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Active Boundary Protection For Distribution Network With Multi-Converter

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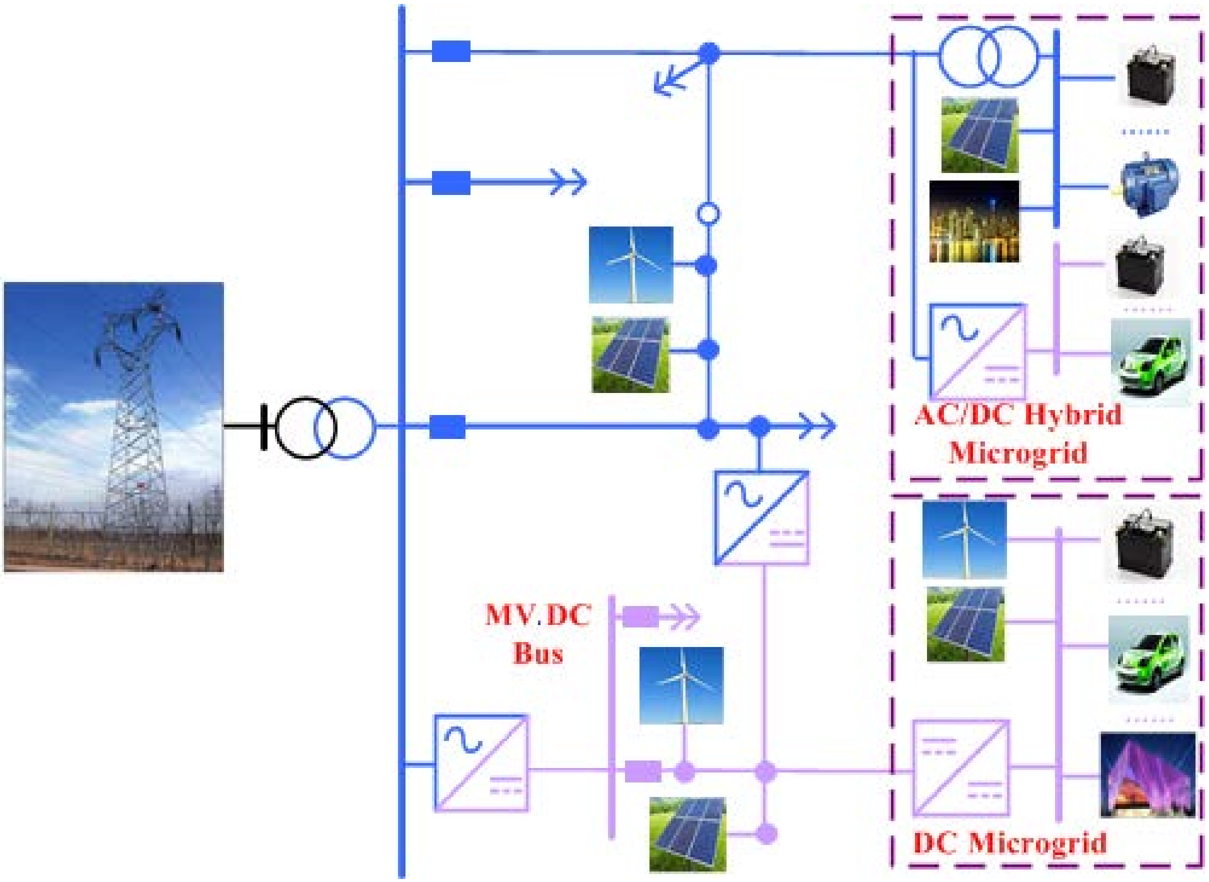
Contents

- Background
- Feasibility of Magnetic-Ring as Line-Boundary
- Line-Protection with Magnetic-Ring Boundary
- Special Issues
- Validation based on Simulation
- Conclusions

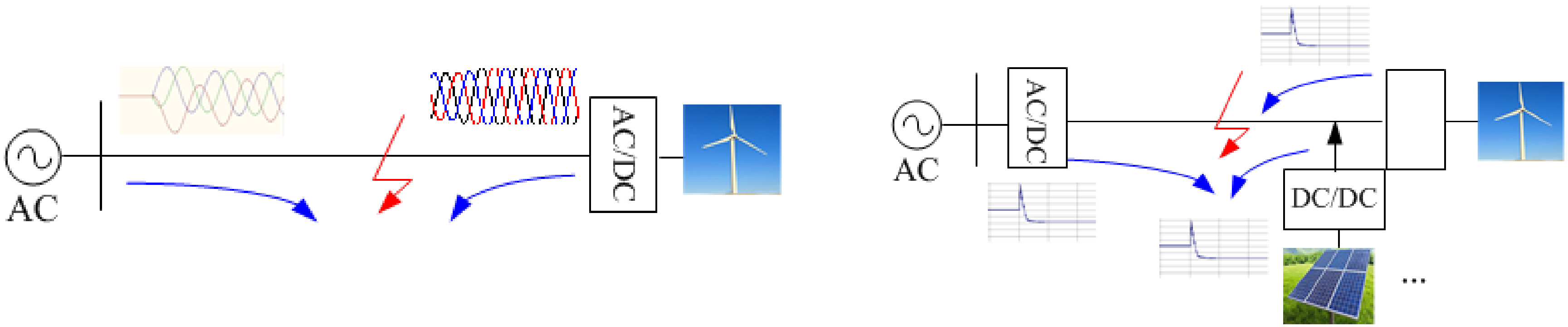
1.1 Trend of Distribution Network



- ✓ **WT**(Wind Turbine)
- ✓ **PV** (photovoltaic)
- ✓ **PET** (Power Electronic Transformer)
- ✓ **BESS** (Battery Energy Storage System)
- ✓ **EV**(Electric Vehicles)
- ✓ **PEL** (Load with power electronics interface)

Distribution network(DN) is including so many types of Power Electronics devices, we should pay attention to protection issue

