy Production</td>
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<tr>
<td>DETC</td>
<td>De-energized Tap Changer</td>
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<tr>
<td>DFAG</td>
<td>Doubly Fed Asynchronous Generator</td>
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<tr>
<td>DFG or DFIG</td>
<td>Doubly-Fed Induction Generator</td>
</tr>
<tr>
<td>EHV</td>
<td>Extra High Voltage</td>
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<tr>
<td>EIR</td>
<td>Environmental Impact Report</td>
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<tr>
<td>EIS</td>
<td>Environmental Impact Study</td>
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<tr>
<td>WFMS</td>
<td>Wind Farm Management System</td>
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<tr>
<td>WPP</td>
<td>Wind Power Plant</td>
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<tr>
<td>WRA</td>
<td>Wind Resources Area</td>
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<td>WTG</td>
<td>Wind Turbine Generator</td>
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### Additional Terms

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# Terms and Definitions

## Terms and Definitions

<table>
<thead>
<tr>
<th>Term - Definition</th>
<th>Paper</th>
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<tbody>
<tr>
<td>200 A load-break elbows</td>
<td>Paper 2</td>
</tr>
<tr>
<td>600 A dead-break style elbows</td>
<td>Paper 2</td>
</tr>
<tr>
<td>A factor – is a utility industry term for the amount of initial transformer capital cost increase that justifies a unit of no-load power loss reduction. a.k.a no-load loss factor.</td>
<td>Paper 8</td>
</tr>
<tr>
<td>Above ground splice box</td>
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<td>ACSR conductor</td>
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<td>ACSS conductor</td>
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<td>Arc blast hazard</td>
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<td>Arc-flash protection boundary</td>
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<tr>
<td>Automatic voltage regulation</td>
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<tr>
<td>Automatic voltage regulator – a device that limits the voltage of a generator to a desired limit.</td>
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<tr>
<td>Availability – a term that refers to the amount of time that a wind power plant is able to produce energy over a given period.</td>
<td>Paper 8</td>
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</tbody>
</table>

## Additional Terms

- **Availability** – MTBF/(MTBF + MTTR)
- **B factor** – is a utility industry term for the amount of initial transformer capital cost increase that justifies a unit of power loss reduction at rated load. a.k.a load loss factor.
- **Backfill**
- **Balance of Plant**
- **Basic impulse level**
- **Basic insulation level** – is the strength of a dielectric to withstand voltage stress.
- **Bolted fault current**
- **Bonding**
- **Bus differential zone**
- **Cable connector**
- **Cable reels**
- **Cable splice**
- **...**
- **Wind Power Plant** - a group of electrically interconnected wind turbine generators having one or more points of interconnection to the utility electric system.
- **Wind turbine generator**
- **Windplant feeders**
- **WTG step-up transformer**
- **Zero sequence admittance**
- **Zero sequence source impedance**
- **Zero-sequence coupling**
- **Zig-zag transformer**
- **Zones of protection**

## Papers

- Paper 2
- Paper 3
- Paper 4
- Paper 5
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- Paper 7
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- Paper 9
- Paper 10
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- Paper 12
THANK YOU

Discussion and Questions

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