# A Study on the Protection system for DC Distribution Lines

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# Contents

# 1. Background

## 1.1 Trend of DC distribution system

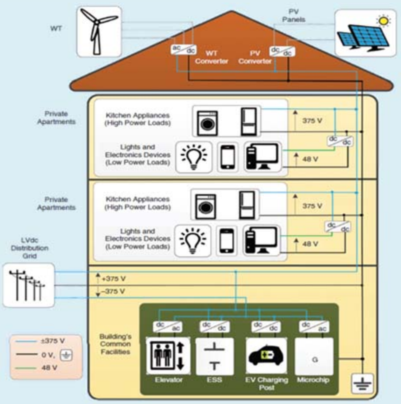
### ◆ Increase of DC-based applications

**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***

✓ Protection system for **DC distribution lines**

→ **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

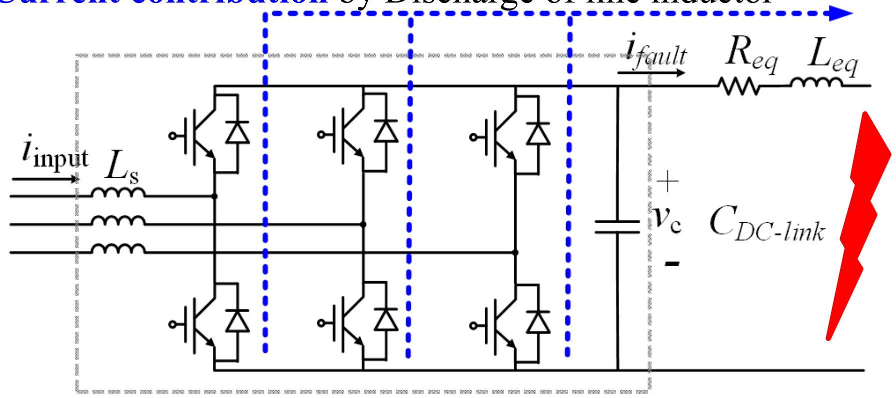
→ **Damage to anti-parallel diodes**

$$i_{fault(1)}(t) = e^{-(R_{eq}/2L_{eq})t}\sqrt{I_0^2+B^2}\,sin(\omega_d t+\theta) \quad (1)$$

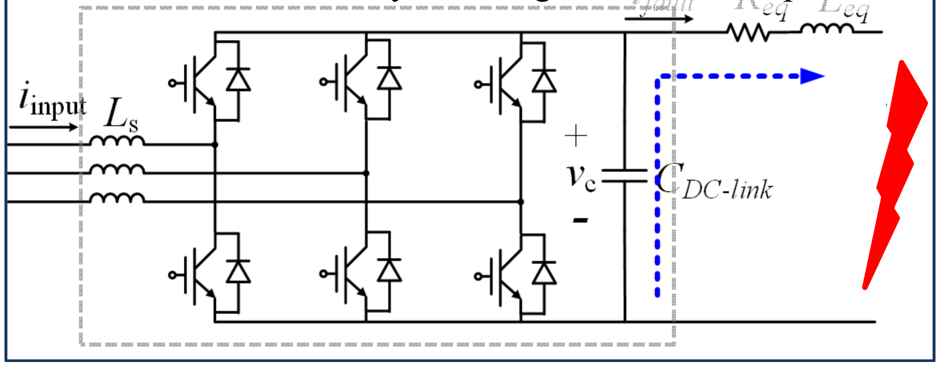
$$i_{fault(2)}(t) = -I_{Lo}e^{-(R_{eq}/L_{eq})t} \quad (2)$$

$$i_{fault(3)}(t) = \frac{V_s}{R_{eq}} + \left(i_{fault(1)}(t_1) - \frac{V_s}{R_{eq}}\right)e^{-(R_{eq}/L_{eq})t} \quad (3)$$

