IMPACT OF DISTRIBUTED GENERATION (DG) ON DISTRIBUTION SYSTEMS

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About the Instructor:

Chuck Mozina -- is a Consultant for Beckwith Electric on Protection and Protection Systems. He is a Life Fellow of the IEEE. Chuck is an active 30-year member of the IEEE Power System Relaying Committee (PSRC) and is the past chairman of the Rotating Machinery Subcommittee. He is a former U.S. representative to the CIGRE Study Committee 34 (now B-5) on System Protection.

Chuck has a Bachelor of Science in Electrical Engineering from Purdue University and is a graduate of the eight month GE Power System Engineering Course. He has authored a number of papers and magazine articles on protective relaying. He has over 25 years of experience as a protection engineer at Centerior Energy (now FirstEnergy), a major investor-owned utility in Cleveland, Ohio where he was the Manager of the System Protection Section. For 10 years, Chuck was employed by Beckwith Electric as the Manager of Application Engineering for Protection and Protection Systems. He has authored a number of papers and magazine articles on protective relaying.

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Seminar Outline

- Brief History of DG
- Interconnection Protection
- Types of Green Power DGs
  - Induction
  - Synchronous
  - Asynchronous
- Green Power DGs Impact on Dist. Feeders
  - Protection
  - Overvoltage
  - Watt/Var Control
Seminar Outline

- Fault Behavior of Various Types of Green Power DGs
- Impact on Feeder Protection Coordination
- Behavior of Inverter Based DGs
- Interconnection Protection and DG Restoration
Brief Summary of DG History

- Until Public Utility Regulatory Policies Act (PURPA) in 1978, U.S. utilities were not required to interconnect with small generators.
  - Started DG
  - Beckwith gets into the interconnection protection business
  - Hot until late 1980’s when tax incentive terminated

- Late 1990’s, DG hot again
  - Driven by high utility rates and de-regulation
  - DGs can generate cheaper at source of consumption
    + Peak Shaving and Load Following
  - Hot until early 2000’s when natural gas prices increased

- Late 2000’s, Green Power drives resurgence of DGs
  - Regulations require utilities to generate a portion of their power from green sources.
Why Green Power?
**DG: Green or Not Green**

- **Not Green**
  - Burn conventional fuel
    - Gas
    - Diesel, oil, gasoline

- **Green**
  - Use renewable sources to reduce reliance of fossil fuels:
    - Solar
    - Methane (from decomposition)
    - Wind
    - Hydro
    - Diesels Powered by Syn Fuel
    - Biomass (burn it)
What is DG Interconnection Protection?

- Protection that allows the DG to operate in parallel to utility

- Large non-utility generators do not require specific interconnection protection
  - Integrated into transmission system
  - Breaker(s) are tripped by transmission line/bus/transformer protection

- Smaller DGs do require specific interconnection protection
Interconnection Protection Placement

Utility

Interconnection Transformer

DG Interconnection Protection

Sync

Ungrounded Primary Only

Point of Common Coupling

DG

Loads

Loads
Interconnection Protection Placement

- DG Interconnection Protection
- Utility Point of Common Coupling
- Interconnection Transformer
- Sync
- DG
- Loads
- Loads
What Utilities Generally Specify:

- **Utility-grade interconnection relays**
  - Pass all pertinent ANSI standards
- **CT and VT requirements (quantities sensed)**
- **Winding configuration of interconnection transformers**
- **Functional protection**
  - 81U/O, 27, 59, etc.
  - Settings of some interconnection functions
    - Pick ups
    - Times (to clear faster than utility reclose)
Greatly complicates restoration
- Requires synchronizing at utility substation
- Inhibits automatic reclosing

Power quality issue
- DG may not be able to maintain voltage, frequency and harmonics within acceptable levels (load ≠ generation; no harmonic “sink”)
DG Facility Islanding to the Utility is Allowed – IEEE 1547

- Feeder deenergizes when utility opens feeder
- Restoration responsibility on the DG
  - Requires synchronizing to utility
  - Inhibits automatic reclosing

DG can create its own island, and synchronize to the utility
Types of Green Power Generators

- **Induction**
  - Wind Power

- **Synchronous**
  - Internal Combustion Engines
  - Small Hydro
  - Gas Turbines

- **Asynchronous (Static Power Inverters)**
  - Solar, PV
  - Fuel Cells
  - Wind
- **Induction**
  - Excitation provided externally by system
    - VAr drain
  - Less costly than synchronous machines
    - No excitation system or control
    - No sync equipment needed
  - Limited in size to <=500 KVA
  - May cause ferroresonance after disconnection from utility (self-excitation from nearby caps)

**Types of Generators**
- Wind Power
Type I Wind Turbine Generator - Induction Generator

§ Pitch Regulated
§ Squirrel Cage
§ Induction Generator
§ Direct Grid Connected
Induction Generator Short Circuit Calculations

Voltage source in series with the direct axis sub-transient inductance

\[ X_d''(pu) = \frac{1}{I_{locked\ rotor}(pu)} \approx \frac{1}{5} \approx 0.2\ pu \]

