M.Sc. Thesis Presentation

Travelling Wave Based DC Line Fault Location in VSC HVDC Systems

K.P.A.N. Pathirana

Department of ECE
University of Manitoba
Canada.

Outline

- Introduction
- Surge detection method
- Modelling of Rogowski coil
- Line fault location performance
- Conclusion and future work

Background

- HVDC transmission lines and cables need repairs quickly as possible after a fault.
- Travelling wave based fault location is the common fault location method applied in HVDC transmission lines.
- IGBT based voltage source converter (VSC) HVDC systems are gradually gaining ground.

Problem definition

- No publications dealing with the fault location in VSC HVDC schemes with such long cable connections.
- The large DC capacitance at the converter terminal.
- Measurement bandwidth of the transducers.

Objectives

- Development of a method of measurement for detecting travelling wave arrival times in a VSC HVDC scheme.

- Testing and verification of the proposed measurement system through simulations.

- Investigate the effect of different parameters on the accuracy of fault location.

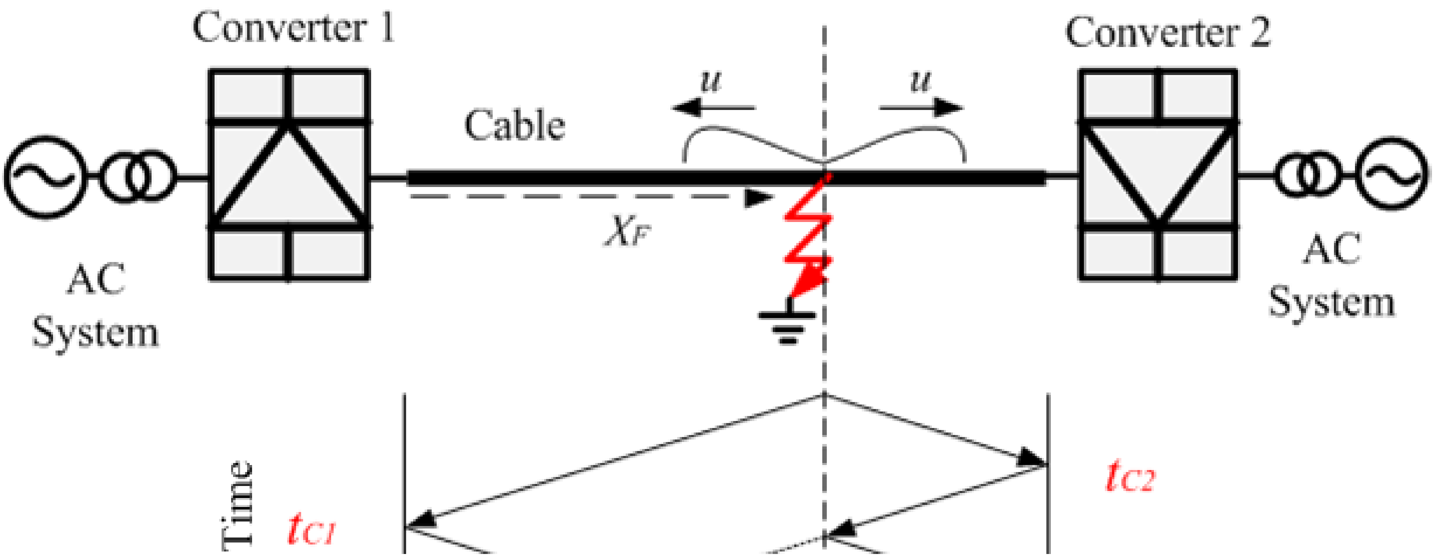
Line fault location methods

- Techniques based on impedance measurement
- Techniques based on high frequency spectrums of the currents and voltages
- Machine learning based approaches
- Techniques based on travelling waves

Line fault location methods

- Techniques based on impedance measurement
- Techniques based on high frequency spectrums of the currents and voltages
- Machine learning based approaches
- **Techniques based on travelling waves**

