A Study on the Protection system for DC Distribution Lines

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1. Background
1.1 Trend of DC distribution system

- **Increase of DC-based applications**

**Internet Data Center**
- Most loads in IDC
  - DC-based server computer
  - Improve the efficiency with DC distribution system
- DC-based IDCs have already constructed and are operating

**DC Home**
- Increase of digital loads in home (TV, PC, LED etc.)
- Introduction of the concept “Zero Net Energy”
- To interconnect efficiently & easily with DER and ESS

**Dispatchable system**
- The system to dispatch DC power to loads
  - To replace conventional one
- Immature protection system in the case of DC-based system
  - To require the development of reliable protection systems
1. Background
1.2 A review on DC distribution system

◆ The limitations of existing researches on protection system for DC distribution lines

A. Rapid fault detection & interruption
   – To protect AC/DC converter (Specifically, the anti-parallel diodes in the AC/DC converter)
     ➔ Possibility to cause **malfunction of protective devices**

B. Protective relay setting in application of non-unit protection methods
   – To be able to protect wide area system
     ➔ **Hard to coordinate** protection system using setting values

C. Protection coordination using communication
   – Effective in monitoring and controlling power system
     ➔ Concern about **poor reliability & financial burden** due to communication errors

*The proposed protection system for DC distribution system*

➔ **Transient-state based distance** (Impedance) relay system

1. Rapid & Exact protection method
2. Prevention from malfunction
2. Protection of DC distribution lines

2.1 DC fault characteristics

- DC faults in distribution lines
  - DC fault characteristics
    - Three factors to contribute the fault current
      - Damage to anti-parallel diodes

\[
\begin{align*}
  i_{\text{fault}(1)}(t) &= e^{-\left(\frac{R}{L}t\right)} \sqrt{\frac{L}{B^2}} \sin(\omega_d t + \theta) \\
  i_{\text{fault}(2)}(t) &= -L_0 e^{-\left(\frac{R}{L}t\right)} \\
  i_{\text{fault}(3)}(t) &= \frac{V_s}{R} \left( i_{\text{fault}(1)}(t_1) - \frac{V_s}{R} e^{-\left(\frac{R}{L}t\right)} \right)
\end{align*}
\]

\(\star\) Fig. 1. DC fault characteristics in line fault

\[ B = \frac{2v_d - R_i I_d}{2L_i} \quad \omega_d = \sqrt{\left(\frac{v_d}{C_{\text{DC-link}}}\right)^{-1} - \left(\frac{R}{2L}\right)^2} \]
2. Protection of DC distribution lines

2.2 Protection requirements

**DC fault characteristics**
- To require fast interruption
  - Protection of AC/DC converter (Speed)

**Protection system**
- To identify fault section exactly
  - High reliability of distribution system (Selectivity)

**Interconnection with DG**
- To detect sympathetic tripping
  - Prevention from malfunction of protective devices (Sensitivity)

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**The concept of DC protection system**

- Trigger to algorithm using current derivative \(\frac{di}{dt}\)
- Fault detection using the proposed distance relay

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**Limitations of steady state-based method**

1. **Additional time** is needed to converge the quantities \((I \ & \ V)\) after the fault occurrence
   - Delay to detect fault
2. Dependent on **load capacity**
   - Decrease of accuracy
3. The proposed protection system
3.1 The principle of the proposed method

The proposed distance relay method

- Transient state-based method is used to detect DC faults rapidly
  - “No zero frequency” during transient state

Step 1. To calculate transient-based impedance using $V_L$ & $I_L$ under fault condition
Step 2. To analyze the magnitude of impedance ($|Z'_{fault}|$) & phase angle ($\theta_{fault}$) using DFT
Step 3. To calculate transient reactance ($X'_{fault}$) using impedance Triangle
Step 4. To calculate $d_X$ using $X'_{fault}$ per $X'_{total-line}$

\[
Z'_{line} = R_{line} + jX'_{line} = R_{line} + j2\pi f L'_{line} \quad (\therefore f \neq 0) \quad (1)
\]

\[
Z_{fault}' = (V'(+)-V'(-))/I_{line} \quad (2)
\]

\[
d_X = X'_{fault}/X'_{total-line} \times 100(\%)
\]

※ DFT : Discrete Fourier Transform

Fig. 2. Diagram of Impedance Triangle
3. The proposed protection system

3.1 The principle of the proposed method

**Prevention of malfunction**

**Sym pathetic Tripping**

- **DC fault occurs in distribution line**
  - Increase of current magnitude on distribution lines interconnected with DG
  - To trip CB on healthy lines → Outage

- **Application of current derivative method**
  - Sensitive to the change of current
  - Sympathetic tripping → Directional relay

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**Fig. 3. Concept of Sympathetic Tripping**

- Pre-fault state
- Post-fault state

- Magnitude: +5.3kA
- Magnitude: -162A
3. The proposed protection system
3.2 The protection algorithm for protecting distribution lines

