Protection and Coordination for Solar Sites on the Distribution Power System

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Overview

- The Impacts of DG on feeder protection and the need for communications assisted tripping schemes
- Direct Transfer Tripping (DTT) Communication Scheme
- Mirror Bits
- Direct Fiber Attributes
DG Impact on Distribution Feeders

• Unintentional islanding
• Increased fault duty
• Relay desensitization
• Nuisance tripping
• Automatic reclosing
Unintentional Islanding

• Occurs when portion of area EPS and DR become electrically isolated from rest of area EPS and DR continues to energize island

• Should be avoided for two major reasons
  • There is potential for negative effects on voltage, frequency, and power quality
  • Islanded generator complicates both automatic reclosing and manual switching
Increased Fault Duty

- Is caused by addition of generating sources and rotating machinery of considerable size
- Affects capability of equipment to carry and interrupt fault currents
- Requires both local and area EPS equipment ratings to be reevaluated
Relay Desensitization

• Available short-circuit current increases with addition of DR
• Short-circuit current splits between substation and DR
• Substation short-circuit contribution can be significantly reduced when compared with value before addition of DR
Relay Desensitization
Fault Current Distribution Without DR

Substation

<table>
<thead>
<tr>
<th>Three-Phase</th>
<th>$3I_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>323 A</td>
<td>198 A</td>
</tr>
</tbody>
</table>

R1

R2

F1
Relay Desensitization
Fault Current Distribution With DR

Substation

<table>
<thead>
<tr>
<th>Substation</th>
<th>DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-Phase</td>
<td>3I₀</td>
</tr>
<tr>
<td>199 A</td>
<td>24 A</td>
</tr>
<tr>
<td>200 A</td>
<td>246 A</td>
</tr>
</tbody>
</table>

200 A
246 A
399 A
270 A

Substation
F1
Operation for Fault in Adjacent Zone

\[ I_{SYS} + I_{FAULT} \]

1. \[ I_{SYS} \] flows into the system.
2. \[ I_{FAULT} \] flows out of the system at node 1.
3. \[ I_{FAULT} \] flows into node 2.
4. \[ I_{FAULT} \] flows into node 3.
5. \[ I_{FAULT} \] flows into the adjacent zone.
Automatic Reclosing

- DR should be disconnected before open interval expires
  - By interconnection protection (81U, 81O, 59, 27)
  - By DTT
- Minimum open or dead time to allow arc deionization and to avoid restrike is
  \[ t = \frac{kV}{34.5} + 10.5 \text{ cycles} \]
Automatic Reclosing

Close Permissives

- Feeder and bus are in synchronism
- Utility bus is hot and line is dead
Nonconventional Power Sources
Under Fault Conditions
Challenges of Nonconventional Power Sources

• Cannot be represented as voltage source behind an impedance

• Do not generate
  • Continuous fault current
  • Any fault current

• Do not generate zero- and negative-sequence currents during nonsymmetrical faults (Type 3, Type 4, and PV)
1.2 MW Inverter Faulted Phase Quantities
1.2 MW Inverter Faulted Sequence Current
Type 4 Wind Turbine (Inverter)
BC Fault as seen from the DC Bus ("Behind Inverter")
Consequences of Nonconventional Power Source Behavior During Faults

- Traditional Overcurrent Elements may not operate
- Fault currents typically reach 1.5 to 1.7 times the inverter’s maximum load current at the moment the fault occurs (fault inception).
- 1-4 ms after fault inception, the inverter will continue to provide fault current at approximately 120% of nominal load current.
Consequences of Nonconventional Power Source Behavior During Faults

• Directional Elements no longer work as expected
  • The inverter produces no sequence currents.
  • The microprocessor relay does not have a polarizing quantity to accurately declare a fault direction.
Fault Behavior Summary by Source

Wind or PV Farm

Conventional Source

Diagram showing fault behavior summary by source.
Anti-Islanding Protection

IEEE 1547 general requirements to be met at point of common coupling (PCC)
# DR Response to Voltage Excursions

