A Creative Line Differential Protection Scheme for the Hudson River Crossing Section of a 345kV Transmission Line

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Application overview

Roseton – East Fishkill 345kV line
- Under river (Hudson River) section WTS – ETS (1.3 mile)
  - Six 3-phase HPOF cables (pipes)

- Cable differential protection, required to...
  - detect cable fault
  - identify actual faulted cable (pipe)
  - at WTS-side, operate LORs to send DTT to Roseton to LO autoreclosing for a fault on the cable portion
Application overview

Situation prior to upgrade

- 18 obsolete solid state differential relays, all located at WTS
  - parts becoming an increasing problem
- To get ETS currents to WTS, used small gauge copper wires installed with the main conductors
- impedance matching transformers were required at ETS to ‘boost’ the strength of the transmitted current signals from ETS to WTS (impedance matching transformers: increased signs of degradation, replacements not readily available, would require a custom build)
Application overview

Requirements for upgrade

- Utilize the existing infrastructure, i.e. no fiber to be installed, so need to use the existing CT circuit copper wires as WTS – ETS inter-IED communications interface
- Do away with the impedance matching transformers - must not be required
- Utilize WTS LORs (lockout relays) and existing DTT (direct transfer trip) equipment and infrastructure
- Identify the faulted phase/s, as well as the actual faulted cable (pipe)
Application overview

New solution
- Install modern numerical line differential IEDs at WTS and ETS
- Optimum solution – 6 IEDs, 2 IEDs per pipe pair
Application overview

87L for pipes 1 and 6

- LDCM (Line Data Communications Module), with X.21 output
- Modem (with X.21 plug-in module) to interconnect the line differential IEDs using the copper wires
- BT insulating barrier transformer
Verification of copper wire usability as communications interface

Measurements made for line attenuation and signal-to-noise (checking purity of the copper)

Result:

Existing copper wires OK to use as communications interface
Operate/Restraint characteristic

- Minimum pickup (IdMin) + one or more slopes
- Operate area above the characteristic
- Operate current (Y-axis value)
  - \( I_{\text{Op}_A} = I_{\text{Diff}_A} = I_{L_A} + I_{R_A} \)
  - Similarly for phases B and C
- Restrain current (X-axis value)
  - Different methods
  - This application
    \[ I_{\text{Res}} = \text{MAX}(|I_{L_A}|, |I_{L_B}|, |I_{L_C}|, |I_{R_A}|, |I_{R_B}|, |I_{R_C}|), \]
      common for all 3 phases
87L – this application

87L characteristic

- Section 1: Minimum pickup
- Section 2: Slope 1
- Section 3: Slope 2

- IDiff (pu)
- Restraint (pu)

- ROSETON
  - WTS
  - ETS

- Data points:
  - Slope = 0.4 at IDiff = 1.25
  - Slope = 0.8 at IDiff = 3.00

- Variables:
  - Local_WTS_P1_currents
  - Local_WTS_P6_currents
  - Remote_ETS_P1_currents
  - Remote_ETS_P6_currents
  - Current1
  - Current2
  - Current3
  - Current4
  - Current5
  - Current6

- Trip
- Pickup

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Faulted pipe identification

The 87L function will…
- operate for an internal fault in the pipe pair (1&6, 2&5, 3&4)
- indicate the faulted phase/s

To determine the actual faulted pipe, need to establish two additional differential zones, one per pipe
Faulted pipe identification

Pipe differential zone

- Sum WTS + ETS currents, per phase, per pipe
Faulted pipe identification

Fault levels

For cables in service < 6

Pickup setting for 50 overcurrent function measuring pipe differential currents?
Faulted pipe identification

3-step IDiff 50 overcurrent function, per pipe

3-step 50 (@ WTS P1_IDiff)

<table>
<thead>
<tr>
<th>Block1</th>
<th>Pickup1_A</th>
<th>Pickup1_B</th>
<th>Pickup1_C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block2</td>
<td>Pickup2_A</td>
<td>Pickup2_B</td>
<td>Pickup2_C</td>
</tr>
<tr>
<td>Block3</td>
<td>Pickup3_A</td>
<td>Pickup3_B</td>
<td>Pickup3_C</td>
</tr>
</tbody>
</table>

Step 1: Pickup1_A > logic1 for IDiff_A > set step1 pickup threshold. Pickup1_A = logic0 for Block1 input = logic1
Likewise step1 Pickup1_C

Likewise step2 and step3

3-step 50 (@ WTS P6_IDiff)

<table>
<thead>
<tr>
<th>Block1</th>
<th>Pickup1_A</th>
<th>Pickup1_B</th>
<th>Pickup1_C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block2</td>
<td>Pickup2_A</td>
<td>Pickup2_B</td>
<td>Pickup2_C</td>
</tr>
<tr>
<td>Block3</td>
<td>Pickup3_A</td>
<td>Pickup3_B</td>
<td>Pickup3_C</td>
</tr>
</tbody>
</table>