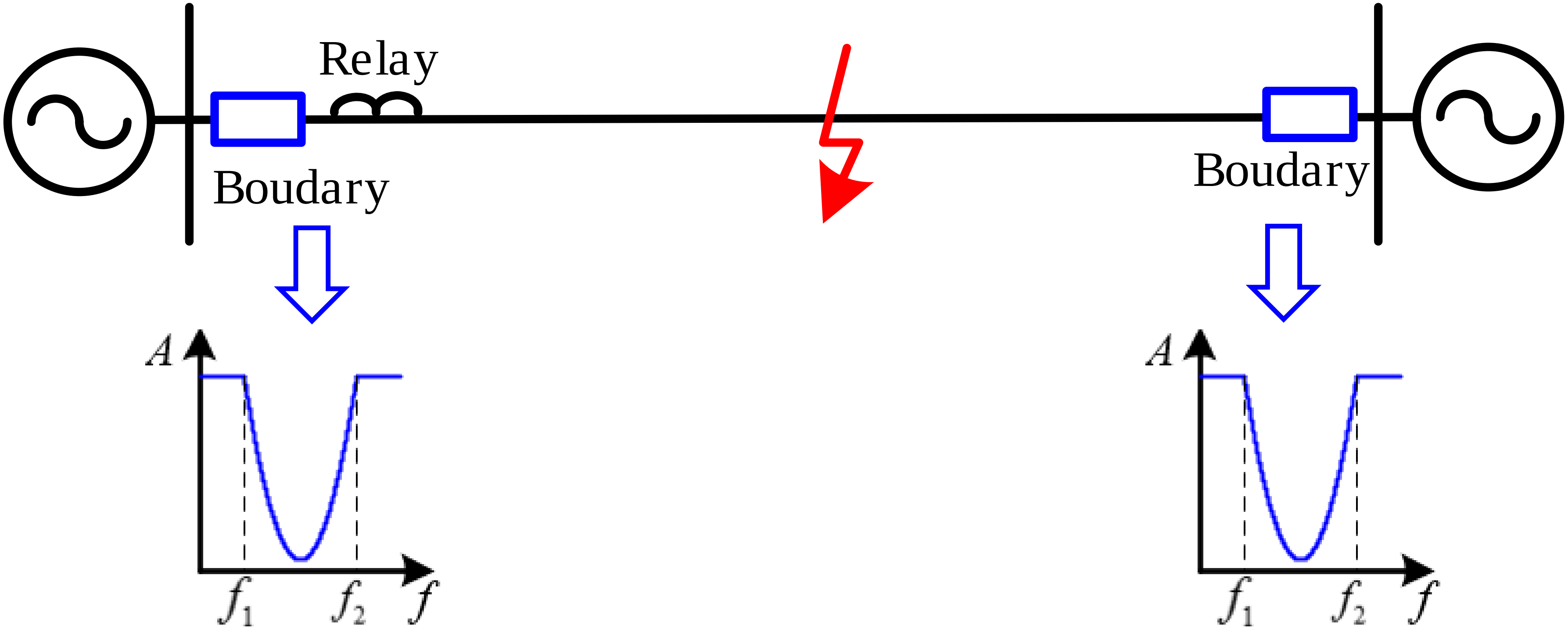
1.2 Challenges of Relay Protection for DN



Properties of DN	Fault Characteristics	Challenges of Relay Protection
Vulnerability of Converter	Limited Current Amplitude	Low Sensitivity
Low Inertia of Converter	High Current Rate of Change	High Speed Fault Detection Requirements
Distributed Generation Integration	Bidirectional Fault Current	Difficulty in Coordination
Topological variability	/	Difficulty in Coordination

How to solve these problems? **Boundary protection?**

1.3 Principle of Boundary Protection



- **One terminal protection, and zone is the whole length of the line**
- **Identify fault by information of special frequency band**
- **Transient protection, with fast speed**
- **No communication, no coordination between protections**

1.4 Problems of Existing Boundary Protection

Line Boundaries

- Wave trap of line, stray capacitance of bus, shunt reactor, series capacitor in AC transmission system.
- Smoothing reactor and DC filter in LCC-HVDC system.
- Shunt capacitor in VSC-HVDC system.
- Series reactor in DC grid.

Protection Criteria

- ROCOV, ROCOC is easily affected by line topology and fault conditions, such as fault resistance, type and distance.
- Width selection of data-window lacks the theoretical basis.
- Computational burden is heavy.

It is important to build a suitable Line-Boundary(LB) and a simple criterion to protect DNs including more converters.

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2.1 Characteristics of MR

- **Magnetic Ring(MR) is widely applied to suppress VFTO in GIS, that is to say, it can damp the very fast transient signals, has a nice boundary characteristics.**
- **MR can be designed as open structure, and easy to install.**
- **MR is cheap and has been widely used in engineering.**

[1] S. Burow, et al. "New methods of damping very fast transient overvoltages in gas-insulated switchgear," *IEEE Transactions on Power Delivery*, vol. 29, pp. 2332-2339, Oct. 2014.
[2] J. He, et al. "Design optimization of ferrite rings for VFTO Mitigation," *IEEE Transactions on Power Delivery*, vol.32, pp.1181-1186, Jun. 2017.

2.1 Characteristics of MR

◆Frequency Dependent Impedance of MR

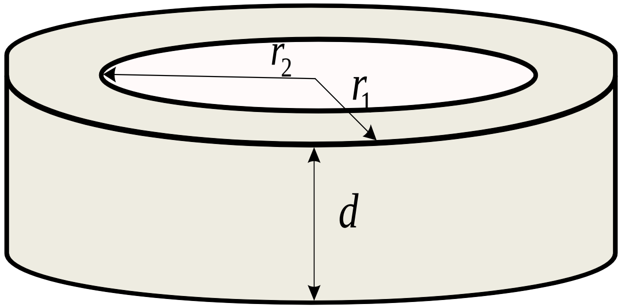


Diagram of a magnetic ring

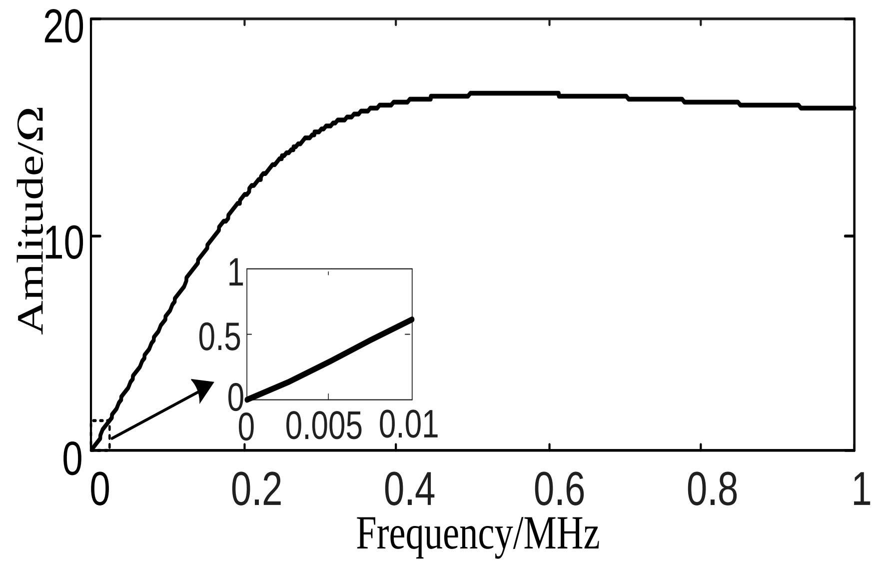
$$Z = \frac{2\pi fA\mu''}{l} + \frac{j2\pi fA\mu'}{l}$$