*Changed in 1547a-2014*

<table>
<thead>
<tr>
<th>Voltage Range (% of base voltage)</th>
<th>Clearing Time (s)</th>
<th>Clearing Time: Adjustable Up To and Including (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V &lt; 45</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>45 ≤ V &lt; 60</td>
<td>1.00</td>
<td>11</td>
</tr>
<tr>
<td>60 ≤ V &lt; 88</td>
<td>2.00</td>
<td>21</td>
</tr>
<tr>
<td>110 &lt; V &lt; 120</td>
<td>1.00</td>
<td>13</td>
</tr>
<tr>
<td>V ≥ 120</td>
<td>0.16</td>
<td>0.16</td>
</tr>
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## DR Response to Frequency Excursions

Changed in 1547a-2014

<table>
<thead>
<tr>
<th>Function</th>
<th>Default Settings</th>
<th>Range of Adjustability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency Range (Hz)</td>
<td>Clearing Time (s)</td>
</tr>
<tr>
<td>UF1</td>
<td>&lt; 57</td>
<td>0.16</td>
</tr>
<tr>
<td>UF2</td>
<td>&lt; 59.5</td>
<td>2</td>
</tr>
<tr>
<td>OF1</td>
<td>&gt; 60.5</td>
<td>2</td>
</tr>
<tr>
<td>OF2</td>
<td>&gt; 62</td>
<td>0.16</td>
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## Islanding Detection
### Elements and Typical DR Source Clearing

<table>
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<tr>
<th>SEL-751 Element</th>
<th>ANSI#</th>
<th>DR Source Clearing Time</th>
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<tr>
<td></td>
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<td>Assumes 3 cycle breaker</td>
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<tr>
<td>Under Voltage</td>
<td>27</td>
<td>0.16 – 2.0 seconds *</td>
</tr>
<tr>
<td>Under Frequency</td>
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<tr>
<td>Under Frequency Rate of change</td>
<td>81R</td>
<td>≈ 7 - 34 cycles Setting dependent</td>
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<tr>
<td>Under Frequency Fast rate of change</td>
<td>81RF</td>
<td>≈ 7 - 10 cycles Frequency rate of change dependent</td>
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<td>3 Phase Voltage Vector Shift</td>
<td>78VS</td>
<td>≈ 4 cycles</td>
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* Reference IEEE 1547 – 2003™
Possible Solutions:
Fast Rate of Change 81RF Element
Vector Shift 78VS Element
Negative Sequence Overvoltage (59Q)
Fast Rate of Change of Frequency

Definitions

• Change in Frequency (FREQ-FNOM)
  • Slip of the frequency
• Speed of the Change of Frequency (FREQ-FNOM)/s
  • Acceleration

In words, “Not only does the frequency have to change by a certain value but it also has to change at a certain rate.”
Fast Rate of Change of Frequency

Islanded

Connected

Acceleration

Slip Frequency

Islanded

Connected

0

0
Fast Rate of Change of Frequency Cont.

![Diagram](image.png)

DF3C Hz/s
(df/dt calculated over 3-cycle window)

Trip Region 1

Trip Region 2
SEL-751 78VS
Element Logic From IM
Simulation Results

Reference Vector data

Three phase vector shift seen at inception of fault and at EPS source clearing
In the cycle prior to 78VSO assertion:

$$VSA\_ang = \left(\frac{\text{Present} - \text{Ref}}{\text{Ref}}\right) \times 360$$

Assume Ref is 16.666 and Present = 17.680

$$VSA\_ang = \left(\frac{17.680 - 16.666}{16.666}\right) \times 360 = 21.9\ degrees$$
Advantages of the 78VS element

• Fastest Method of islanding detection
• Relies total on DR source voltage monitoring
• Includes under voltage supervision

Disadvantages of the 78VS element

• Requires 20% loading increase at islanding
• Requires system studies for secure settings
• Requires DR close circuit monitoring
# Islanding Detection

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Faulted Phase and Sequence Voltages of the Inverter
Set a Unbalanced Voltage Element
(Just like Weak Infeed Detection!)