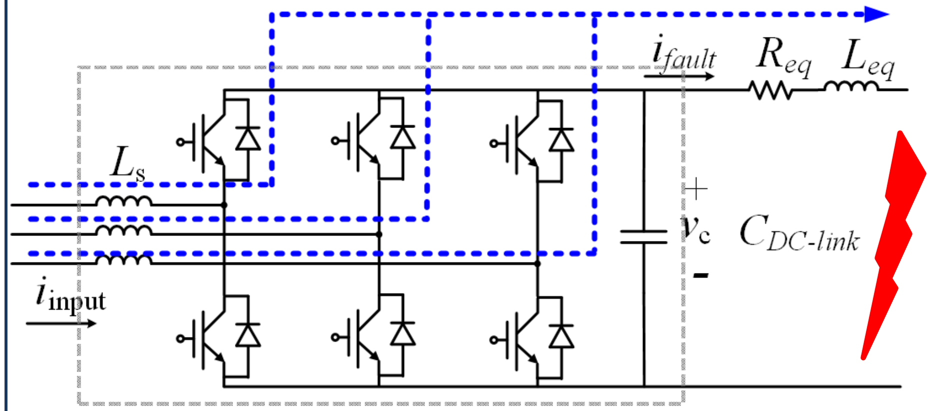
**Current contribution** by Discharge of line inductor




**Current contribution** by Discharge of DC-link capacitor




**Current contribution** by AC source




※ $B=(2v_C - R_{eq}I_o)/2L_{eq}\omega_d$ $\quad \omega_d = \sqrt{(L_{eq}C_{DC-link})^{-1} - (R_{eq}/2L_{eq})^2}$

Fig. 1. DC fault characteristics in line fault

# 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)**

**The concept of DC protection system**

**Trigger to algorithm** using **current derivative(*di*/*dt*)**

+

**Fault detection** using **the proposed distance relay**

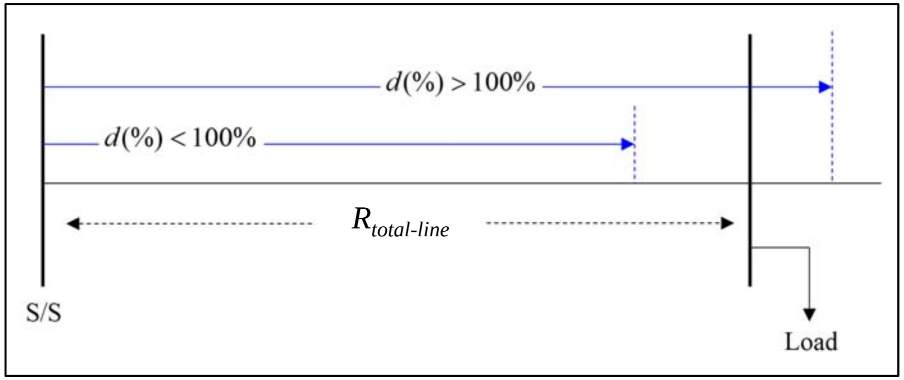
***Limitations of steady state-based method***

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**

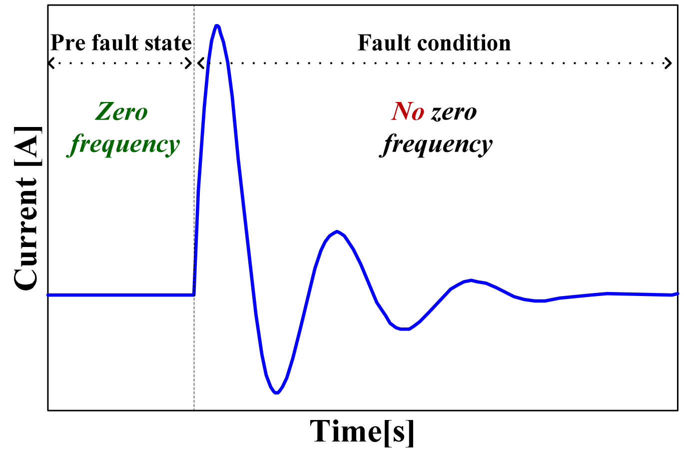
- **Transient state-based method is used to detect DC faults rapidly**
  - "No zero frequency" during transient state