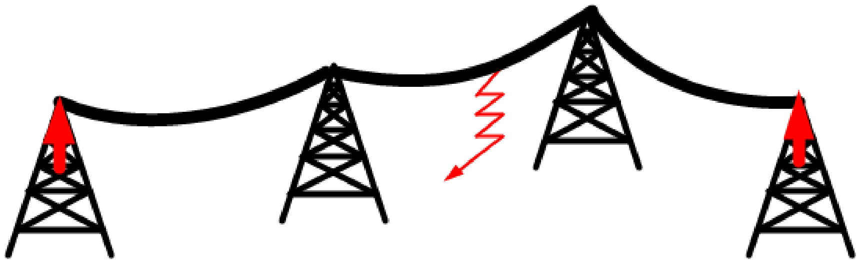
Travelling wave based fault location



$$X_F = \frac{l - u.(t_{C2} - t_{C1})}{2}$$

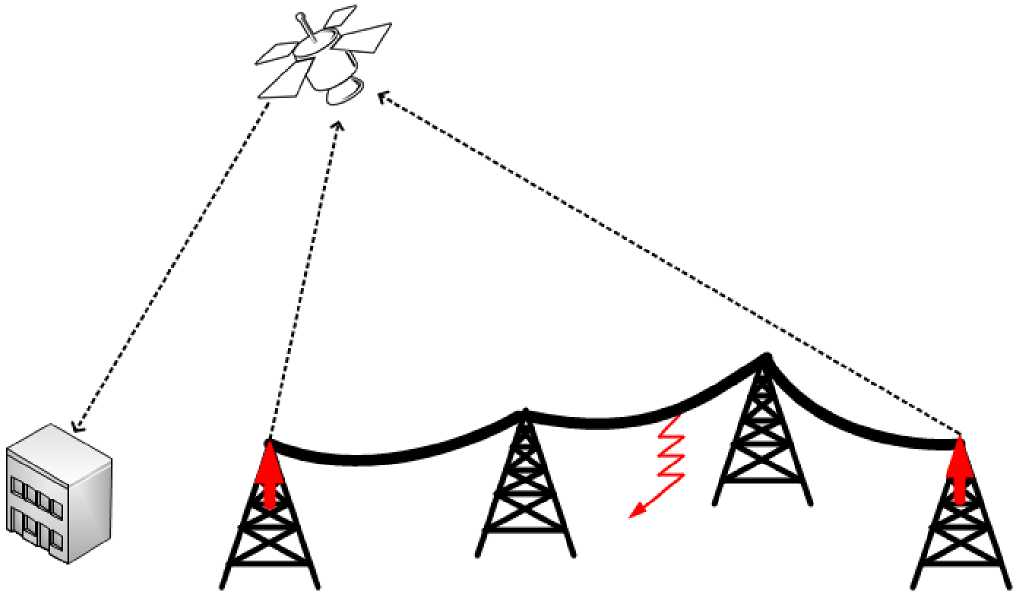
Current LFL technology

- Detection methods



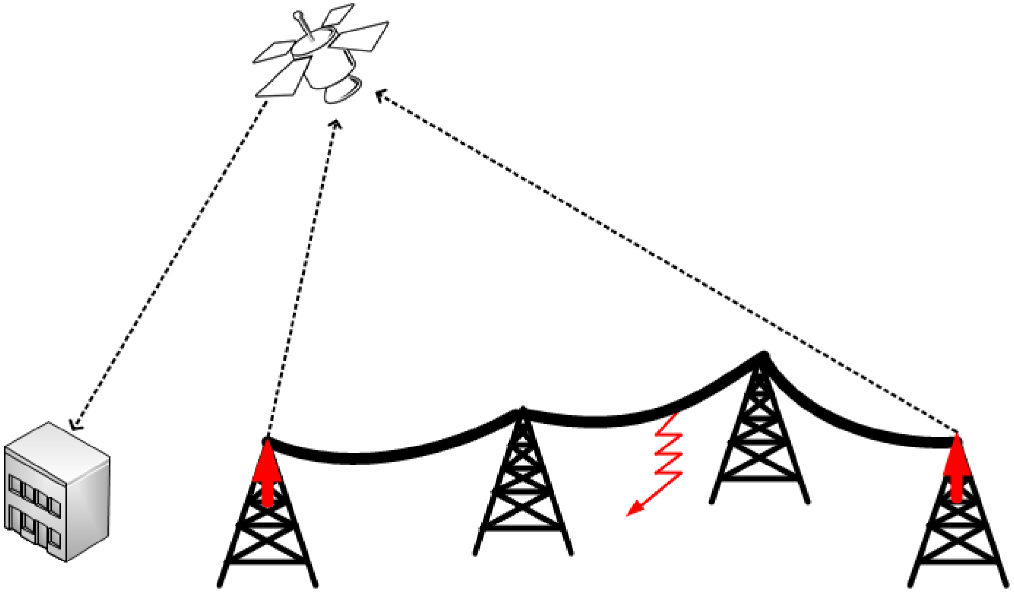
Current LFL technology

- Detection methods
- Time stamping



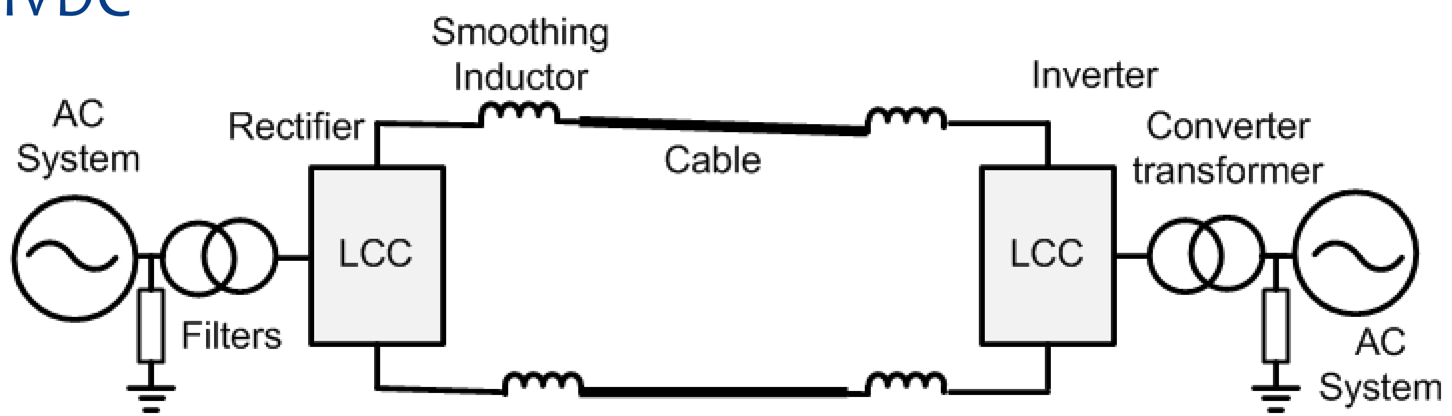
Current LFL technology

- Detection methods
- Time stamping
- Typical accuracies

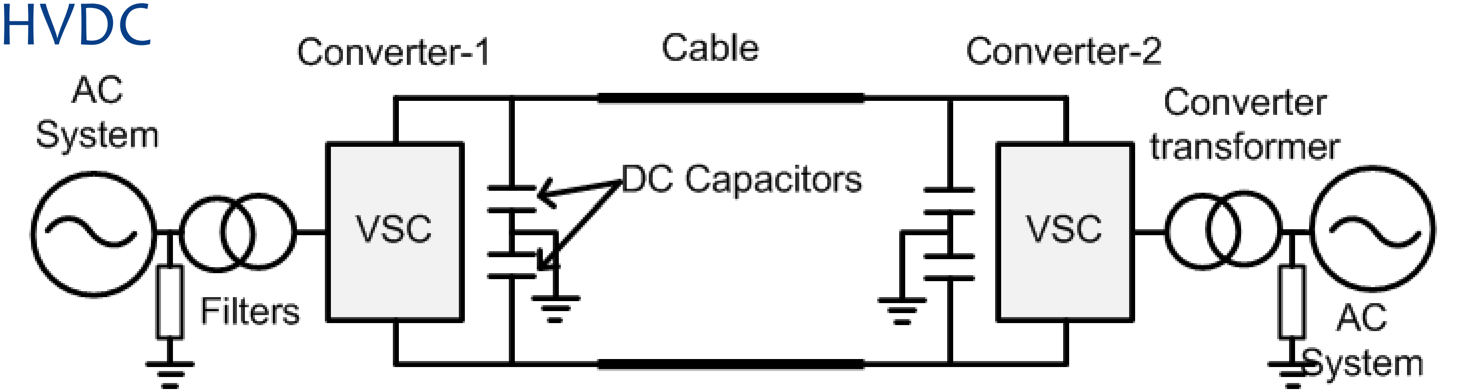


Line Termination in LCC and VSC Schemes

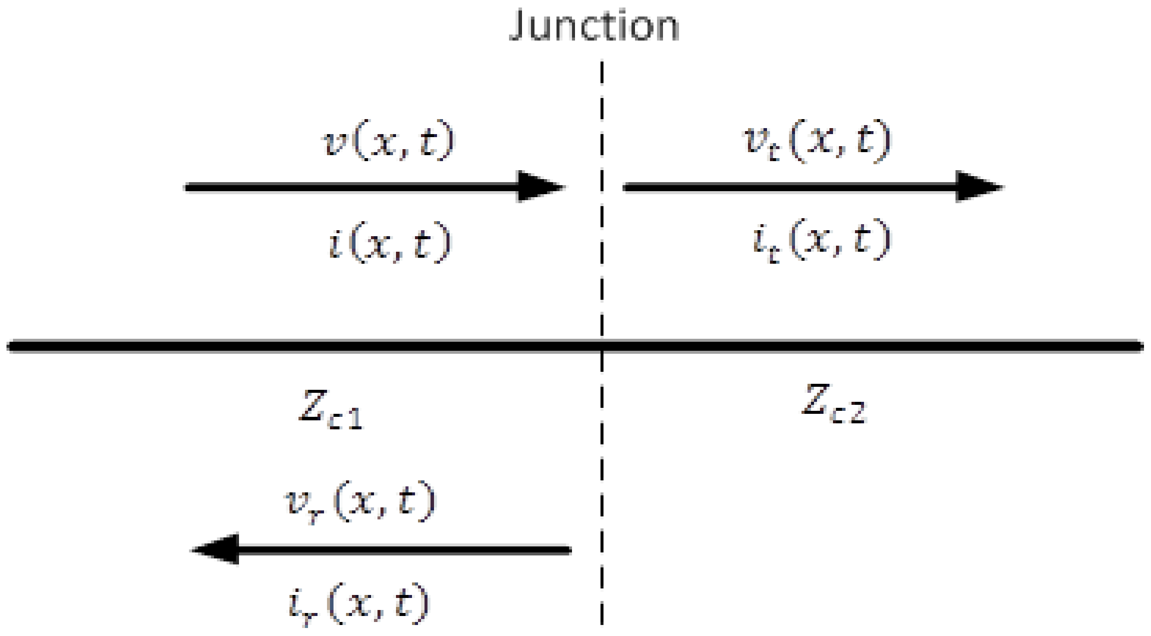
LCC HVDC



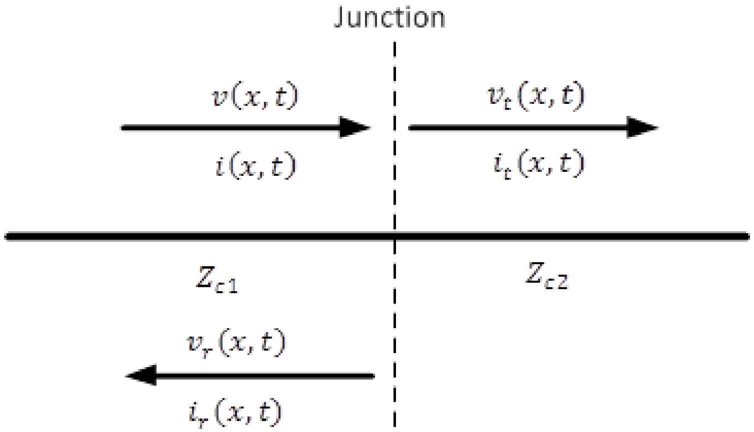
VSC HVDC



Travelling waves incident on junction



Travelling waves incident on junction



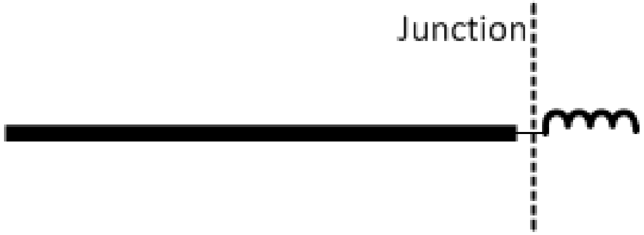
$$v_r(x_o,t) = \rho . v(x_o,t)$$

$$v_t(x_o,t) = \tau . v(x_o,t)$$

$$\rho = \frac{Z_{c2} - Z_{c1}}{Z_{c2} + Z_{c1}}$$

$$\tau = \frac{2Z_{c2}}{Z_{c2} + Z_{c1}}$$

Travelling waves incident on junction



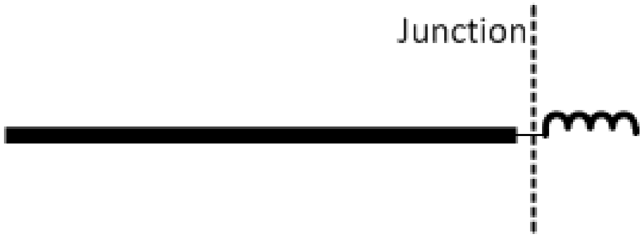
$$Z_{c2} = \sqrt{\frac{L}{C}} \rightarrow \infty \qquad Z_{c1} = Z_{cable}$$