where $A=(r_1-r_2)\times d$

$l=\pi(r_1+r_2)$

μ' and μ'' are the real and imaginary part of complex magnetic permeability

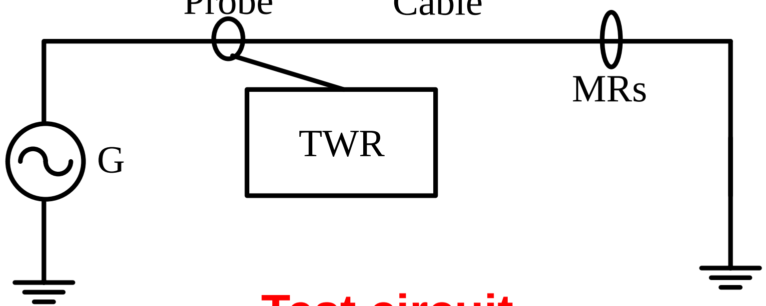
One Mn-Zn ferrite magnetic ring with r1=25mm, r2=15mm, d=20mm



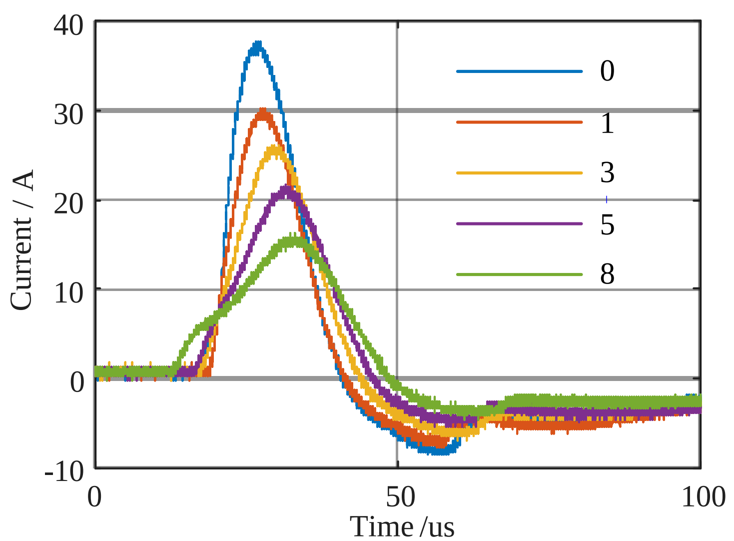
Frequency dependent characteristic of impedance of MR

2.1 Characteristics of MR

◆Frequency Dependent Impedance of MR



Test circuit

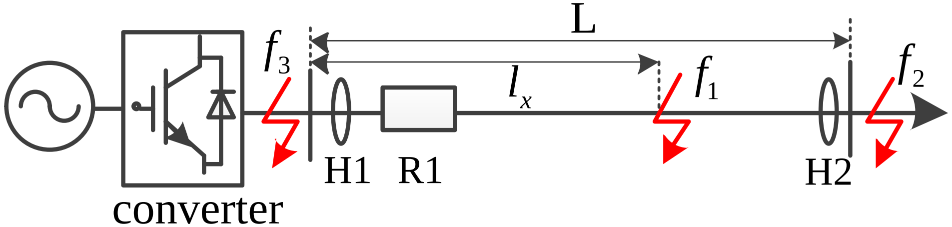


Measured currents under different numbers of MRs

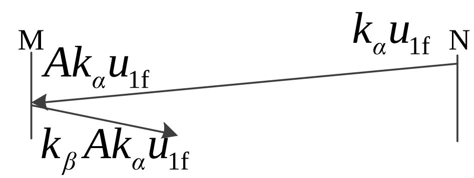
- G is the **voltage-step wave** generator.
- TWR(Transient waveform recorder) is used to record the current wave and its sampling frequency is 100MHz.
- **The number of MRS is changed from 0 to 8.**

2.2 influence of MRs on voltage travelling wave

Fault analysis

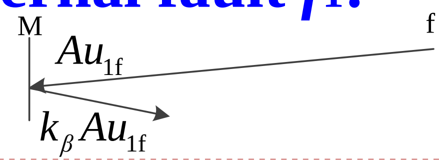


(2) Forward external fault f_2:



$$u_{m2} = (2-k_\alpha)k_\alpha u_{1f} e^{-\gamma L}$$

(1) Internal fault f_1:

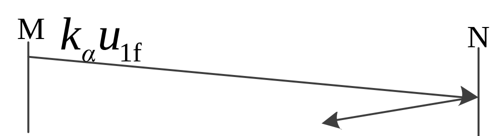


$$u_{m1} = u_{1f} e^{-\gamma l_x} + u_{1b}$$

$$u_{1b} = u_{1f} e^{-\gamma l_x} - u_{2f} = (1-k_\alpha) u_{1f} e^{-\gamma l_x}$$

$$u_{m1} = (2-k_\alpha) u_{1f} e^{-\gamma l_x}$$

(3) Reverse external fault f_3 :