**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 $X'_{total\text{-}line}$




$$Z'_{line} = R_{line} + jX'_{line} = R_{line} + j2\pi f L'_{line} \quad (\because f \neq 0) \qquad (1)$$

$$Z_{fault}' = (V'_{(+)} - V'_{(-)})/I_{line}' \qquad (2)$$

$$d_X = X'_{fault} / X'_{tatal-line} \times 100(\%) \qquad (3)$$

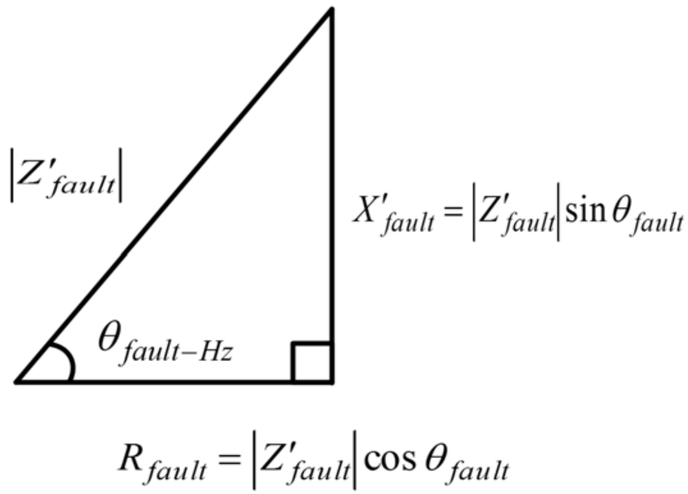



Fig. 2. Diagram of Impedance Triangle

※ DFT : Discrete Fourier Transform

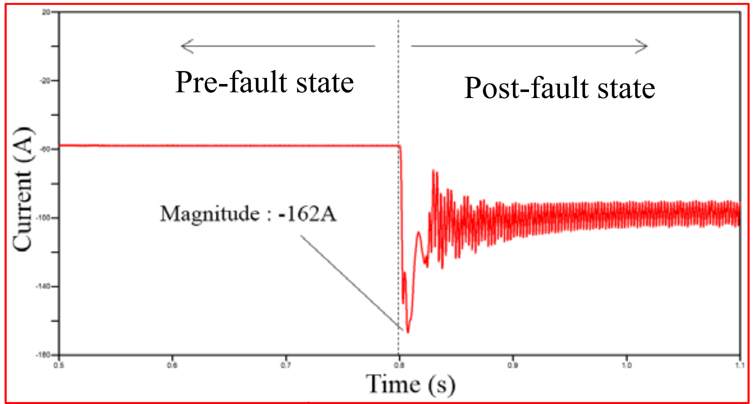
# 3. The proposed protection system

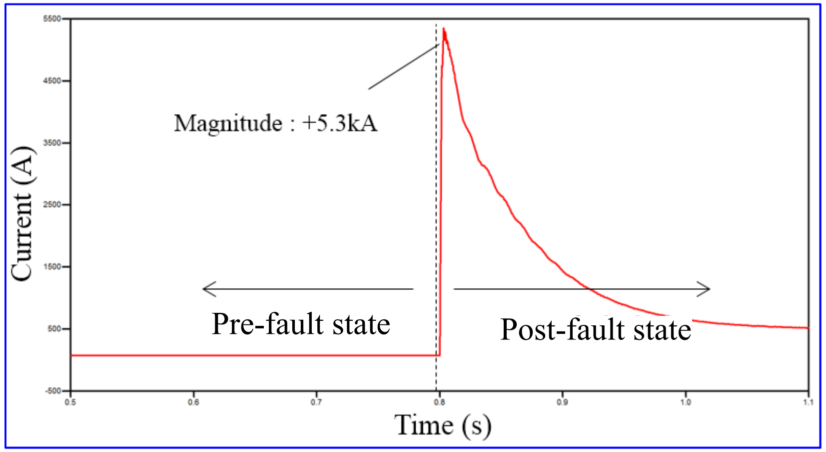
## 3.1 The principle of the proposed method