$$\rho = \frac{Z_{c2} - Z_{c1}}{Z_{c2} + Z_{c1}} \qquad \rho \rightarrow 1$$

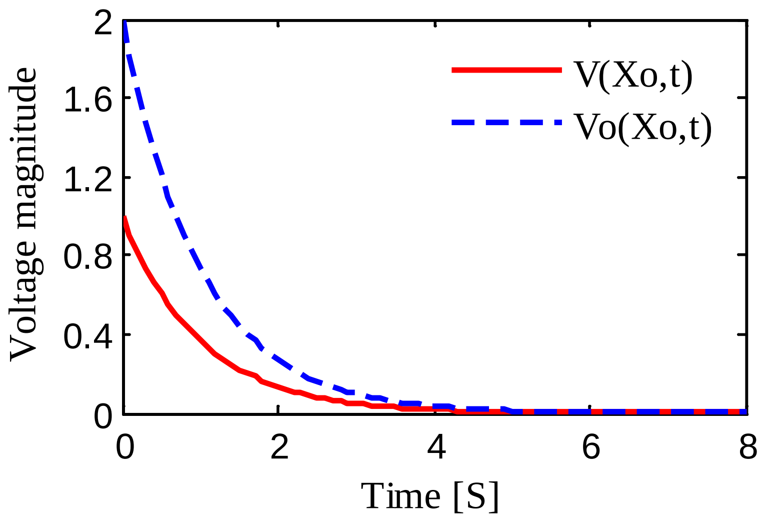
$$v_o(x_o, t) = (1 + \rho).\, v(x_o, t)$$

$$v(x_o, t) = Ae^{-(x_o - \alpha t)}$$

Travelling waves incident on junction



$$Z_{c2} = \sqrt{\frac{L}{C}} \rightarrow \infty \qquad Z_{c1} = Z_{cable}$$



$$\rho = \frac{Z_{c2} - Z_{c1}}{Z_{c2} + Z_{c1}} \qquad \rho \rightarrow 1$$

$$v_o(x_o, t) = (1 + \rho).\left(Ae^{-(x_o - \alpha t)}\right)$$

$$v(x_o, t) = Ae^{-(x_o - \alpha t)}$$

Travelling waves incident on junction

$$Z_{c2} = \sqrt{\frac{L}{C}} \rightarrow 0 \qquad Z_{c1} = Z_{cable}$$

$$\rho = \frac{Z_{c2} - Z_{c1}}{Z_{c2} + Z_{c1}} \qquad \rho \rightarrow -1$$

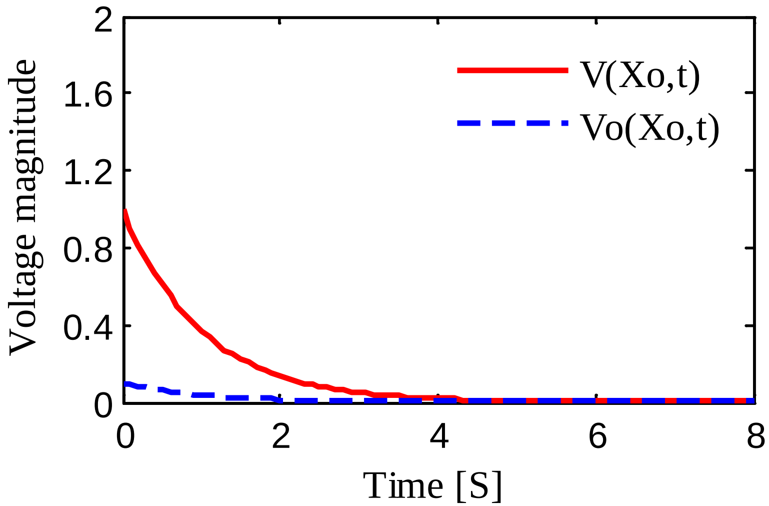
$$v_o(x_o, t) = (1 + \rho).\, v(x_o, t)$$

$$v(x_o, t) = Ae^{-(x_o - \alpha t)}$$

Travelling waves incident on junction

$$Z_{c2} = \sqrt{\frac{L}{C}} \to 0 \qquad Z_{c1} = Z_{cable}$$

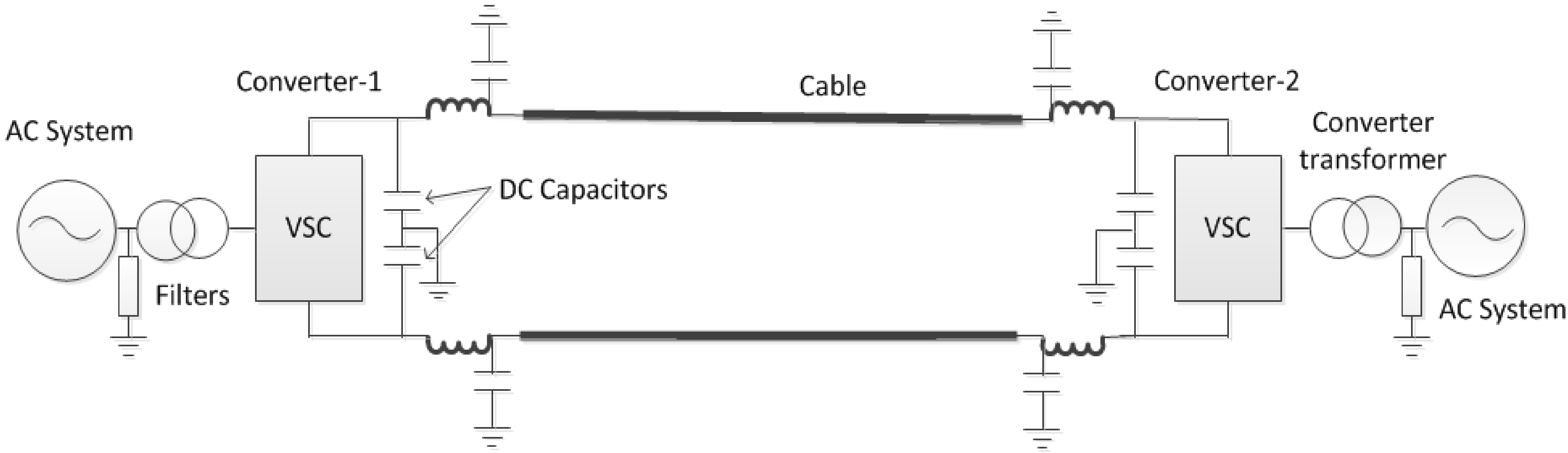
$$\rho = \frac{Z_{c2} - Z_{c1}}{Z_{c2} + Z_{c1}} \qquad \rho \to -1$$



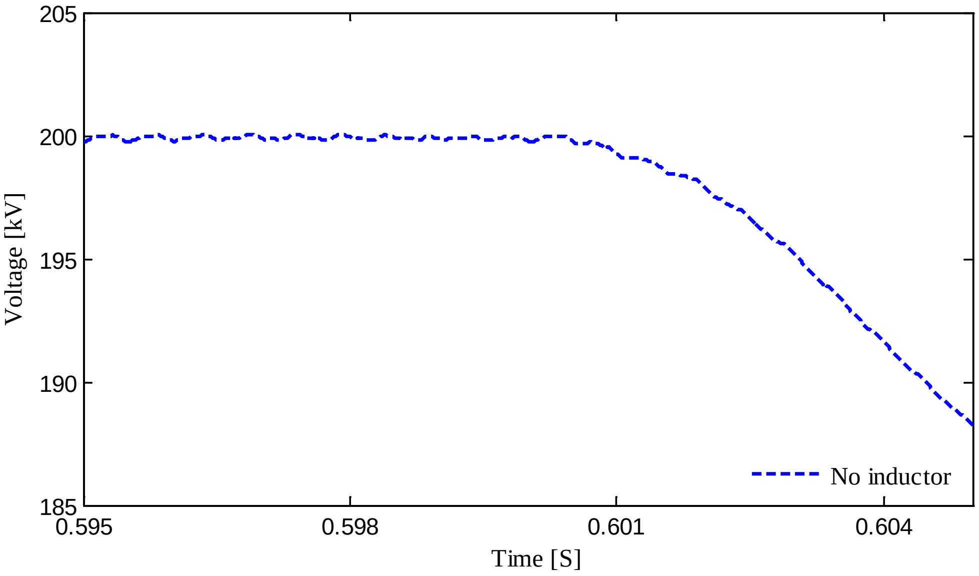
$$v_o(x_o, t) = (1 + \rho).\left(Ae^{-(x_o - \alpha t)}\right)$$