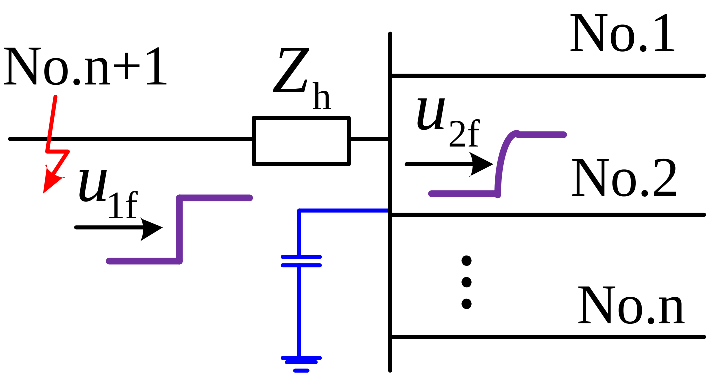


$$u_{m3} = k_\alpha u_{1f}$$

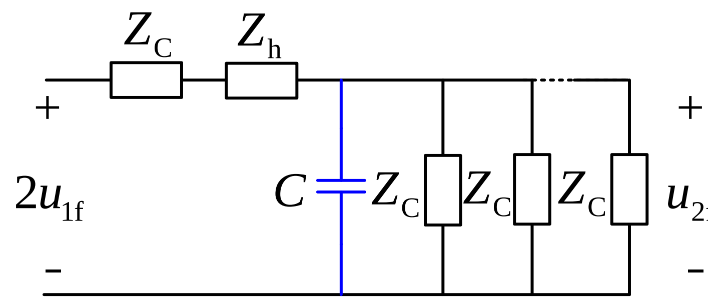
The difference in voltage calculation of internal and external faults is mainly determined on the **refraction coefficient k_α**

2.2 influence of MRs on voltage travelling wave

Refraction Coefficient Ka



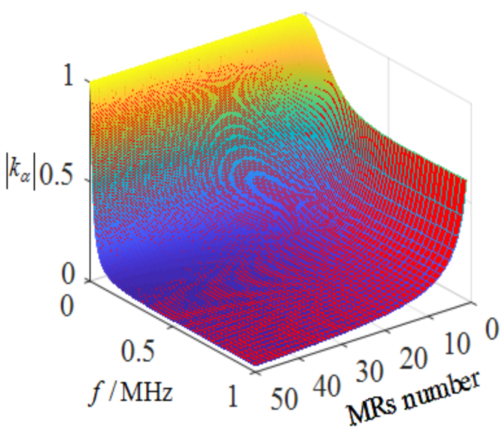
Refraction of voltage travelling wave



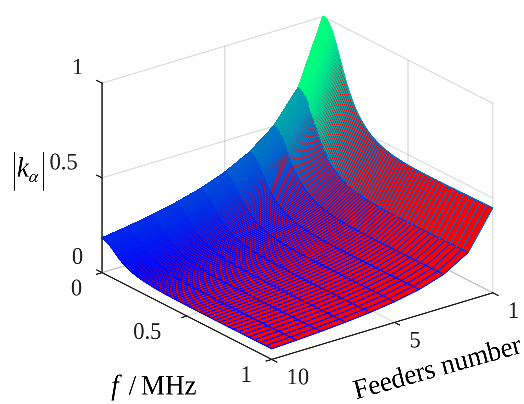
Peterson's equivalent circuit

For MMC based DN or AC DN:

$$k_\alpha = \frac{u_{2f}}{u_{1f}} = \frac{2Z_C}{Z_C + n(Z_h + Z_C)}$$



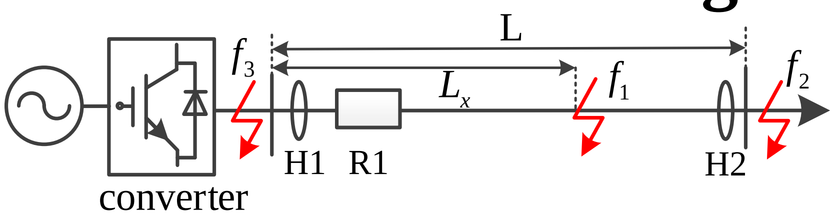
Different MR number



Different feeder number

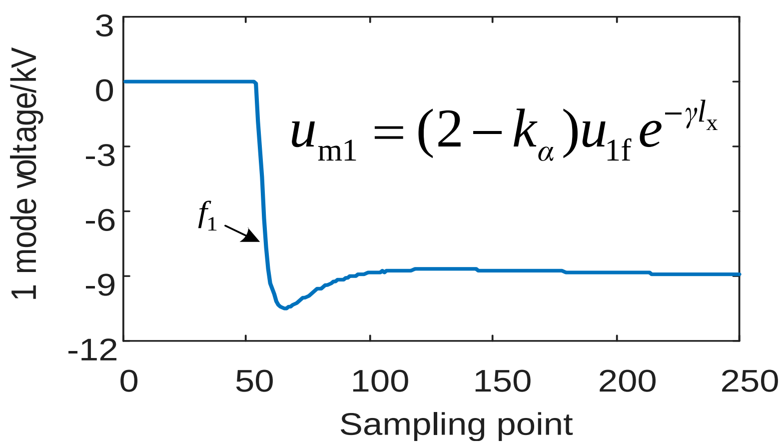
2.2 influence of MRs on voltage travelling wave