### ◆ Prevention of malfunction

**Sympathetic 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**



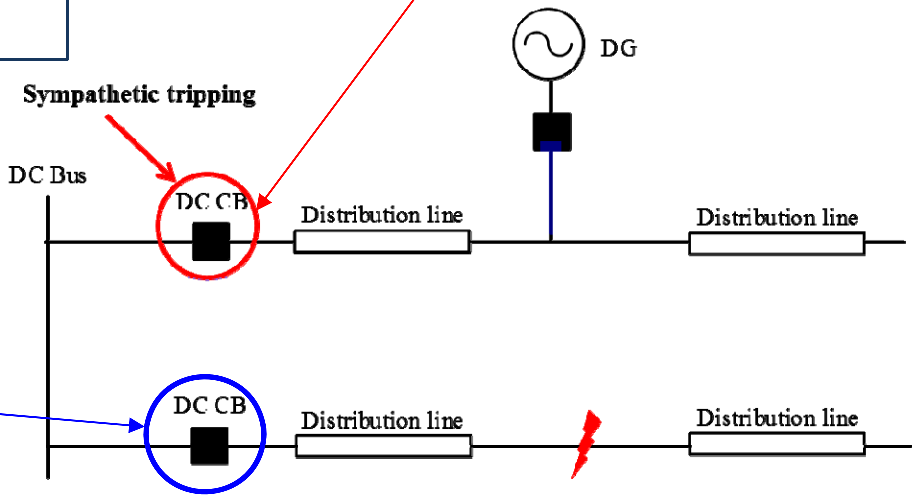




Fig. 3. Concept of Sympathetic Tripping

# 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)**

**Distribution Line Protection Algorithm**

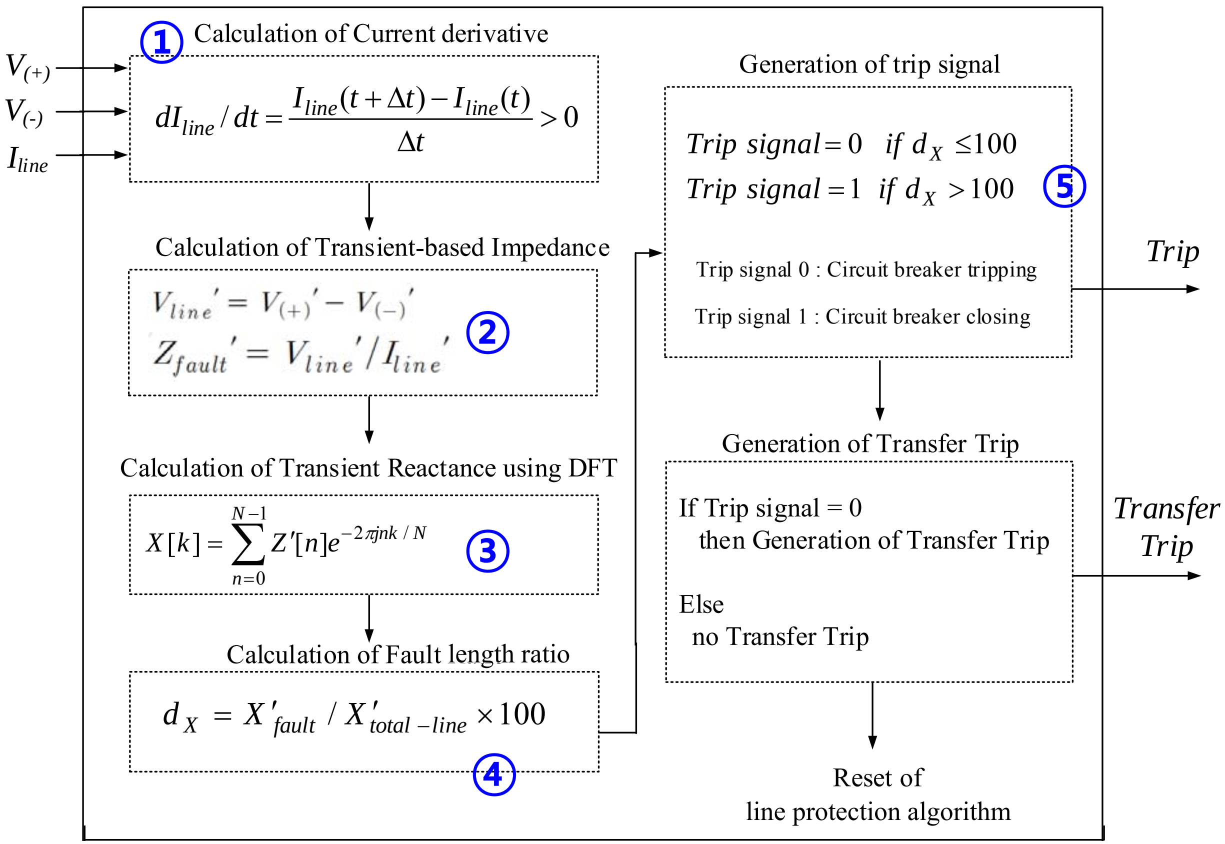



Fig. 4. The proposed protection algorithm

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# 4. Simulation results

## 4.1 Test system & simulation conditions

- **Test system modeled using Electromechanical Transients Program (EMTP)**
  - <u>3-division 2-link DC distribution system in radial type</u>