$$v(x_o, t) = Ae^{-(x_o - \alpha t)}$$

Test network



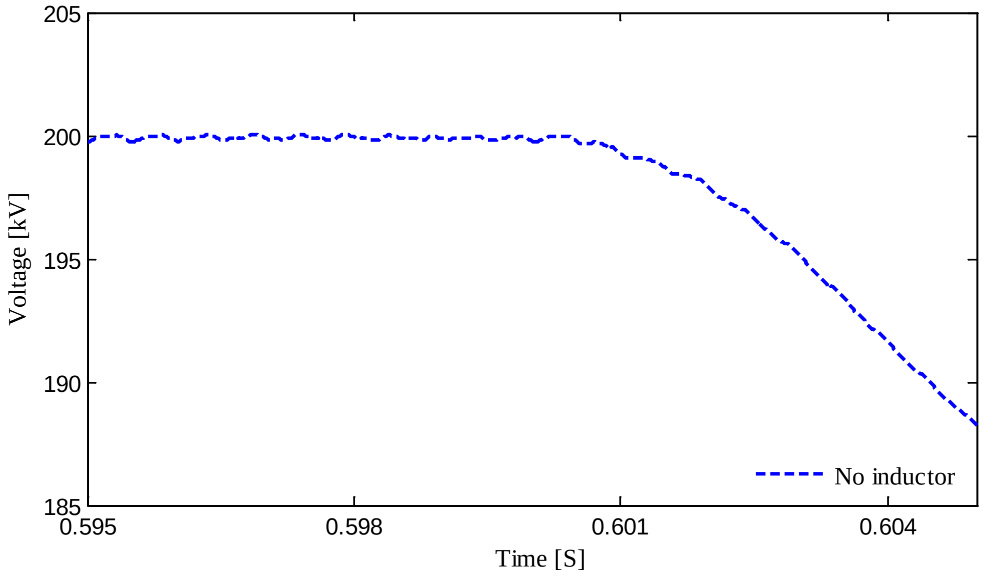
Terminal voltage



- Solid P-G fault 70 km away from Converter-1

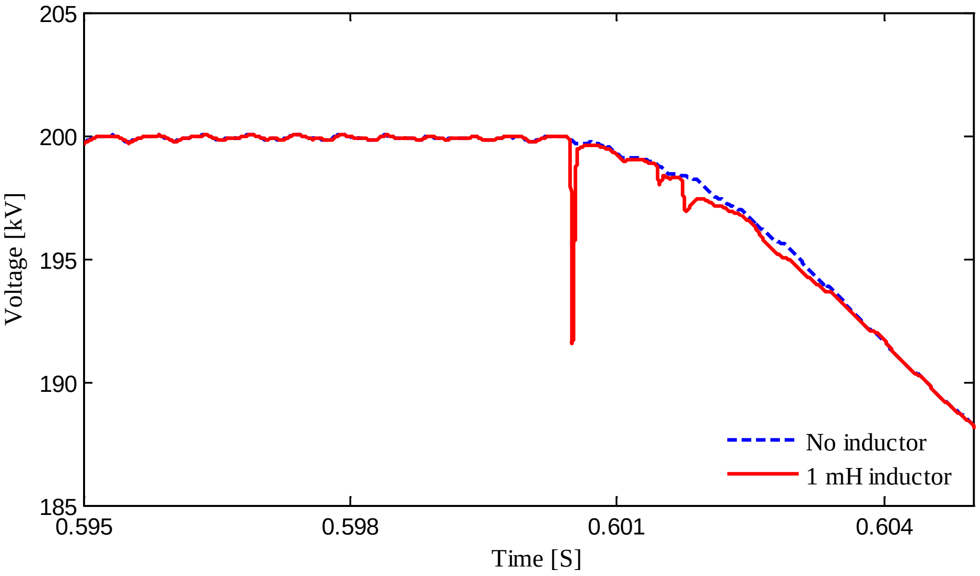
Terminal voltage

- Gradual Change



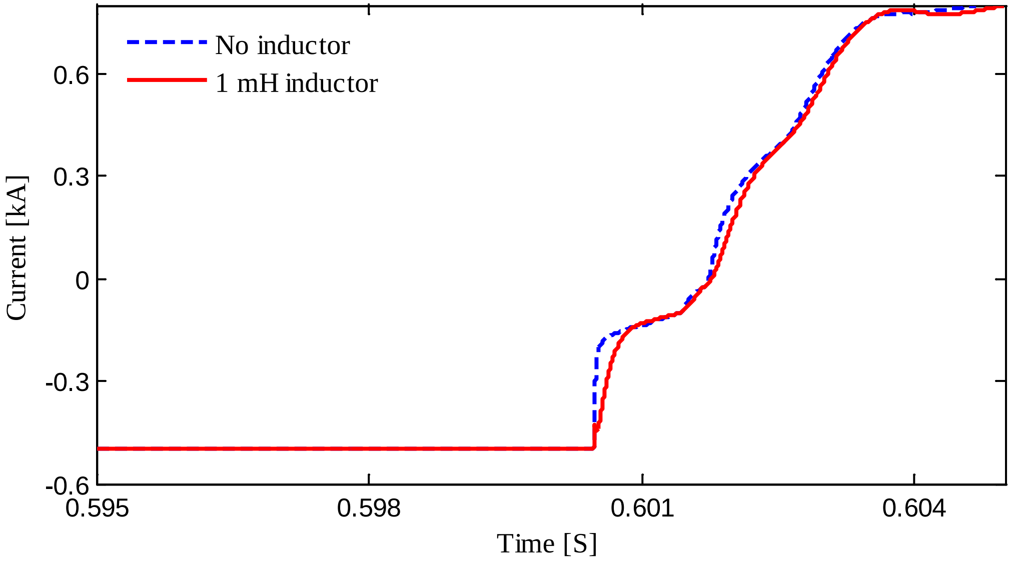
- Solid P-G fault 70 km away from Converter-1

Terminal voltage



- Solid P-G fault 70 km away from Converter-1

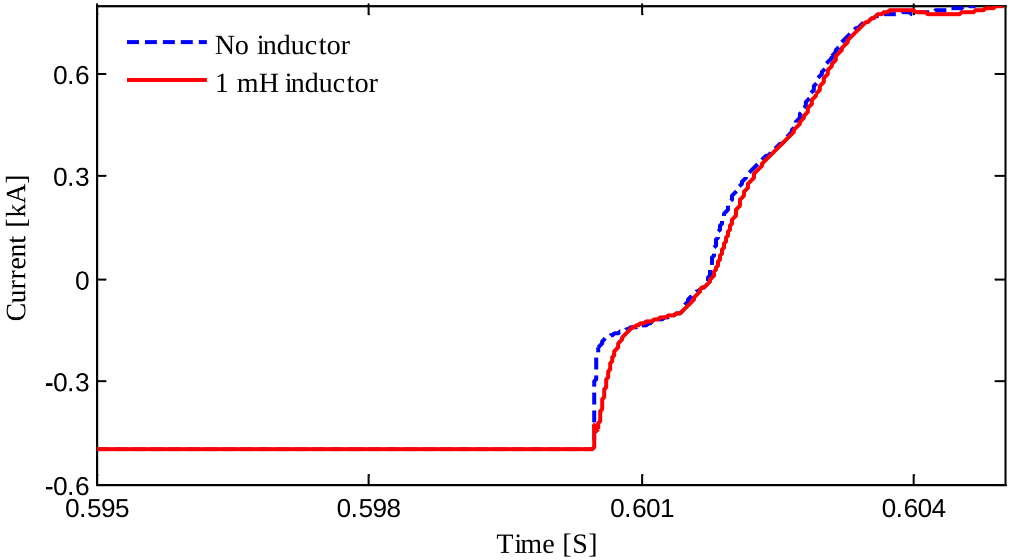
Terminal Current



- Solid P-G fault 70 km away from Converter-1

Terminal Current

- Less sharp terminal Current



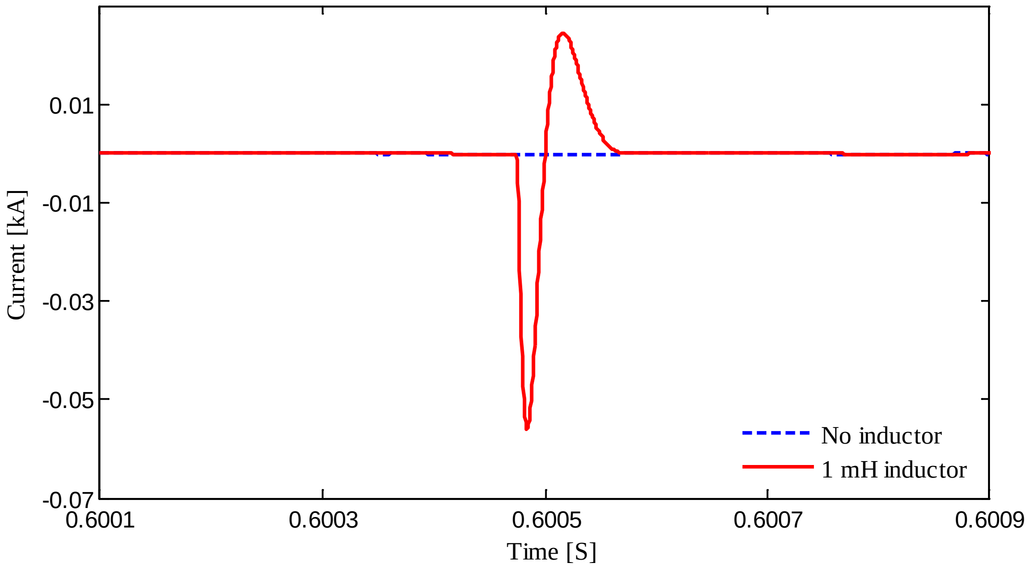
- Solid P-G fault 70 km away from Converter-1

Problems with line voltage and current measurements

- Transducers need to be installed at very high potentials.
  - Insulations requirements.
  - Electrical isolation between sensor output and the data acquisition system.
  - Bulky and expensive instrumentation.