◆Difference in Voltage of Internal and External Faults



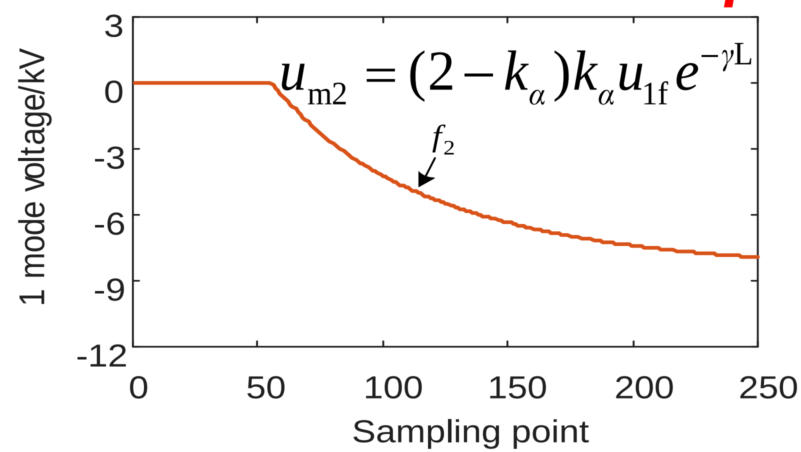
Lx=8km； L=10km； MRs=20

Internal fault f_1

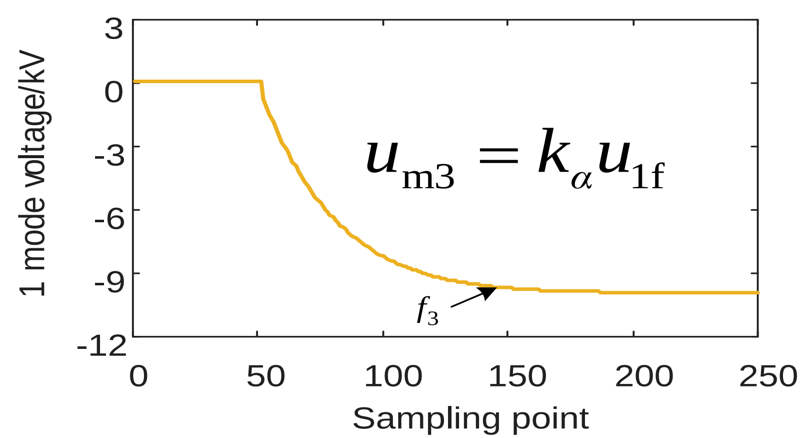


MRs can change the **steepness and peak time** of voltage of travelling wave in different fault points.

Forward external fault f_2



Reverse external fault f_3



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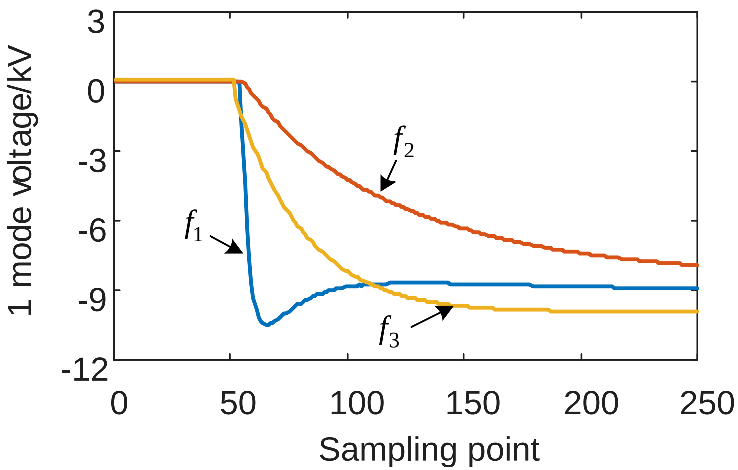
3.1 Peak Time Based Fault Detection

◆Fault detection criterion

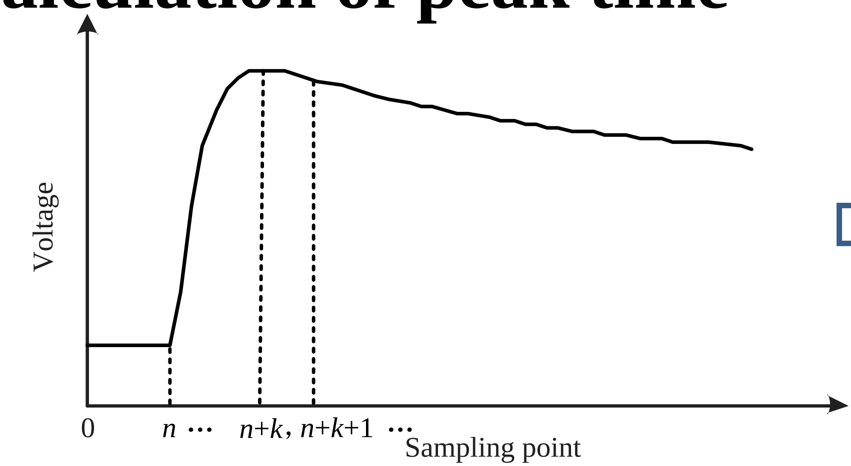


The threshold has to be smaller than the minimum peak time of forward external fault and reverse external fault

$$\begin{cases} t_p < t_{set} \\ t_{set} = k_{rel} \cdot \min(t_r, t_f) \end{cases}$$

Where k_{rel} is reliability coefficient, can be chosen as 0.8

◆Calculation of peak time



$$\begin{cases} \rho(n+k+1)\rho(n) \le 0 \\ t_p = (k+1)T_S \\ N_p = (k+1) \end{cases}$$

3.1 Peak Time Based Fault Detection

◆Theoretical Calculation of Threshold

$$\begin{cases} u_{m2} = (2-k_\alpha)k_\alpha u_{1f} e^{-\gamma L} \\ u_{m3} = k_\alpha u_{1f} \end{cases}$$

Fitting of Transfer Function of Transmission Line[1]

$$H(s) = \frac{1}{s(T_m s+1)} \Rightarrow \begin{cases} \dfrac{-\omega^2 T_m}{\sqrt{(\omega^2 T_m)^2 + \omega^2}} = A_{mR} \\ \dfrac{-\omega}{\sqrt{(\omega^2 T_m)^2 + \omega^2}} = A_{mI} \end{cases} \Rightarrow \omega T_m = \frac{A_{mR}}{A_{mI}} \Rightarrow T_m = \frac{\boldsymbol{\omega}^T \boldsymbol{k}_{RI}}{\boldsymbol{\omega}^T \boldsymbol{\omega}} = \frac{\sum_{i=1}^{N} \boldsymbol{\omega}(i) \cdot \boldsymbol{k}_{RI}(i)}{\sum_{i=1}^{N} \boldsymbol{\omega}^2(i)}$$

Calculation of peak time of external fault

$$\begin{cases} u_{1f} = 1/s \\ u_{m2} = (2-k_\alpha)k_\alpha u_{1f} H(s) \\ u_{m3} = k_\alpha u_{1f} \end{cases} \xrightarrow{\text{Vector fitting[2]}} \begin{cases} u_{m2}(s) \\ u_{m3}(s) \end{cases} \xrightarrow{\text{Inverse Laplace transform}} \begin{cases} u_{m2}(t) \\ u_{m3}(t) \end{cases}$$

[1] M. Xu, et al, "Analysis of line faults on HVDC transmission system considering frequency-dependent parameters and HVDC control," *Automation of Electric Power Systems*, vol. 39, no. 11, pp. 37-44, Jun. 2015

[2] B. Gustavsen, et al, "Rational approximation of frequency domain responses by vector fitting," *IEEE Transactions on Power Delivery*, vol.14, pp. 1052- 1061, Jul , 1999.