- That means for a 3-phase fault at the LV terminals, it contributes approximately a maximum symmetrical short-circuit current with a magnitude equal to the induction generator locked rotor current during the first cycle after the fault.
Induction Generator Short Circuit Current Decay

3-phase fault
Ferroresonance can take place between an induction machine and capacitors after utility disconnection from feeder. **Ferroresonance can also occur on Synchronous Generators!**

- Generator is excited by capacitors if the reactive components of the generator and aggregate capacitors are close.
- This interplay produces non-sinusoidal waveforms with high voltage peaks. This causes transformers to saturate, causing non-linearities to exacerbate the problem.
Induction Generator: Ferroresonance

- The overvoltage can damage insulation, damage arrestors and cause flashovers

- Standard overvoltage (59) element may not detect this condition...they “RMS” the waveform, missing the high peaks, and may have a long time delay (e.g. 30+ cycles)

- A peak instantaneous overvoltage (59I) element will detect and protect against this condition
  - This element should sense all three phases!
Test Circuit Setup
New York Field Tests- 1989
Field Test Circuit

Schematic of Test Circuit.
Induction/Synchronous Generator:

Ferroresonance can also occur on synchronous generators
Conditions for Ferroresonance

1. DG must be separated from the utility system (islanded condition).

2. KW load in the island must be less than 3 times DG rating.

3. Capacitance must be greater than 25 and less than 500 percent of DG rating.

4. There must be a transformer in the circuit to provide nonlinearity.

SOLUTION: USE 59I ELEMENT
Synchronous Generator

- Dc field provides excitation
- Need to synchronize to the utility system

Types of Generators
- Internal Combustion Engines
- Small Hydro
- Gas Turbines
Asynchronous Generator

- Static Power Converter (SPC) converts generator frequency to system frequency (dc-ac or ac-dc-as)
- Generator asynchronously connected to Power System
  - may be self-commutating (needs sync relay)
  - may be line-commutating (no sync relay needed)
- IEEE P 929 and UL 1741 Provide Guidance on SPC’s

Types of Generators
- Solar, PV
- Fuel Cells
- Wind
Asynchronous Generator: Static Power Converter

- Some have built-in anti-islanding protection
  - SPC tries to periodically change frequency
    - If grid is hot, SPC cannot change the frequency
    - If grid has tripped, frequency moves and controller trips machine

- Difficult to test; some utilities do not trust and require other protection
Conventional Synchronous DG Generators Impact on Distribution Feeders
Impact of Interconnection Transformer

- **Ungrounded Primary Transformer Winding**
  - Overvoltage may be caused by DG when ungrounded primary transformer windings are applied (no ground source) and DG backfeeds once utility disconnects

- **Grounded Primary Transformer Winding**
  - Ground fault current contribution caused by DG grounded primary transformer windings during utility faults
  - Source feeder relaying and reclosers responding to secondary ground faults within the DG facility
Sensing Ungrounded System Ground Faults with 3 Voltage Transformers

DG Facility

Backfeed to Utility

Unfaulited

Ground Fault

DG Facility
Many utilities only allow use of ungrounded primary windings if the DG sustains an overload on islanding. The overload prevents the overvoltage from occurring.
Overvoltage on the Unfaulted Phases

Lightning Arrester Capability
- 156% TOV -- 100 ms
- 147% TOV -- 1.0 sec.
- 128% --- Continuous
Ungrounded - Primary Interconnection Transformers

**Advantages**

- Provide no DG ground fault backfeed for fault at F₁ & F₂
- No ground current from breaker A for a fault at F₃
- No DG ground current - helps Fuse Saving Coordination

**Problems**

Can supply feeder circuit from an ungrounded source after substation breaker A trips—causing overvoltage
**Grounded – Primary Interconnection Transformers**

**Advantages**
- No ground current from breaker A for faults at F₃ (delta sec. only)
- No overvoltage for ground fault at F₁
- No overvoltage for ground fault at F₂

**Problems**
- Provides an unwanted ground current for supply circuit faults at F₁ and F₂
- Allows source feeder relaying at A to respond to a secondary ground fault at F₃ (Yₕnd-Yₕnd only)
- Ground current from DG makes fuse saving difficult
More on Wye gnd – Wye gnd Transformers – Are You Really Effectively Grounded ???