Surge capacitor current

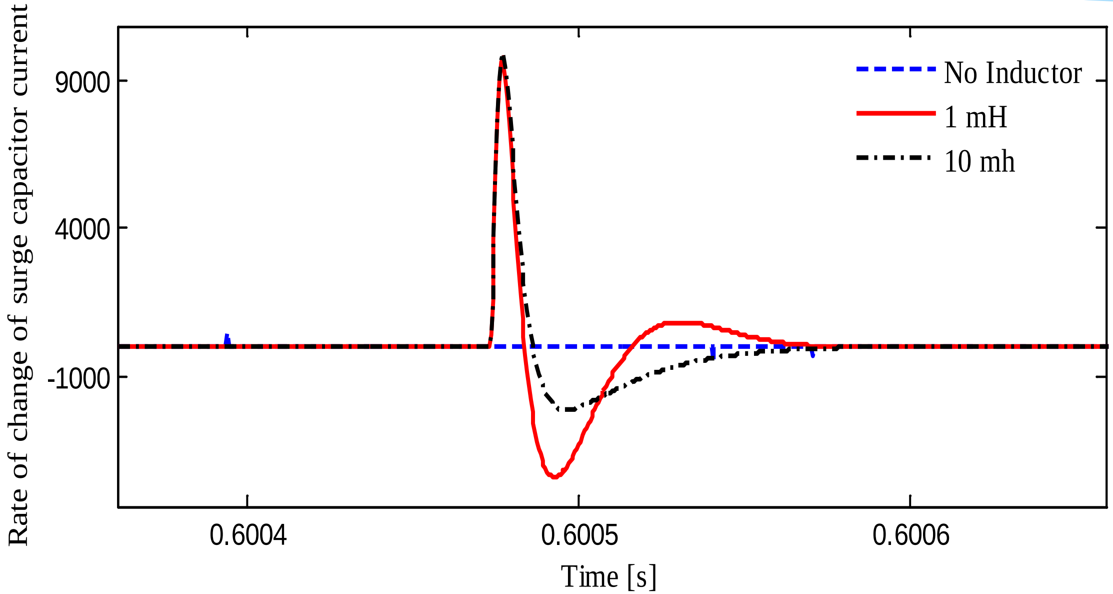
- Rate of change of terminal voltage



- Solid P-G fault 70 km away from Converter-1

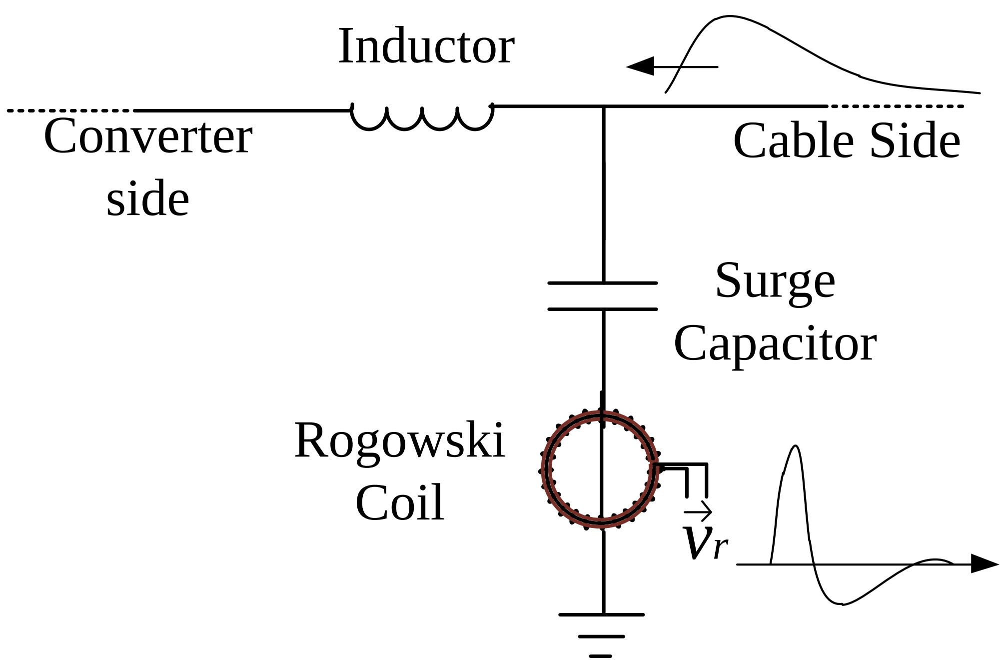
Rate of change of the surge capacitor current

- Small effect on value of inductance



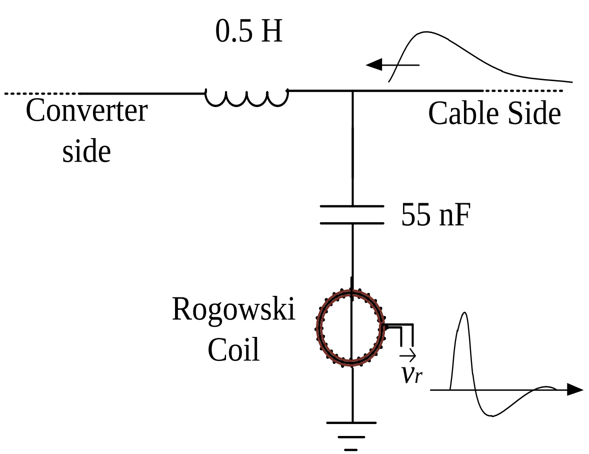
- Solid P-G fault 70 km away from Converter-1

Proposed termination



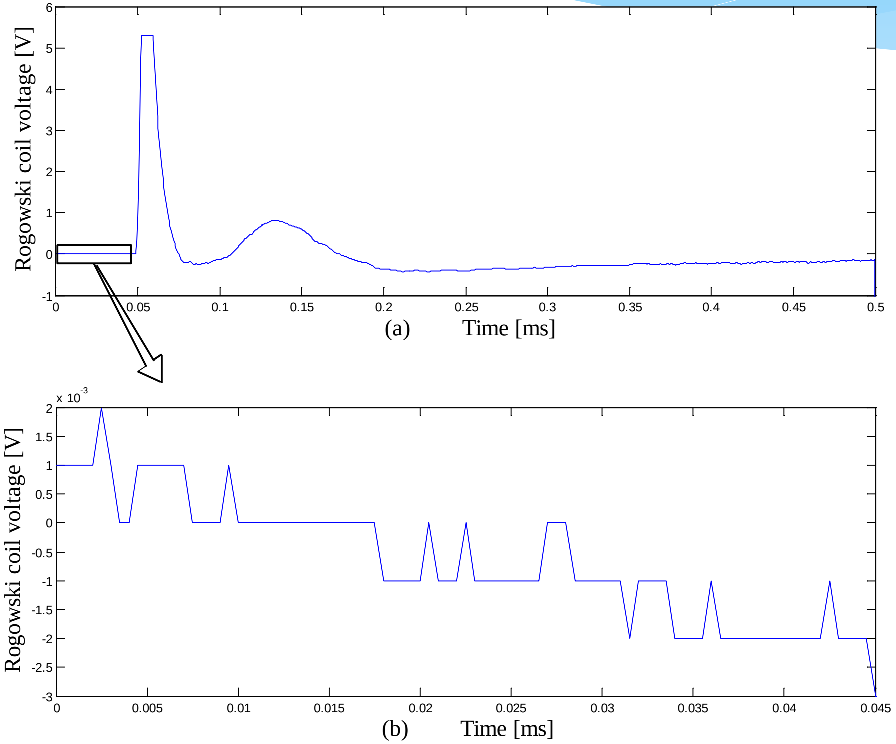
Experimental results

- Dorsey converter station
  - LCC HVDC
  - ± 500 kV
  - 900 km Overhead line



Inner radius	260 mm
Outer radius	284 mm
Resistance	468 Ω
Self-Inductance	3.5 mH
Capacitance	60.93 pF
Mutual-Inductance	0.55 μH

Experimental results



- Rogowski coil voltage for a fault 356 km away from Dorsey converter station.