    → To use line parameters of **real Korean distribution systems**

※ Tie switches are normally opened (N/O)

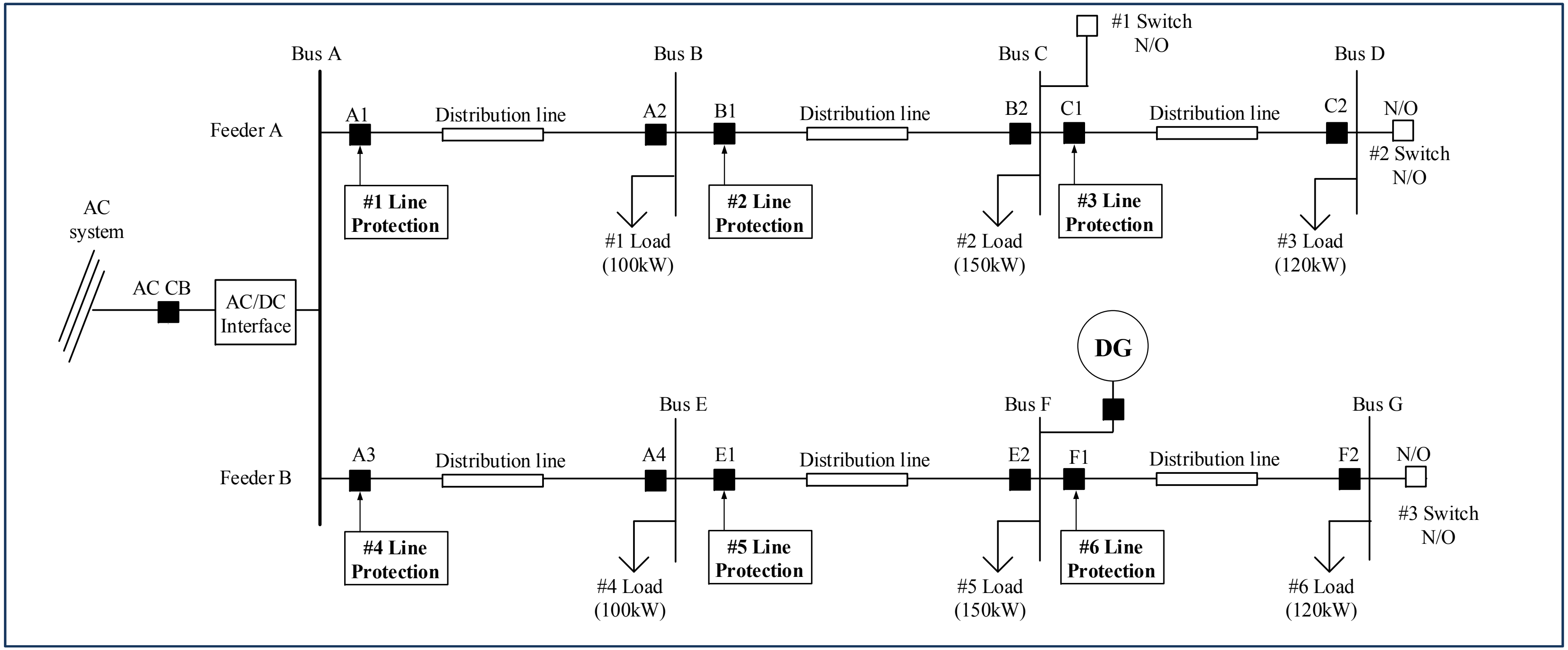



Fig. 5. Test system

# 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

| Parameters | Input value |
|---|---|
| Distribution voltage level | 1500Vdc |
| The number of poles | Uni-pole |
| Line length (for each section) | 2km |
| Line resistance ($R_L$) | 0.164 Ω/km |
| Line inductance ($X_L$) | 0.26 mH/km |
| Pick-up value for current derivative | (+) 5 kA/μs |
| Range of Zone 1 | 80% |
| Operation time for Zone 1 (Fault detection) | 1ms |
| Interruption time of CB | 2ms |