- Assume maximum load conditions create a system unbalance 10%
- Assume a 5% safety margin
- The nominal system line-to-neutral system voltage in the previous example is 7.2 kV

\[
59Q \text{ Pickup} = 7.2 \text{ kV} \times (10\% + 5\%)
59Q \text{ Pickup} = 1.08 \text{ kV}
\]
Communications Assisted Tripping
Why Are Pilot Protection Schemes Required?

- Safeguard system stability
  - Minimize fault-clearing times
  - Allow high-speed reclosing
- Reduce equipment damage
- Improve power quality – reduce voltage sag duration
- Provide coordination – long-line and short-line applications
Types of Directional Comparison Protection Schemes

- DTT
- POTT
- PUTT
- DCB
- DCUB
Applying MIRRORED BITS Technology and Serial Radios for DTT
Mirrored Bits Communications
Mirrored Bits Communications
Transmit “Mirrored” to Receive

Relay 1

TRANSMIT

TMB1
TMB2
::
TMB8

RECEIVE

RMB1
RMB2
::
RMB8

1
0
0
0

Relay 2

TRANSMIT

TMB1
TMB2
::
TMB8

RECEIVE

RMB1
RMB2
::
RMB8

0
0
0
0
Understanding MIRRORED BITS Message

- Each message consists of 4 bytes
- Each byte contains 1 start bit, 6 TMBs, 1 parity bit, and 1 stop bit
- Each of the 8 TMBs is repeated three times within these 4 bytes
- Selected TMBs are inverted based on TX_ID setting to provide unique address used for loopback detection
When Mirrored Bits channel is operating correctly, ROK bit is set to 1

When channel is disturbed, ROK drops out
Understanding ROK and RBAD

Serial Data -> MIRRORED BITS Decoder and Integrity Checks -> ROK

RBAD Timer

RBAD
How Does CBAD Bit Work? How Would I Use It?

• Problem – channel is experiencing many short noise bursts (intermittent)

• Solution – CBAD provides means to measure and report channel unavailability
MIRRORED BITS Communications

Relay Without MIRRORED BITS

Relay With MIRRORED BITS
Relay Communications Media
Types of Digital Communications

- Direct fiber
- Multiplexed fiber optics
  - SONET
  - Ethernet
- Digital radio
Benefits of Fiber-Optic Cable

- High bandwidth
- Low attenuation
- Noise immunity
- Dielectric properties
- Lightweight
- Small size
- No arcs
• Wavelength is “color” of light in electromagnetic spectrum
• Attenuation of glass is reduced at higher wavelengths
• Standard wavelengths are 850, 1,300, and 1,550 nm

Now select the “pipe” to transmit the signal through
Fiber-Optic Cable Design

• Cladding bends light waves back toward fiber center and prevents leaking

• Core is glass medium through which light travels
Multimode Fiber

- Operates best at 850 and 1,300 nm
- Has core diameter of 50, 62.5, or 100 µm (large)
- Uses LED to transmit
- Disperses light waves into numerous paths as they travel through core
- Is good for short and medium distances (within building or campus)
- Has blue or orange jacket
Single-Mode Fiber

- Operates best at 1,300 and 1,550 nm
- Has core diameter of 8 to 10 µm (narrow)
- Uses laser diode to transmit
- Includes no distortion from overlapping light pulses
- Has higher bandwidth than multimode, up to 50 times more distance
- Has yellow jacket
Fiber-Optic Data Transmission

Input

Transmitter

LED or Laser

Connectors

Output

Receiver

Photodiode

Connectors
Considerations When Choosing Wavelength and Fiber Type

- Distance to cover
- Necessary bandwidth
- Budget
  - Fiber itself
  - Transmission hardware
- Multiplexerer involvement (IEEE C37.94)
Conclusions

• An Inverter cannot be represented as voltage source behind an impedance like traditional power sources.

• Traditional Distribution Protection struggles to detect fault currents supplied by inverters because inverters do not generate high fault or sequence currents.

• Voltage elements are a possible alternative to overcurrent elements (Vector shift is the fastest anti-islanding detection method).

• Communications-Assisted Tripping schemes are a simple and effective way to provide protection for a DG.
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