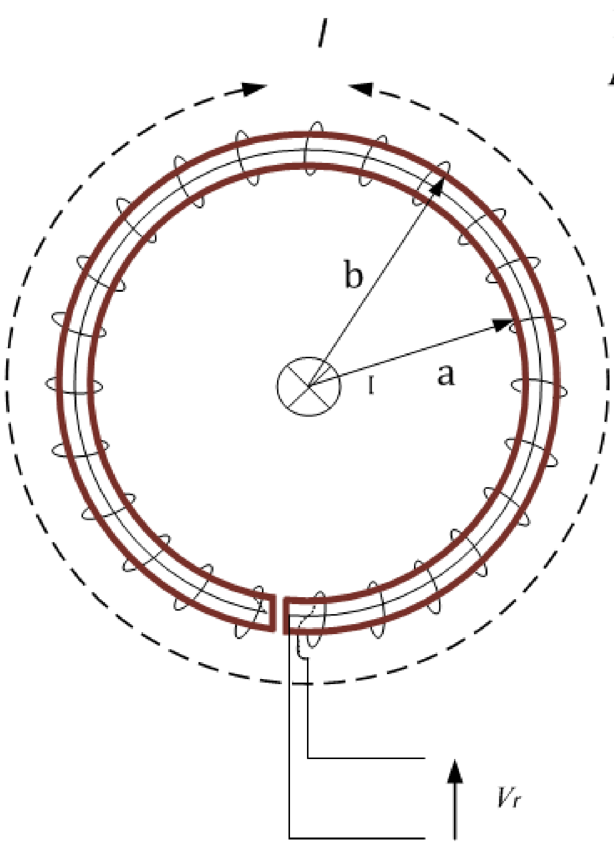
Remarks

- If there is no series inductor
  - voltage or surge cap cannot be used
  - Current can be used

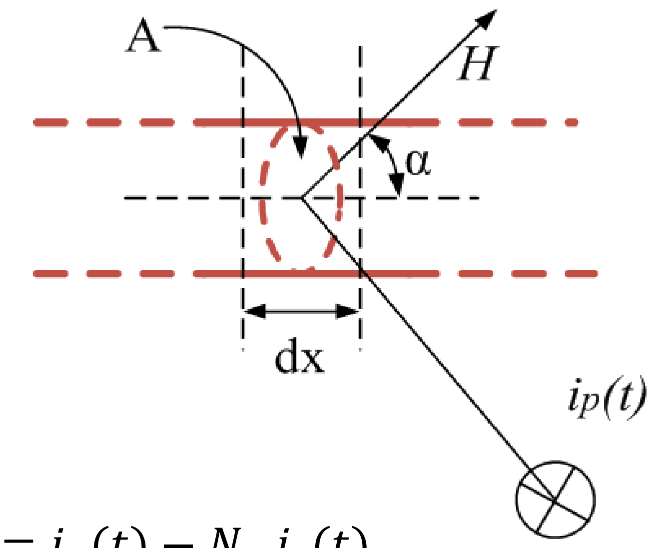
- With series inductor
  - voltage or surge cap can be used

- The value of the series inductor is not that important as long as it is above 1 mH.

Modelling of Rogowski Coil



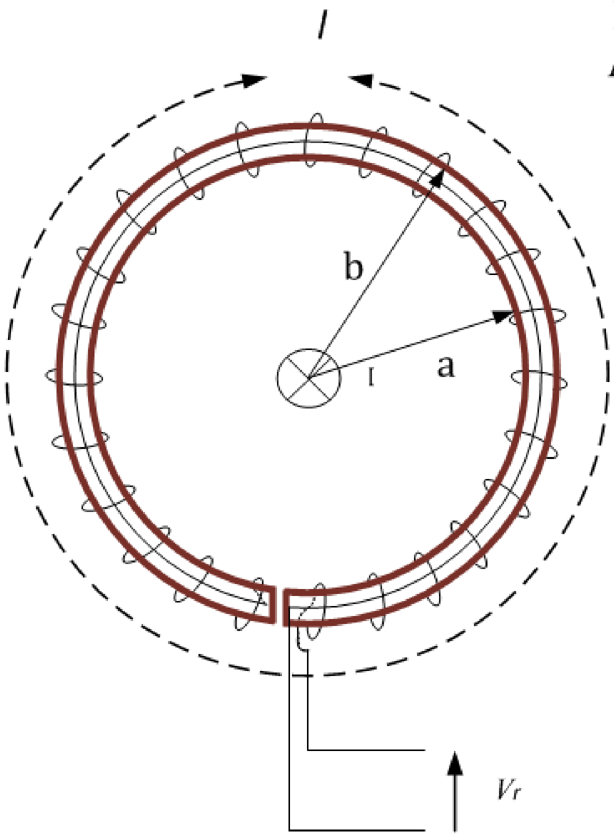
H ⊥α– Magnetic Field
A – Cross section area of Rogowski coil
I – Circumference of Rogowski coil



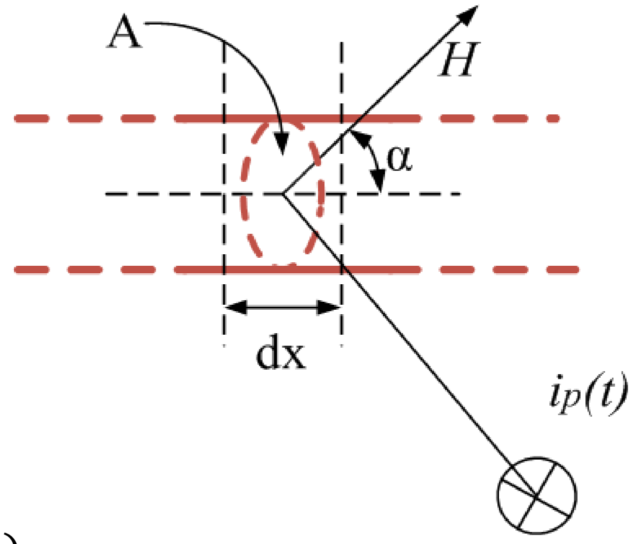
$$\oint H(t).\cos(\alpha).dx = i_p(t) - N_s.i_s(t)$$

$$d\varphi = A.\frac{N_s}{l}dx.\mu_0.H(t).\cos(\alpha)$$

Modelling of Rogowski Coil



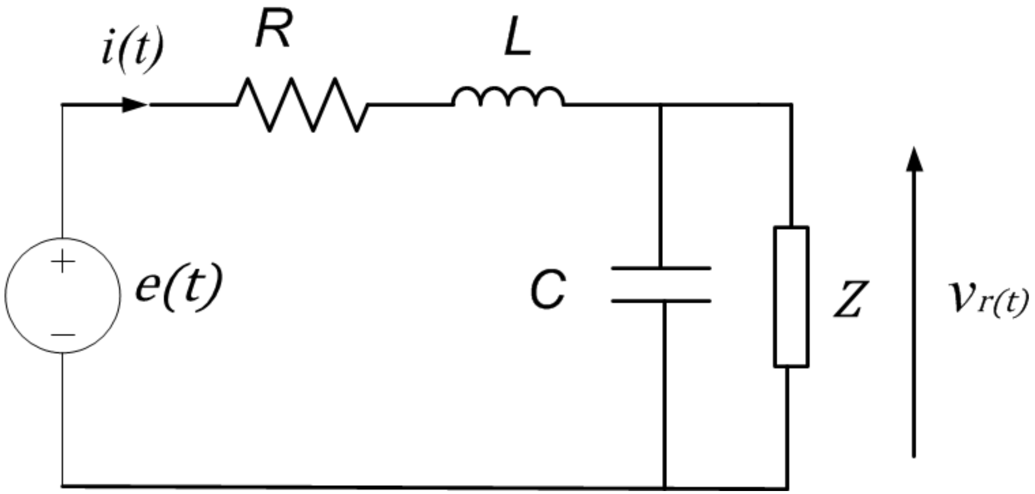
H ⊥α– Magnetic Field
A – Cross section area of Rogowski coil
I – Circumference of Rogowski coil



$$\varphi(t) = \mu_0 . A . n . i_p(t)$$

$$e(t) = -\frac{d\varphi(t)}{dt} = -\mu_0 . A . \frac{N_s}{l} . \frac{di_p(t)}{dt}$$