Effective Grounding Test

- $\frac{X_0}{X_1} < 3$
- $\frac{R_0}{X_1} < 1$
- Neutral rise on Unfaulted phase less than 140%
- $X_0 =$ Zero Sequence Reactance
- $X_1 =$ Positive Sequence Reactance
- $R_0 =$ Zero Sequence Resistance

Problems

Can supply the feeder circuit from a high-impedance source after substation breaker A trips, causing overvoltage for fault at F1
**More on Wye gnd – Wye gnd Transformers – Are You Really Effectively Grounded ??? --- Inverter Based Technology**

**Problems**
Can supply the feeder circuit from a high-impedance source after substation breaker A trips, causing overvoltage for fault at F1

**SOLUTION ?????**
Interposing Transformer can provide a grounded source if \( X_o/X_1 < 3 \) and \( R_o/X_1 < 1 \)
Inverter-Based DG Generators’ Impact on Distribution Feeders
Fault Behavior of Inverter Based DGs:

- Fault behavior Determined by Controls
- No Generalized DG models to Predict Fault Behavior
- Two Basic Types Based on Control Scheme.
  - Voltage Control
  - Current Control
- Hardware Protection in Many Cases Determines Fault and Overvoltage Capabilities.
Fault Current Contributions

- A1 determined by Impedance between DG and Fault – smaller the impedance higher the fault current. Threshold determined by hardware Typically 2-3pu

- T1 depends on control bandwidth. Current control – less than ½ cycle. Voltage control – several cycles.

- A2 determined by application requirements DG subject to during fault. Typically 1.0-1.3 pu

- T2 end when DG trips or fault is cleared. Future Voltage –ride through will extend this time. IEEE 1547 sets limits. T2 time critical to distribution coordination.

T1: transient fault duration
A1: transient fault current magnitude
T2: steady-state fault duration
A2: steady-state fault current magnitude
Fault Current Example:

<table>
<thead>
<tr>
<th>Distance between Substation to Lateral</th>
<th>DG Terminal Voltage (^{(1)})</th>
<th>DG Output Current (^{(2)})</th>
<th>DG Output Current Contribution (degrees that I lags behind V)</th>
<th>Trip Time (second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Miles</td>
<td>0.14 pu</td>
<td>1.2 pu</td>
<td>102.5</td>
<td>0.12</td>
</tr>
<tr>
<td>5 Miles</td>
<td>0.43 pu</td>
<td>1.2 pu</td>
<td>66.0</td>
<td>0.12</td>
</tr>
<tr>
<td>10 Miles</td>
<td>0.61 pu</td>
<td>1.2 pu</td>
<td>51.8</td>
<td>1.8</td>
</tr>
<tr>
<td>15 Miles</td>
<td>0.72 pu</td>
<td>1.2 pu</td>
<td>42.1</td>
<td>1.8</td>
</tr>
</tbody>
</table>

\(^{(1)}\), \(^{(2)}\): Voltage and current base is rated voltage and rated current of DG
Advantages

- Less fault current than a synchronous generator
- Makes fuse save easier
- Are there overvoltages due to neutral shift?
- Inverters are generally ungrounded

Problems

- Provides an unwanted fault current for supply circuit faults at $F_1$ and $F_2$
- Allows source feeder relaying at A to respond to a secondary ground fault at $F_3$ ($Y_{gnd}$-$Y_{gnd}$ only)
- Ground current duration from DG difficult to determine.
Wye gnd – Wye gnd Transformers – Are You Really Effectively Grounded ??? --- Traditional Utility Thinking

Problems

Can supply the feeder circuit from a high-impedance source after substation breaker A trips, causing overvoltage for fault at F1

SOLUTION ????

Interposing Transformer can provide a grounded source if Xo/X1 < 3 and Ro/X1 <1. But is this a good solution???
**Wye gnd – Wye gnd Main Transformers & Wye –Wye Ungrounded Interposing Trans.**

Voltages on the 480 V load bus during an LG fault on the customer side of a YgYg distribution transformer. Generation:load ratio = 1:1; inverter isolation transformer is YY (ungrounded).
Summary of Overvoltages for a Fault on Feeder:

Solid columns correspond to grounded inverters (grounded isolation transformers), and the cross-hatched columns correspond to ungrounded inverters. Delta of dist. Transformer is on the primary.
Interconnect Protection and Restoration
Comprehensive DG Interconnection Package: Ungrounded Transformer Primary
Comprehensive DG Interconnection Package: Wye-Grounded Transformer Primary

- **T**: Transfer Trip
- **R**: Fault Backfeed Removal
- **51N**: Multifunctional Relay
- **67**: 2 or 3 VT's
- **51V**: 3-CT
- **G**: DG
- **1-CT**: 1-CT
- **Substation**

* or 21 Function
** may be required depending on IPP size
CASE #1 - Local Load Exceeds Generation Restoration Practice

- Interconnection relays trip DG generator breakers (B&C)
- When utility restores, DG generator(s) auto synchronize to return to service

DG Trip & Restoration Possibilities

**Multifunction Intertie Relay**

- *Protection*
- *Supervises "A" Reclosing*
- *Trips "B" & "C"*
- *Trips Breakers B&C if:
  - Generation cannot support local load
  - Re-sync at breakers B&C after utility restoration*

UTILITY

LOADS

A

B

C

G

G

L
CASE #2 - Local Load Matches Generation Restoration Practice

- Interconnection relays trip main incoming breaker (A)
- When utility restores, 25 function (with $\Delta \Phi$, $\Delta F$, and $\Delta V$) supervises recloses A which is auto sync by switching VT Sources as shown
Key References:


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QUESTIONS?