3.2 Identification of Single Phase/Pole to Ground Fault

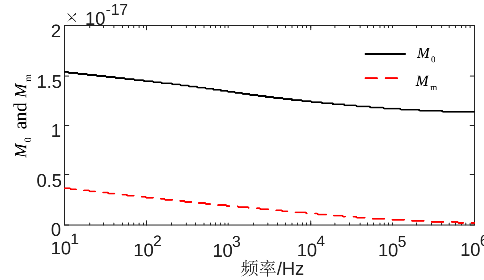
Define the ratio of the absolute value of 2-pole or 3-phase voltage derivatives, and calculation the root-mean-square value of zero mode voltage as follows

$$k_{\mathrm{nd}} = \left|\frac{\rho_{\min}}{\rho_{\mathrm{mid}}}\right| \qquad U_0 = \sqrt{\frac{1}{H}\sum_{k=1}^{H} u_0^2(k)}$$

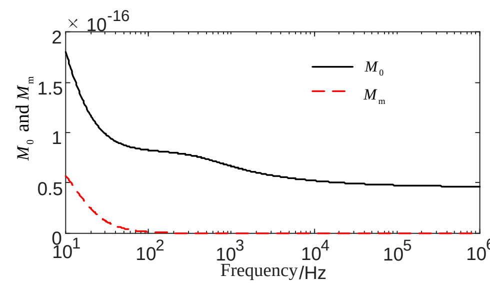
$$\frac{\partial^2 \boldsymbol{u}(x,t)}{\partial x^2} = \boldsymbol{M}\frac{\partial^2 \boldsymbol{u}(x,t)}{\partial t^2}$$

Single phase/pole to ground fault identification criterion

AG	BC	BCG	ABCG	PTG	PTP
$k_{\mathrm{nd}} \approx 1$	$k_{\mathrm{nd}} \approx 0$	$k_{\mathrm{nd}} \approx 0.67$	$k_{\mathrm{nd}} \approx 1$	$k_{\mathrm{nd}} \approx 0$	$k_{\mathrm{nd}} \approx 1$
$U_0 > 0$	$U_0 = 0$	$U_0 > 0$	$U_0 = 0$	$U_0 > 0$	$U_0 = 0$

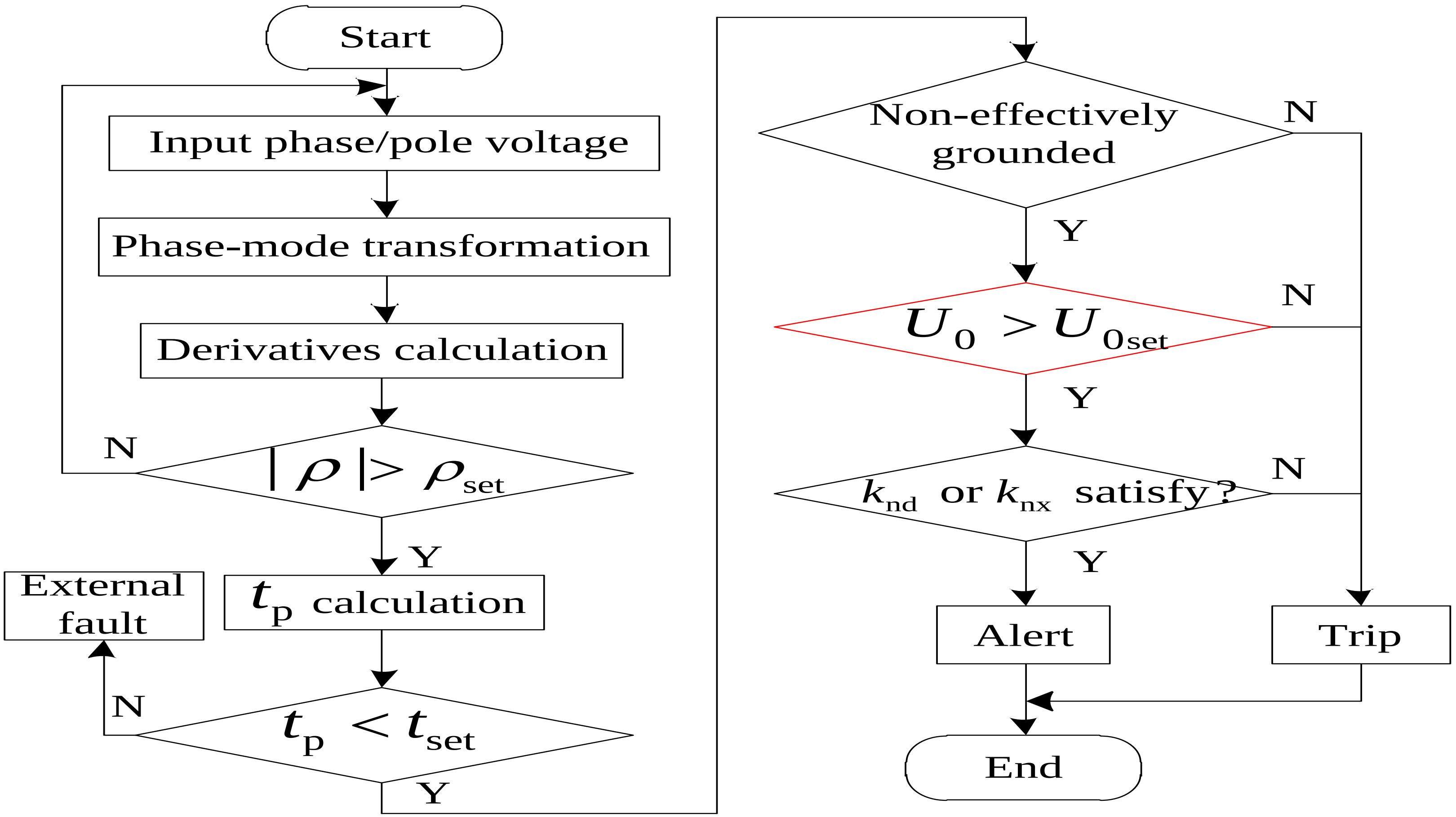


AC $\begin{cases} U_0 > U_{0\mathrm{set}} \\ k_{\mathrm{nd}} > k_{\mathrm{set.ac}} \end{cases}$ DC $k_{\mathrm{nd}} < k_{\mathrm{set.ac}}$



Based on the features of derivatives of voltage travelling wave and zero mode voltage amplitude, fault type can be identified