Equivalent Circuit of Rogowski Coil



$$v_r(t) = e(t) - L.\frac{di(t)}{dt} - i(t).R$$

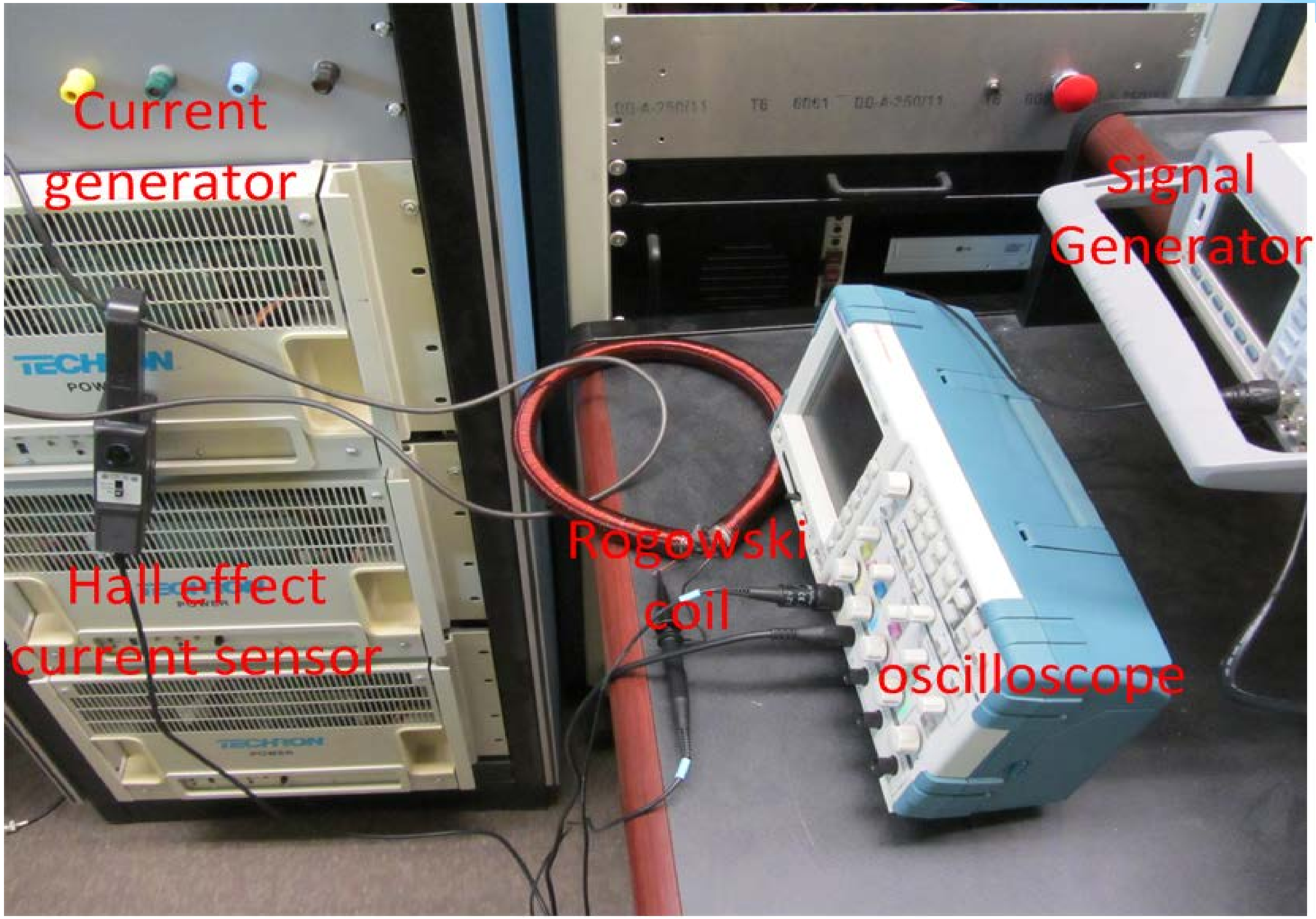
$$i(t) = C.\frac{dv_r(t)}{dt} + \frac{v_r(t)}{Z_b}$$

Parameters of the designed Rogowski coil

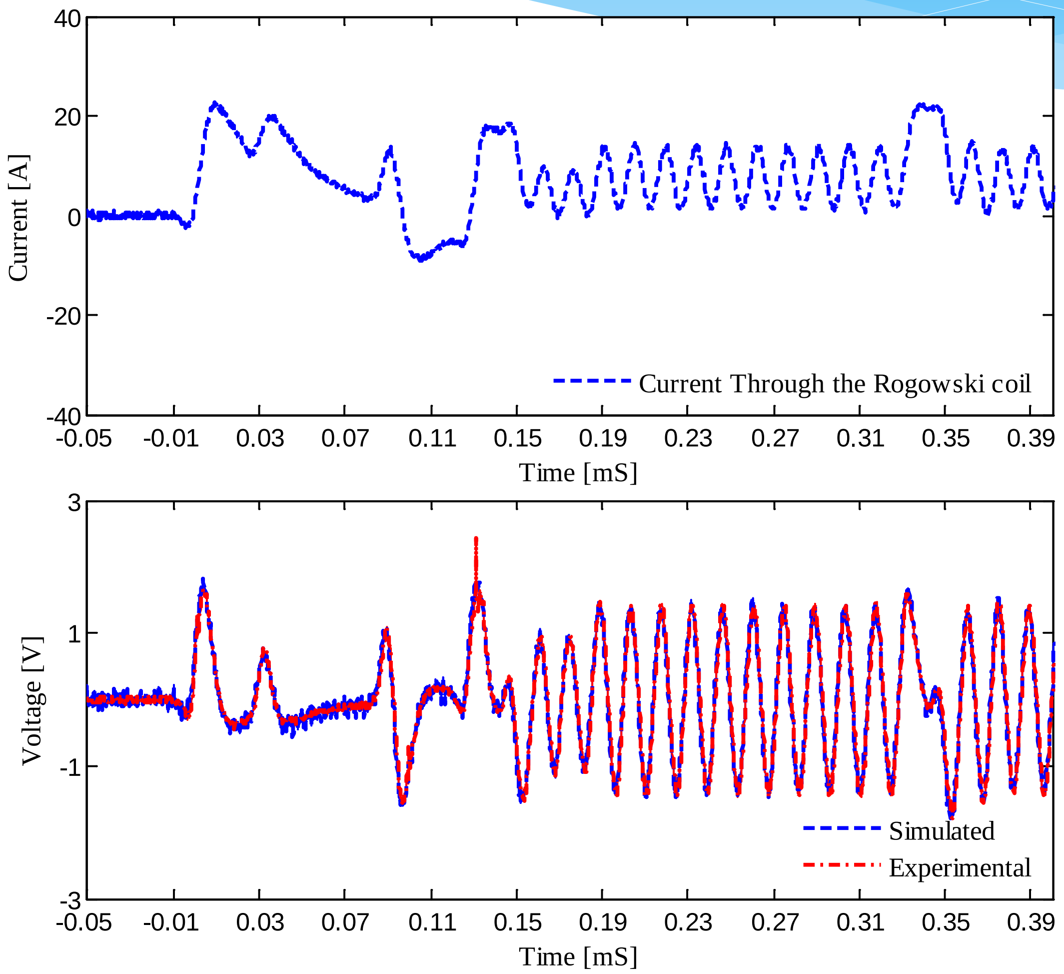
Inner radius	51.37 mm	
Outer radius	57.49 mm	
Number of Turns	870	
	measured	calculated
Resistance	4 Ω	3.9 Ω
Self-Inductance	81 μH	81 μH
Capacitance *	-	13 pF
Mutual-Inductance	0.093 μH	0.093 μH

* Capacitance is too small to measure

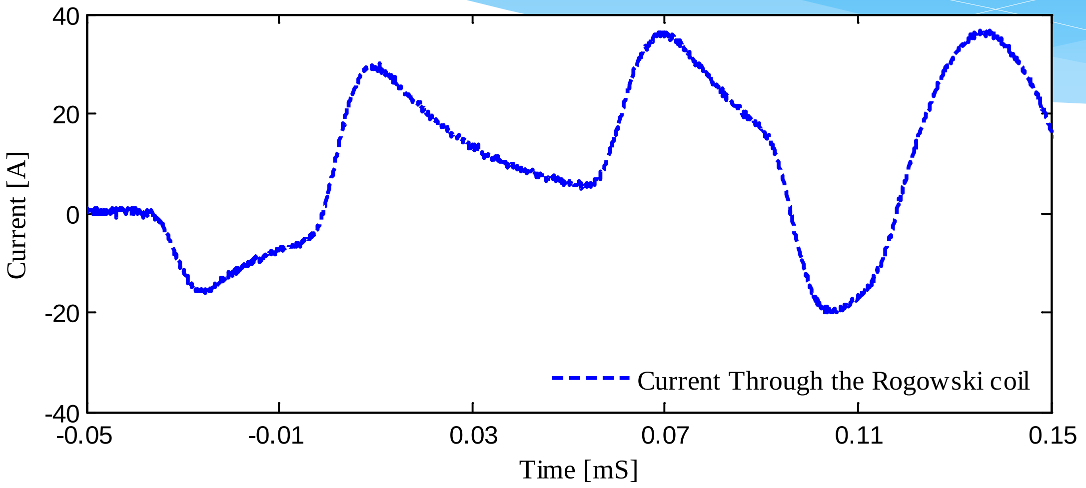
Test setup

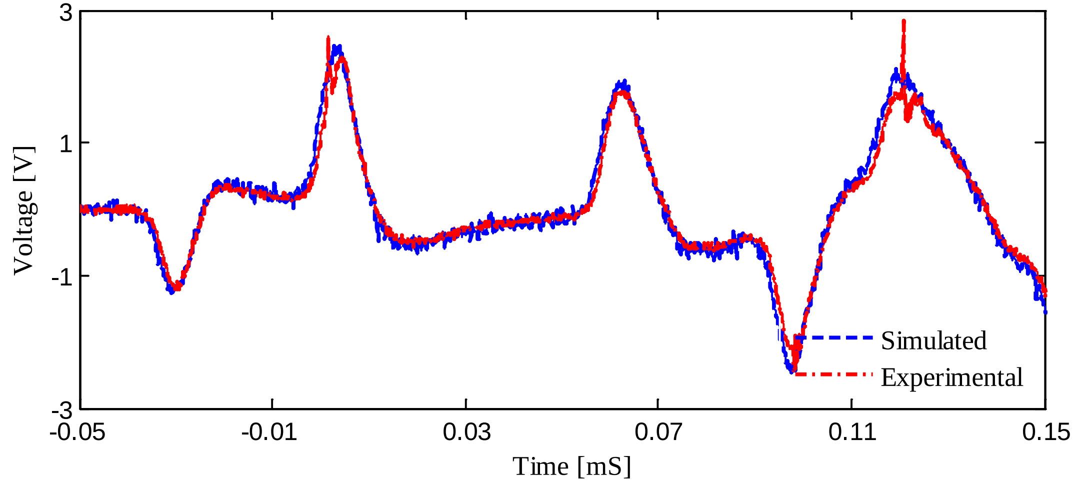

Current
generator
Signal
Generator
Rogowski
coil
Hall effect
current sensor
oscilloscope