# 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** ➔ trigger the algorithm
    - ① Case I & II ➔ within the protective section(~80%)
      - → Fault detection and CB operation
    - ② Case III ➔ Outside of the protective section
      - → No operation of CB

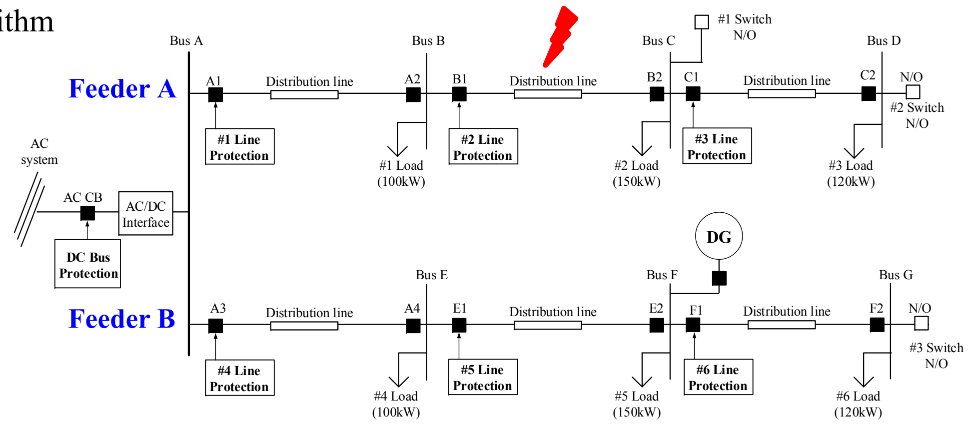



Table 2. Simulation results according to fault location

| Parameters | Fault location | | |
|---|---|---|---|
| | Case I(10%) | Case II(50%) | Case III(90%) |
| $\lvert Z'_{fault} \rvert$ [Ω] | 0.078814 | 0.40427 | 0.59194 |
| $\theta_{fault}$ [deg] | 26.195 | 36.84 | 31.887 |
| $X'_{fault}$ [Ω] | 0.03479 | 0.24239 | 0.31268 |
| $d_x$ [%] – 100% | 12.43 | 86.57 | 111.67 |
| $di/dt$ [kA/µs] – (+)5kA/µs | 2485.4 | 523.28 | 284.6 |
| CB operation | Open | Open | Not open |

# 4. Simulation results

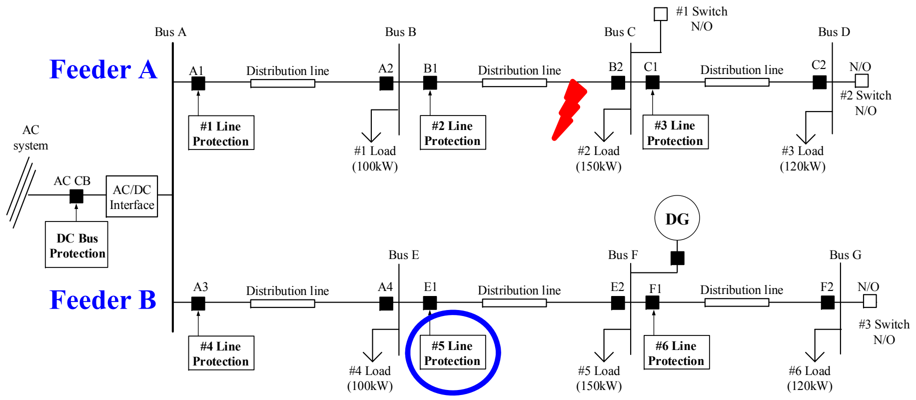
## 4.2 Performances of the proposed protection system