- The proposed protection algorithm

< Procedure >

① Calculation of current derivative
  - To trigger algorithm
  - To prevent malfunction
    (sympathetic tripping)

② Calculation of transient-based impedance

③ Performance of DFT for fixed time-window

④ Calculation of $d_X$

⑤ Identification the fault within specific protection area (Zone 1)

Fig. 4. The proposed protection algorithm
4. Simulation results
4.1 Test system & simulation conditions

- Test system modeled using Electromechanical Transients Program (EMTP)
  - 3-division 2-link DC distribution system in radial type
  - To use line parameters of real Korean distribution systems
- Tie switches are normally opened (N/O)

Fig. 5. Test system
4. Simulation results
4.1 Test system & simulation conditions

◆ Simulation conditions

- The parameters for test systems are summarized in Table 1
  - Operation time for Zone 1: The time to require until detecting a DC fault
  - Interruption time of CB: The time to operate CB physically after fault detection

Table 1. Simulation conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Input value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution voltage level</td>
<td>1500Vdc</td>
</tr>
<tr>
<td>The number of poles</td>
<td>Uni-pole</td>
</tr>
<tr>
<td>Line length (for each section)</td>
<td>2km</td>
</tr>
<tr>
<td>Line resistance ($R_L$)</td>
<td>0.164 $\Omega$/km</td>
</tr>
<tr>
<td>Line inductance ($X_L$)</td>
<td>0.26 mH/km</td>
</tr>
<tr>
<td>Pick-up value for current derivative</td>
<td>(+) 5 kA/$\mu$s</td>
</tr>
<tr>
<td>Range of Zone 1</td>
<td>80%</td>
</tr>
<tr>
<td>Operation time for Zone 1 (Fault detection)</td>
<td>1ms</td>
</tr>
<tr>
<td>Interruption time of CB</td>
<td>2ms</td>
</tr>
</tbody>
</table>
4. Simulation results
4.2 Performances of the proposed protection system

1) DC fault within the protective section or outside

- To verify if CBs operate only for the protective section
  - If **high initial current derivative**Rightarrow trigger the algorithm
    ① Case I & II Rightarrow within the protective section (~80%)
    → Fault detection and CB operation
    ② Case III Rightarrow Outside of the protective section
    → No operation of CB

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Case I(10%)</th>
<th>Case II(50%)</th>
<th>Case III(90%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Z' fault</td>
<td>[Ω]</td>
<td>0.078814</td>
</tr>
<tr>
<td>θ fault [deg]</td>
<td>26.195</td>
<td>36.84</td>
<td>31.887</td>
</tr>
<tr>
<td>X' fault [Ω]</td>
<td>0.03479</td>
<td>0.24239</td>
<td>0.31268</td>
</tr>
<tr>
<td>dx [%] – 100%</td>
<td>12.43</td>
<td>86.57</td>
<td>111.67</td>
</tr>
<tr>
<td>di/dt [kA/μs] – (+)5kA/μs</td>
<td>2485.4</td>
<td>523.28</td>
<td>284.6</td>
</tr>
<tr>
<td>CB operation</td>
<td>Open</td>
<td>Open</td>
<td>Not open</td>
</tr>
</tbody>
</table>
2) Malfunction - Sympathetic tripping

- To verify the performance to prevent sympathetic tripping of CB on healthy line
  - Simulation scenario
    ① Feeder A: DC fault occurrence
    ② Feeder B: Interconnection of DG
  - **Sympathetic tripping**: #5 line protective relay could be tripped
    - To consider *directional function* of current derivative
    - Prevention of sympathetic tripping

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#5 line protective relay are not tripped although the current derivative has high magnitude because of its direction

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Fig. 6. Waveform of reverse current derivative by interconnection of DG
5. Conclusions

The proposed protection system

- To protect distribution lines in DC distribution systems
  - To propose new distance relay method for DC distribution systems
    - Transient impedance-based method
  - To prevent malfunction by sympathetic tripping
    - Use of sign of current derivative

Simulations & Verification using EMTP

- To model test system based on real data of Korean distribution systems
  - Line parameters, 3-division 2-link configuration

- Simulations for various cases
  - A DC fault occurs at different fault location on distribution lines
  - The situation that sympathetic tripping could occur

- It verifies that the proposed protection system is effective to protect DC faults on distribution lines
6. Future & related works

**Future works**

- The current study targets radial DC distribution systems under **the condition of N/O state**
  - Future works are to develop **the advanced protection system**
    1. Transient analysis under the condition of **N/C state**
    2. Consideration of the conventional protection system (To check the limitations)
    3. Development of the **advanced protection system under the condition of N/C state**
6. Future & related works

Related works

- We’ve already developed the integrated protection system for DC distribution systems
  - Integrated protection system coordinating both protection systems
    ① Line protection system (discussed in this presentation)
    ② Bus protection system (not included in this presentation)
    ③ Integrated protection system for DC distribution systems
Thank you!