Likewise for P6
Faulted pipe identification

IRestraint 50 overcurrent functions, per pipe (shown for P1)
Faulted pipe identification “characteristic”

- More sensitive than 87L characteristic
- Task 1: select values for IRestraint> and IRestraint>>
  - IRestraint>: set = 1.75 pu
  - IRestraint>>: set = 3.50 pu
- Task 2: select values for 3-step IDiff 50 function
  - Step1: set = 87L minimum pickup = 0.30 pu
  - Step2: set = 87L pickup at IRestraint = 1.75 pu
  - Step3: set = 87L pickup at IRestraint = 3.50 pu

Step2: set = 0.30 + (0.40*(1.75 - 1.25))
= 0.50 pu

Step3: set = 0.30 + (0.40*(3.00 - 1.25))
+ (0.80*(3.50 - 3.00))
= 1.40 pu
Faulted pipe identification

Faulted pipe identification “characteristic” + 87L characteristic
Faulted pipe identification, per phase
Faulted pipe identification

LOR relay operation

- 87L trip
- Pipe1 fault
  - No faulted pipe identified
- t 0
  - Faulted pipe identified
- Pipe6 fault
  - No faulted pipe identified
- OR
  - Pulse timer
  - Operate pipe1 LOR
- OR
  - No faulted pipe identified
- OR
  - Pulse timer
  - Operate pipe6 LOR
- OR
  - Faulted pipe identified
Evaluation Testing (FAT)

Complete assembly of both IED panels, including the communications interconnections

- Also served as a ‘dry-run’ for the on-site commissioning
# Evaluation Testing (FAT)

## Single ended

<table>
<thead>
<tr>
<th>Inject @ WTS IED</th>
<th>Inject @ ETS IED</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00</td>
<td>2.0</td>
</tr>
<tr>
<td>6.25</td>
<td>2.0</td>
</tr>
<tr>
<td>8.25</td>
<td>2.0</td>
</tr>
<tr>
<td>9.25</td>
<td>2.0</td>
</tr>
<tr>
<td>12.50</td>
<td>2.0</td>
</tr>
<tr>
<td>15.00</td>
<td>2.0</td>
</tr>
<tr>
<td>17.00</td>
<td>2.0</td>
</tr>
<tr>
<td>18.00</td>
<td>2.0</td>
</tr>
</tbody>
</table>

![Graph showing IDiff vs restraint values]
5.00A (= 1 pu) phase A injection at WTS IED

- $Loc_{WTS\_P1\_IA} =$ injected current
- $IDiff_{P1\_IA} = Loc_{WTS\_P1\_IA} + Rem_{ETS\_P1\_IA}$

- Output from $\sum$
  - released on 87L pickup
  - connected to the P1 pipe identification 3-step IDiff 50 overcurrent function
Evaluation Testing (FAT)

Single ended, cont.

- 5.00A (= 1 pu) phase A injection at WTS IED
  - No Restraint level exceeded
    - No steps of the 3-step IDiff 50 overcurrent function are blocked
  - IDiff 50 overcurrent function
    - P1 differential current > step1 and step2, but < step3
Evaluation Testing (FAT)

Single ended, cont.

- 5.00A (= 1 pu) phase A injection at WTS IED
- 87L pickup and trip, phase A
- P1 fault identified, phase A
- Restrain level > (IB>) not exceeded
- IDiff 50 function pickup step 1 phase A
- Restrain level >> (IB>>) not exceeded
- IDiff 50 function pickup step 2 phase A
- Operate P1 LOR
Evaluation Testing (FAT)

Single ended, cont.

- 15.00A (= 3 pu) phase A injection at WTS IED
  - $Loc_{WTS\_P1\_IA}$ = injected current
  - $IDiff_{P1\_IA} = Loc_{WTS\_P1\_IA} + Rem_{ETS\_P1\_IA}$
- Output from $\sum$
  - released on 87L pickup
  - connected to the P1 pipe identification 3-step IDiff 50 overcurrent function
Evaluation Testing (FAT)

Single ended, cont.

- 15.00A (= 3 pu) phase A injection at WTS IED
  - Restraint level \( I_{\text{Restraint}} > \) is exceeded, but not \( I_{\text{Restraint}} >> \)
    - Step1 of the 3-step \( I_{\text{Diff}} 50 \) overcurrent function will be blocked
  - \( I_{\text{Diff}} 50 \) overcurrent function
    - \( P1 \) differential current > all steps, but step1 is blocked
Evaluation Testing (FAT)

Single ended, cont.