### 2) Malfunction - Sympathetic tripping

- To verify the performance to <u>prevent sympathetic tripping</u> 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




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

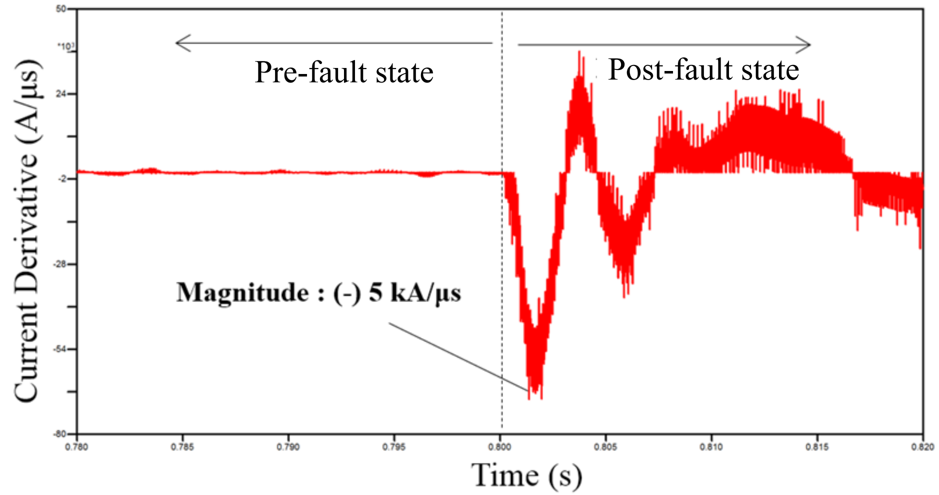



Fig. 6. Waveform of reverse current derivative by interconnection of DG

# 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

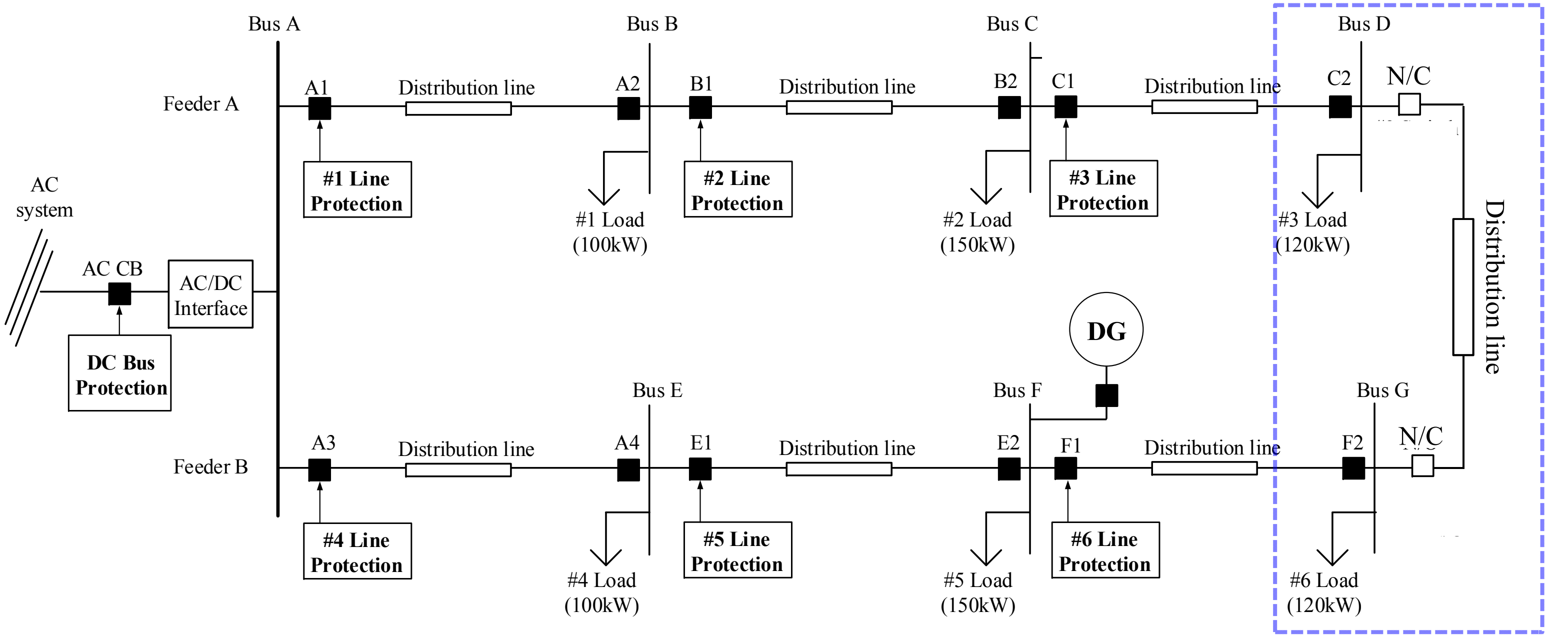
## Simulations & Verification using EMTP