3.3 Protection Scheme



The flowchart of the proposed protection scheme

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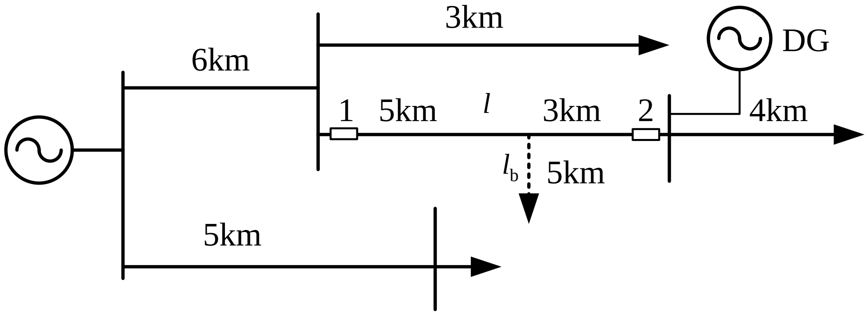
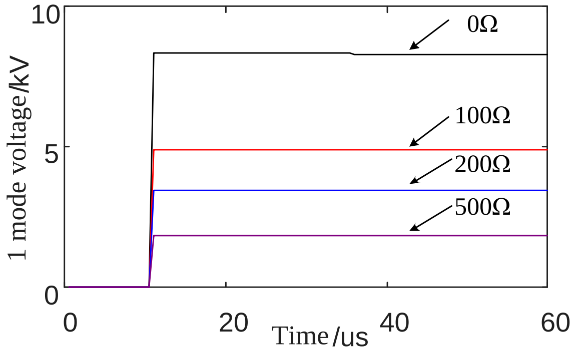
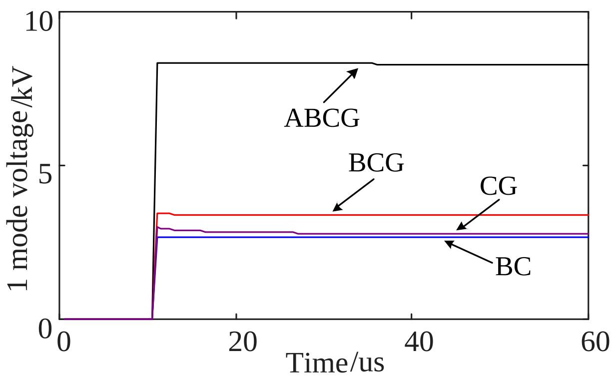
4.1 influence of fault conditions



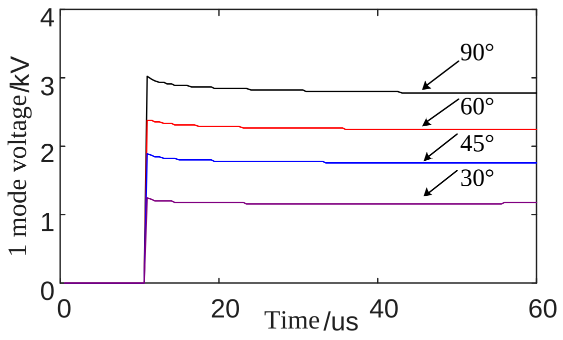
Simulation model



Different fault resistances



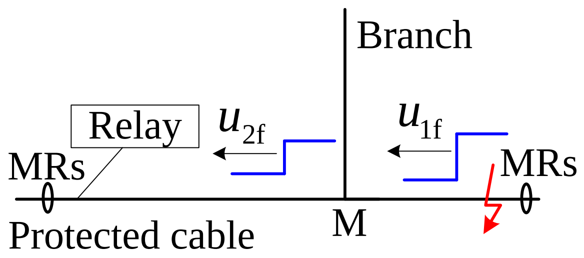
Different fault types



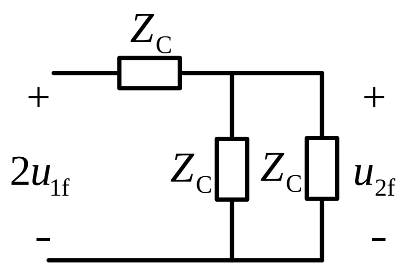
Different fault inception angles

Fault conditions only affect the magnitude of voltage traveling wave, but not the peak time!

4.2 influence of feeder branches



The topology of T-type connection



Peterson's equivalent circuit

Refraction coefficient:

$$k_{\alpha.\mathrm{br}} = \frac{u_{2f}}{u_{1f}} = \frac{2\times(Z_C\,//\,Z_C)}{Z_C + Z_C\,//\,Z_C} = \frac{2}{3}$$

If the protection zone has T-type feeder, the voltage amplitude of measurement point will be 2/3 time as that of two terminal transmission systems, but the peak time is not changed.

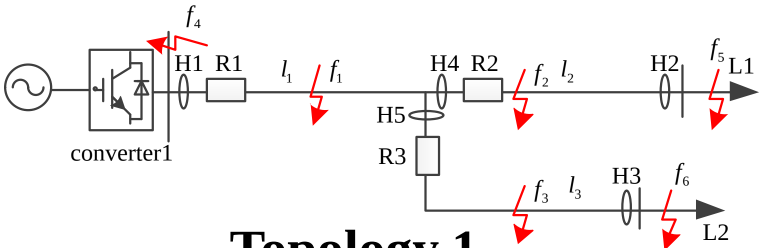
4.3 Configuration of MRs

◆ Number (Choice of number of MRs)

- Peak time needs to be well detected.
- The lower sampling frequency is used, the more MRs is needed.

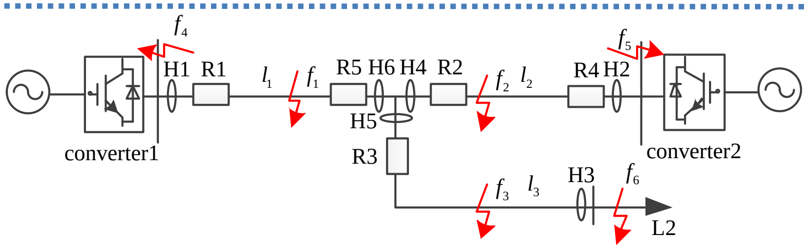
◆ Installation location (Where MRs need to be installed?)

- R1 and H1~H3 should be equipped at least.
- To isolate fault in smallest zone, R2~R3 and H4~H5 are needed



Topology 1

- R1, R4 and H1~H3 should be equipped at least
- To isolate the fault in smallest zone, R2, R3, R5, and H4-H6 should also be configured



Topology 2

Conclusion: Relay are located at the power side, and the MRs are located at the boundary point of the protection zone.

