Impact of Inverter-based Resources on Impedance-based Protection Functions

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Introduction

- Fault current characteristic of IBRs depends on
  - Its control logic
  - Control settings
  - Pre-fault condition

- For unbalanced faults, IBR may inject
  - only positive sequence current
  - positive sequence and undesired negative sequence
  - positive sequence and desired negative sequence

- Latest German code mandates negative sequence current injection
Introduction

• Phase selection and direction based on negative sequence may be impacted

• Relay vendors use different techniques to implement 21
  • Phase comparator
  • Different methods to estimate X and R

• Analyze the impact by
  • Theory
  • Simulation
  • Hardware Test
FRT Requirements

- Dynamic Positive Sequence (DPS) injection
  \[ I_{1q} = jK_1 \times (|V_{1\text{fault}}| - |V_{1\text{pre-fault}}|) \]
  \( \angle V_1 \) is reference

- Dynamic Positive and Negative Sequence (DPNS) injection
  \[ I_2 = jK_2 \times (|V_{2\text{fault}}| - |V_{2\text{pre-fault}}|) \angle V_2 \]

- Rest of the capacity may be used for \( I_{1d} \)
Test System and High-Level Evaluation

- Unknown non-homogeneity in DPS and DPNS
Test System and High-Level Evaluation

- Voltage profile of healthy phases (AG fault)
Test System and High-Level Evaluation

- Change in positive sequence voltage angle

**Strong System**

**Weak System**
Impedance-based Protection Function

• Phase comparator
  • Mho Characteristic
    \[ S_{Pol} = V_{mem1} \]
    \[ S_{Opr} = -V_a + Z_{Set}(I_a + K_0 I_0) \]
  
  
• In DPS, susceptible to
  • Smaller expansion
  • Larger non-homogeneity

\[ S_{Pol} = V_{mem1} (bc) = -j V_{mem1} \]
\[ S_{Opr} = -V_{bc} + Z_{Set} I_{bc} \]
Impedance-based Protection Function

- **Quadrilateral (Ground)**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Polarizing signal</th>
<th>Operating signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactance</td>
<td>$jI_0$ or $jI_2$</td>
<td>$Z (I + K_0 I_0) - V$</td>
</tr>
<tr>
<td>Reverse reactance</td>
<td>$jI_0$ or $jI_2$</td>
<td>$Z_{Rev} (I + K_0 I_0) - V$</td>
</tr>
<tr>
<td>Right blinder</td>
<td>$Z_R (I_a + K_0 I_0)$</td>
<td>$- V + Z_R (I_a + K_0 I_0)$</td>
</tr>
<tr>
<td>Left blinder</td>
<td>$Z_L (I_a + K_0 I_0)$</td>
<td>$- V + Z_L (I_a + K_0 I_0)$</td>
</tr>
</tbody>
</table>

- **In DPS,**
  - Use of $I_2$ results in mal-operation
  - Higher Non-homogeneity
Impedance-based Protection Function

• Impedance Measurement
  • Method I
    \[ mZ_1 = \frac{V_a}{(I_a+K_0 I_0)} \]
  • Error is introduced in estimated resistance and reactance
  • Method II
    \[ R_{seen} = \frac{Im\{V_a\} Im\{I_X\} + Re\{V_a\} Re\{I_X\}}{Re\{I_X\} Re\{I_R\} + Im\{I_X\} Im\{I_R\}} \]
    \[ mX_1 = \frac{Im\{V_a\} Re\{I_R\} - Re\{V_a\} Im\{I_R\}}{Re\{I_X\} Re\{I_R\} + Im\{I_X\} Im\{I_R\}} \]
    \[ I_R = I_a + \left(\frac{R_0}{R_1}\right) I_0 \text{ and } I_X = I_a + \left(\frac{X_0}{X_1}\right) I_0 \]
  • Error is introduced in estimated resistance
Impedance Measurement

• Method III

\[ mX_1 = \text{Im}\{ V_a I_F^* \} / \text{Im}\{ (R_1/X_1 + j)(I_a + K_0 I_0) I_F^* \} \]

\[ R_F = \text{Im}\{ V_a (Z_1^* (I + K_0 I_0))^* \} / \text{Im}\{ I_F (Z_1^* (I + K_0 I_0))^* \} \]

• \( I_F \) is estimated by \( 3I_0, 3I_2, 1.5I_2 + 1.5I_0 \)

• In DPS,
  
  • \( 3I_2 \) shall be avoided.
  