- 15.00A (= 3 pu) phase A injection at WTS IED
- 87L pickup and trip, phase A
- P1 fault identified, phase A
- Restrain level > (IB>) exceeded
- Restrain level >> (IB>>) not exceeded
- IDiff 50 function pickup step2 phase A
- IDiff 50 function pickup step3 phase A
- Operate P1 LOR
## Evaluation Testing (FAT)

Double ended, 2 stage injection
- stage1, balanced through current
- stage2, reduce one side by a pre-determined amount

<table>
<thead>
<tr>
<th>Inject @ WTS IED</th>
<th>Inject @ ETS IED</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.50 0° 300 ~</td>
<td>2.50 180° 300 ~</td>
</tr>
<tr>
<td>2.50 0° 2.0 ~</td>
<td>0.50 180° 2.0 ~</td>
</tr>
<tr>
<td>5.00 0° 300 ~</td>
<td>5.00 180° 300 ~</td>
</tr>
<tr>
<td>5.00 0° 2.0 ~</td>
<td>3.00 180° 2.0 ~</td>
</tr>
<tr>
<td>6.25 0° 300 ~</td>
<td>6.25 180° 300 ~</td>
</tr>
<tr>
<td>6.25 0° 2.0 ~</td>
<td>4.25 180° 2.0 ~</td>
</tr>
<tr>
<td>8.25 0° 300 ~</td>
<td>8.25 180° 300 ~</td>
</tr>
<tr>
<td>8.25 0° 2.0 ~</td>
<td>5.45 180° 2.0 ~</td>
</tr>
<tr>
<td>9.25 0° 300 ~</td>
<td>9.25 180° 300 ~</td>
</tr>
<tr>
<td>9.25 0° 2.0 ~</td>
<td>6.05 180° 2.0 ~</td>
</tr>
<tr>
<td>12.50 0° 300 ~</td>
<td>12.50 180° 300 ~</td>
</tr>
<tr>
<td>12.50 0° 2.0 ~</td>
<td>8.00 180° 2.0 ~</td>
</tr>
<tr>
<td>15.00 0° 300 ~</td>
<td>15.00 180° 300 ~</td>
</tr>
<tr>
<td>15.00 0° 2.0 ~</td>
<td>9.50 180° 2.0 ~</td>
</tr>
<tr>
<td>17.00 0° 300 ~</td>
<td>17.00 180° 300 ~</td>
</tr>
<tr>
<td>17.00 0° 2.0 ~</td>
<td>9.90 180° 2.0 ~</td>
</tr>
<tr>
<td>18.00 0° 500 ~</td>
<td>18.00 180° 500 ~</td>
</tr>
<tr>
<td>18.00 0° 2.0 ~</td>
<td>10.10 180° 2.0 ~</td>
</tr>
</tbody>
</table>
Evaluation Testing (FAT)

Double ended, 2 stage injection

– At IRestraint (X-axis) = 2.50A = 0.50 pu, IDiff (Y-axis) value for pickup = 0.30 pu
– Add margin of 0.10 pu → 0.40 pu = 2.00A

– Stage2, keep one current (WTS) unchanged (= 2.50A), and drop the other (ETS) by 2.00A to 0.50A
– X-axis point remains unchanged, and Y-axis point jumps to 0.40 pu

– Expected result: P1 fault identified, phase A
– No restraint level exceeded, no IDiff 50 overcurrent function steps blocked, only step1 pickup phase A
Evaluation Testing (FAT)

Double ended, 2 stage injection

– At IRestraint (X-axis) = 9.25A = 1.85 pu, IDiff (Y-axis) value for pickup = 0.54 pu
– Add margin of 0.10 pu → 0.64 pu = 3.20A

– Stage2, keep one current (WTS) unchanged (= 9.25A), and drop the other (ETS) by 3.20A to 6.05A
– X-axis point remains unchanged, and Y-axis point jumps to 0.64 pu

– Expected result: P1 fault identified, phase A
– Restraint level (> ) exceeded, step1 of IDiff 50 overcurrent function blocked, only step2 pickup phase A
Conclusion

FAT

- Successful – ‘expected’ operation for all test cases

- E.G. for test indicated
  - \( I_{\text{Diff}} = 1.85 \text{ pu} \gg \) pickup setting = 0.30 pu (step1)
  - \( I_{\text{Restraint}} = 1.85 \text{ pu} \) just > pickup setting = 1.75 pu (\( I_{\text{Restraint}} > \))
  - \( I_{\text{Diff}} \) step1 operated faster than \( I_{\text{Restraint}} \), picking up momentarily before being blocked by \( I_{\text{Restraint}} \) pickup
  - OK for increased margin between \( I_{\text{Restraint}} \) and pickup setting
  - ‘Gray’ area around the transition point

Commissioning

- Put into service 12 May 2017
- All equipment, including the communications, has to date performed as expected