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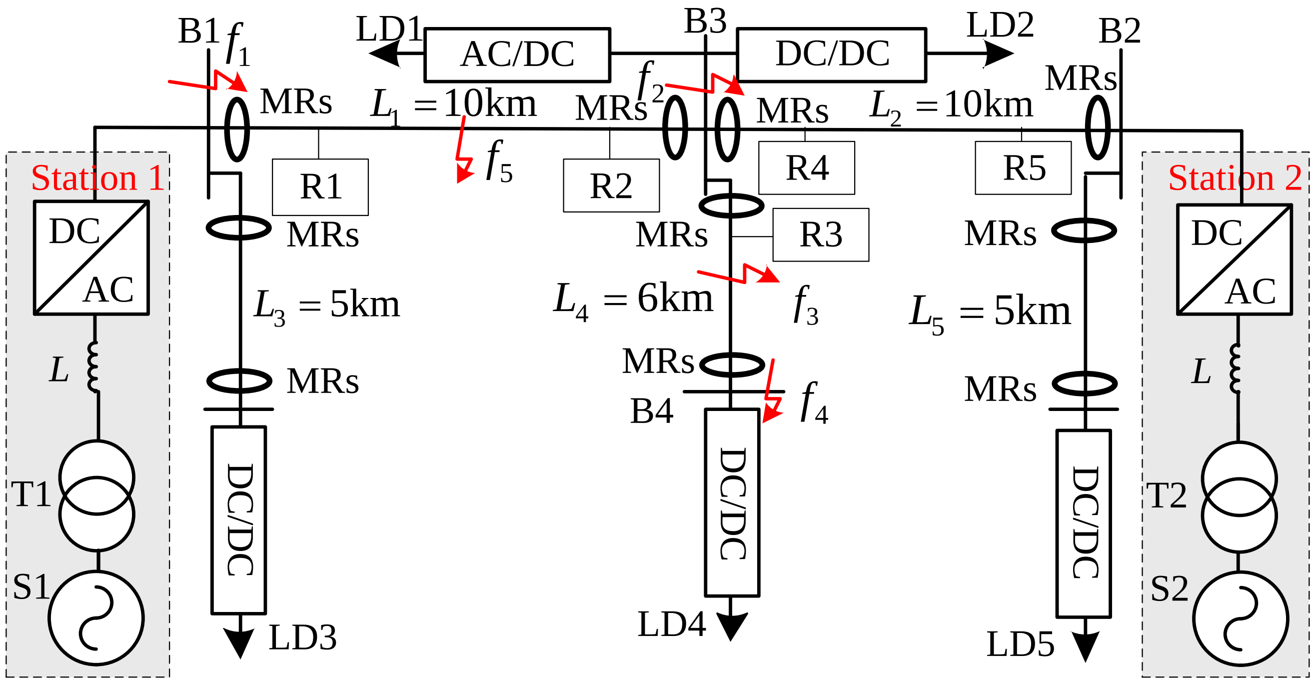
5.1 Simulation model

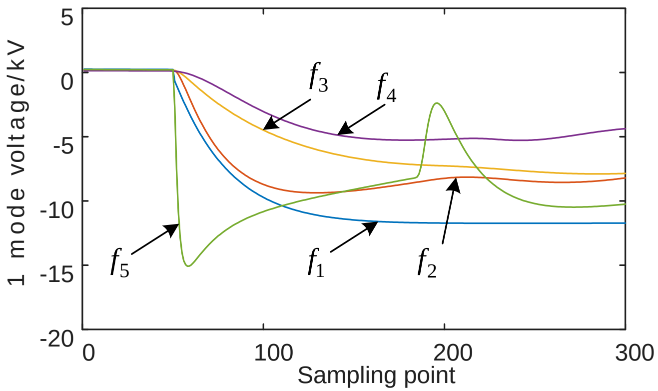


MMC-based structure DN Simulation Model

- DC voltage is ±7.5 kV, sampling frequency is 2MHz.
- Number of MRs at each ends of cables is 20.
- **The peak time of sampling points of thresholds for relay R1, R2, R3 are 62, 50, 45**

5.2 Validation of the Fault Detection Criterion

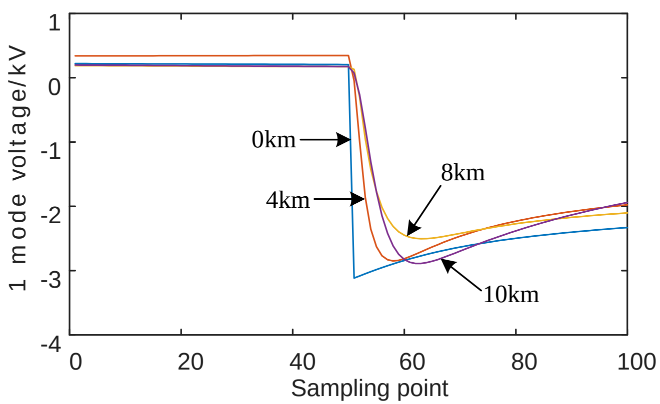
Thresholds for relay R1, R2, R3 are 62, 50, 45



Different faults measured at R1

Peak time of different faults

Relay	Fault points				
	f_1	f_2	f_3	f_4	f_5
R1	166	79	234	129	8
R2	63	132	313	194	9
R3	241	132	1	58	135



Different fault distance measured at R1

Peak time of internal fault f5

Relay	Fault distance from relay R1			
	0km	4km	8km	10km
R1	1	8	10	12
R2	13	11	6	1

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6 Conclusions

- **MRs can be used as Line-Boundary to identify internal and external faults.**
- **The peak time based fault detection is unaffected by fault conditions and T-type connection topology. Thus, it is suitable for distribution network.**
- **Experimental platform and test method and other fault detection criteria still need further study.**
- **The papers about the method already published on *IEEE Transactions on Power Delivery*** [1-2]

[1] G. Song, et al, "A High Speed Single-ended Fault Detection Method for DC Distribution Feeder—Part II: Protection Scheme,". DOI: 10.1109/TPWRD.2019.2939051
[2] G. Song, et al, "A High Speed Single-ended Fault Detection Method for DC Distribution Line—Part I: Feasibility analysis of Magnetic Ring as Line Boundary,“. DOI: 10.1109/TPWR D. 2019. 2939022

Thank you！