- **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

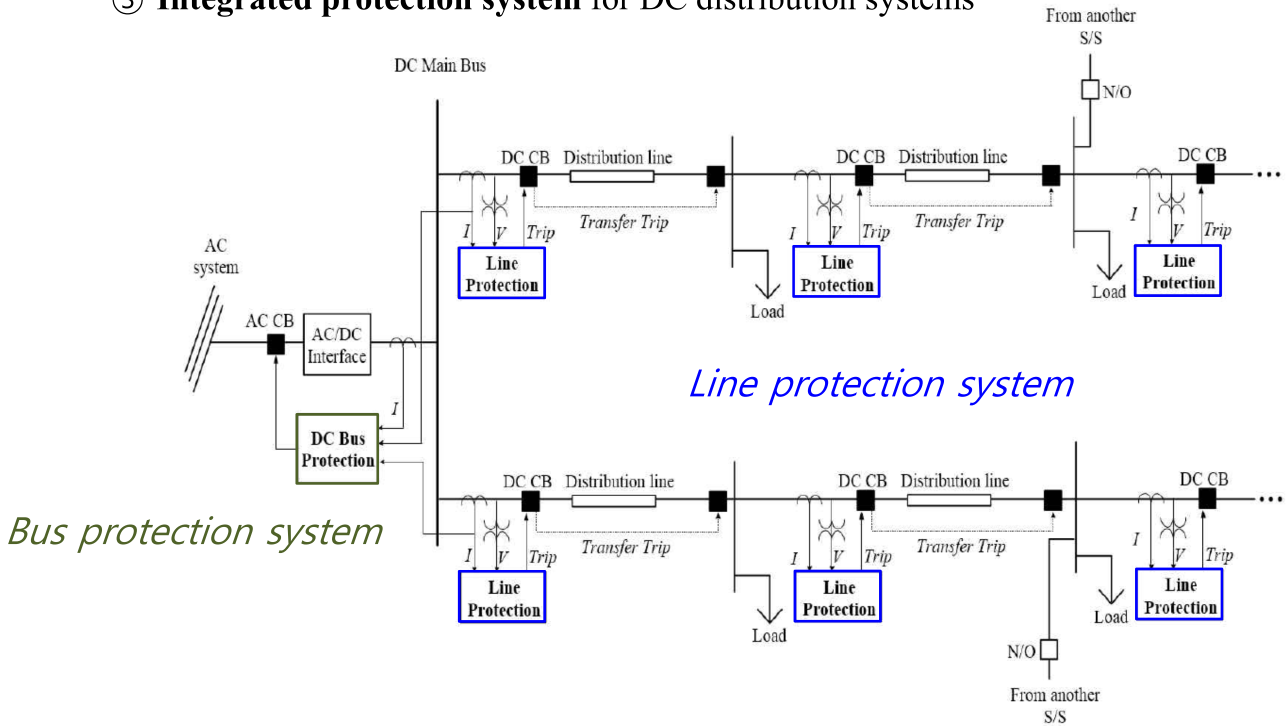
- The current study targets radial DC distribution systems under **the condition of N/O state**
  - ➢ Future works are to develop **the advanced protection system**
    - ① Transient analysis under the condition of **N/C state**
    - ② Consideration of the conventional protection system (To check the 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!