  • \( R_F \) estimation is adversely impacted when \( 1.5I_2 + 1.5I_0 \) is used
  
  • \( 3I_0 \) may be not be a good choice if there is a mutual coupling
Impedance Measurement

- **Method III Phase loop**
  
  \[ mX_1 = \text{Im}\{V_{bc} \times I_{\text{comp}}^*\} \sin \varphi / \text{Im}\{(R_1/X_1+j)I_{bc} \times I_{\text{comp}}^*\} \]
  
  \[ 0.5R_F = \text{Im}\{V_{bc} (Z_1 I_{bc})^*\} / \text{Im}\{2 I_{\text{comp}} (Z_1 I_{bc})^*\} \]

- \( I_{\text{comp}} = j1.73 \ I_2 \) for BC

- This method will not work correctly for DPS injection.
**Impedance Measurement**

- **Method IV**

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<thead>
<tr>
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<tbody>
<tr>
<td>Reactance</td>
<td>$jI_0$ or $jI_2$</td>
<td>$Z (I + K_0 I_0) - V$</td>
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<td>$Z_{rev} (I + K_0 I_0) - V$</td>
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</table>

$$R_F = \text{Im}\{ V_a (Z_1^* (I + K_0 I_0))^* \}/\text{Im}\{I_F (Z_1^* (I + K_0 I_0))^* \}$$

- **In DPS,**
  - $3I_2$ shall be avoided.
  - $R_F$ estimation is adversely impacted when $1.5I_2 + 1.5I_0$ is used.
  - $3I_0$ may be not be a good choice if there is a mutual coupling.
Simulation and Test Results

- **Phase Comparator (Mho)**
  
  - Expected trip for LG fault in a strong system
    
    ![Graph](image1.png)
    
    Expected trip for LG fault in a weak system
    
    ![Graph](image2.png)
  
  - Hardware test

<table>
<thead>
<tr>
<th>IBR injection</th>
<th>Fault location (from IBR)</th>
<th>RF</th>
<th>Expected Trip (ETAP)</th>
<th>Relay Output (D60)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPNS</td>
<td>60</td>
<td>35</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>DPNS</td>
<td>60</td>
<td>45</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>DPS</td>
<td>60</td>
<td>15</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>DPS</td>
<td>60</td>
<td>25</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
Simulation and Test Results

• Impedance-based Methods

$\Delta R_{\text{seen}}$ for LG fault in a strong system at $R_f = 5$ ohms

$\Delta R_{\text{seen}}$ for LG fault in a weak system at $R_f = 5$ ohms
Simulation and Test Results

- Impedance-based Methods

$\Delta X_{\text{seen}}$ for LG fault in a strong system at $R_f = 5 \text{ ohms}$

$\Delta X_{\text{seen}}$ for LG fault in a weak system at $R_f = 5 \text{ ohms}$
Simulation and Test Results

- Method 3 set to over $R_F = 20$ ohm
- LL Fault, DPNS
- Adversely impacted by infeed
Summary

- Lack of negative sequence injection by IBR results in
  - High voltage in healthy phases
  - Smaller voltage angle change (fault and pre-fault)
  - Unknown non-homogeneity effect
- Phase Comparator Method – Smaller resistive coverage for LG, LL faults
- Impedance based for LG faults
  - Method I, II and Method III with 3 $I_0$ are not affected
  - Method III employing 3 $I_2$, 1.5$I_0$+1.5$I_2$ should be avoided
Thank You!
Questions?