Verification of the Rogowski coil model

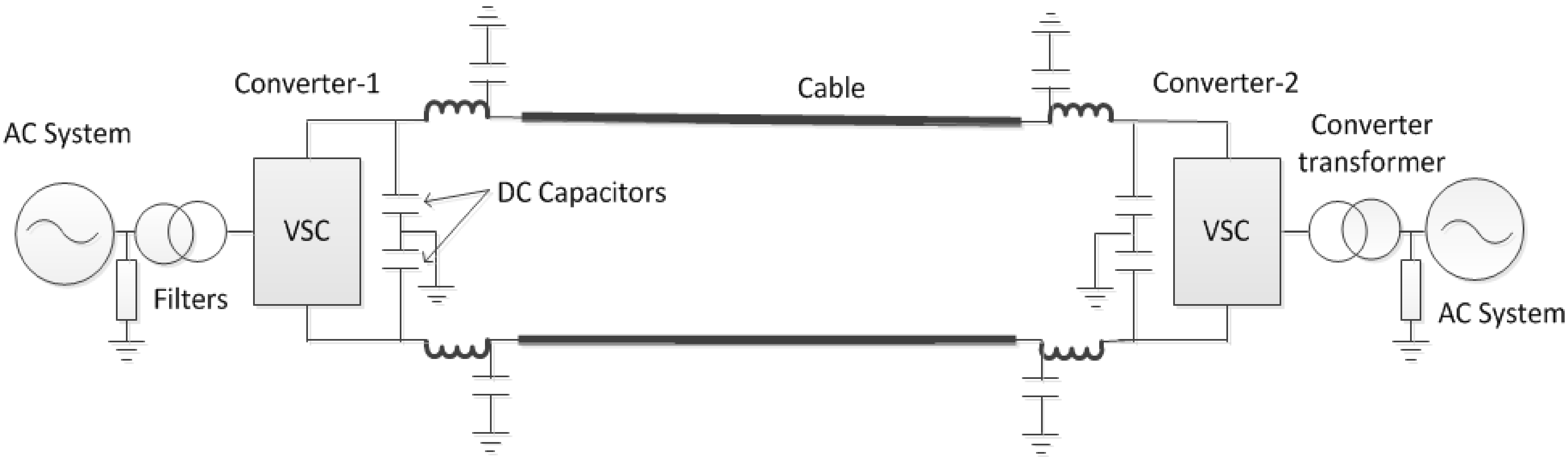


Verification of the Rogowski coil model

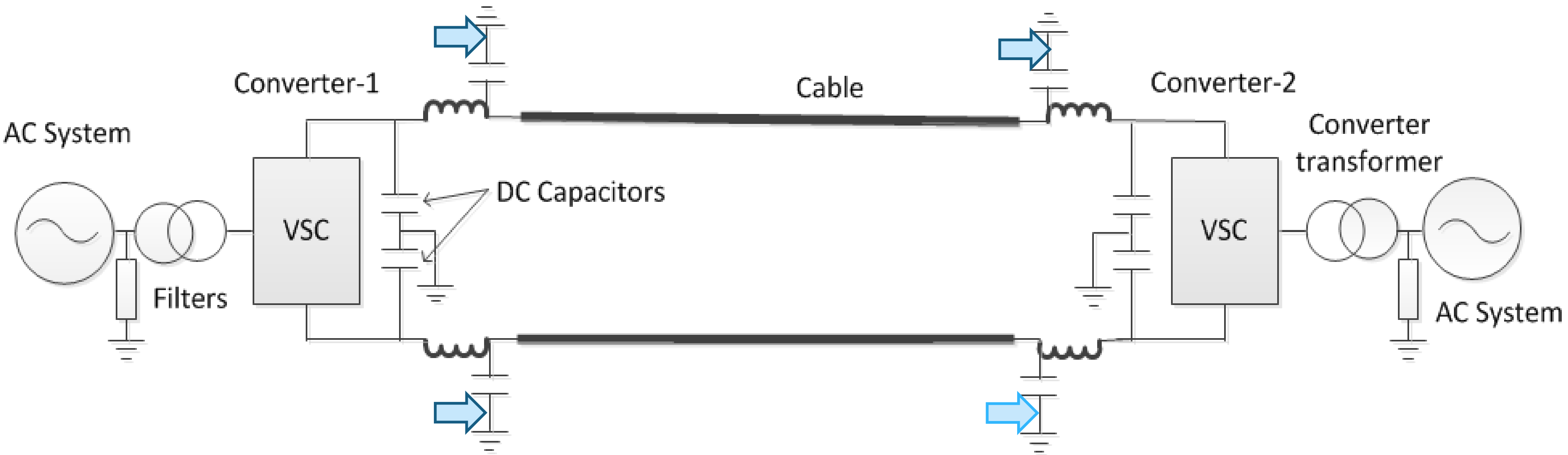




Line Fault Location Performance



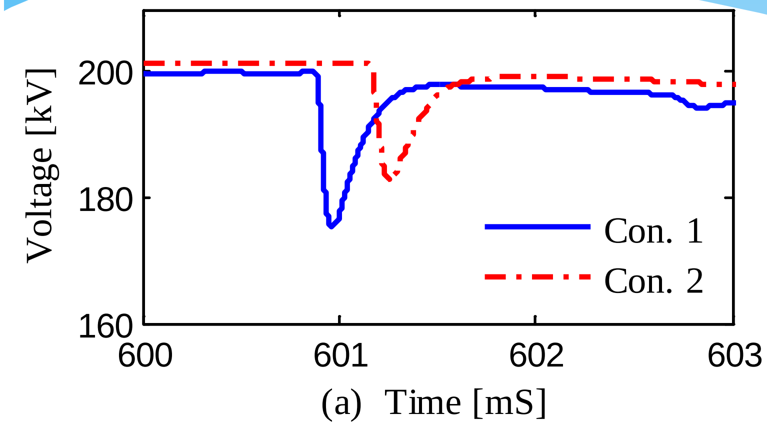
Line Fault Location Performance

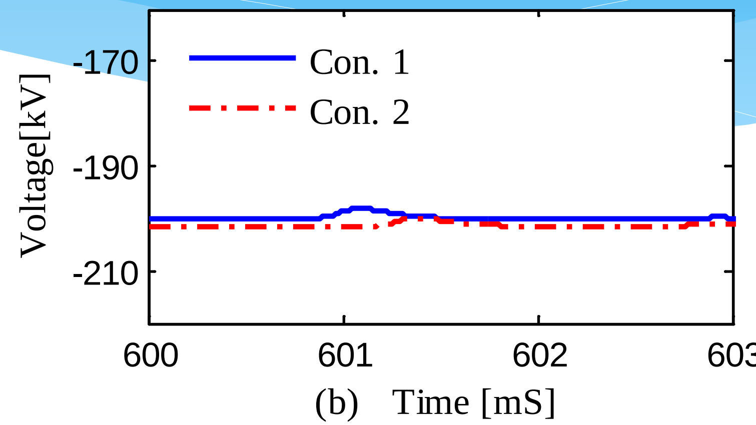


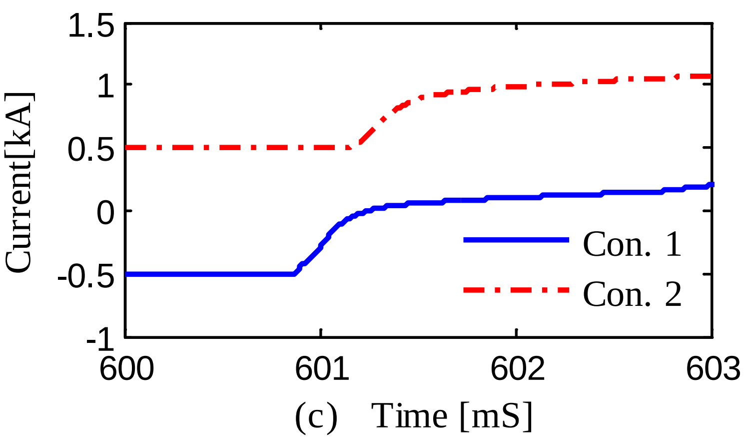
Terminal voltages and Currents

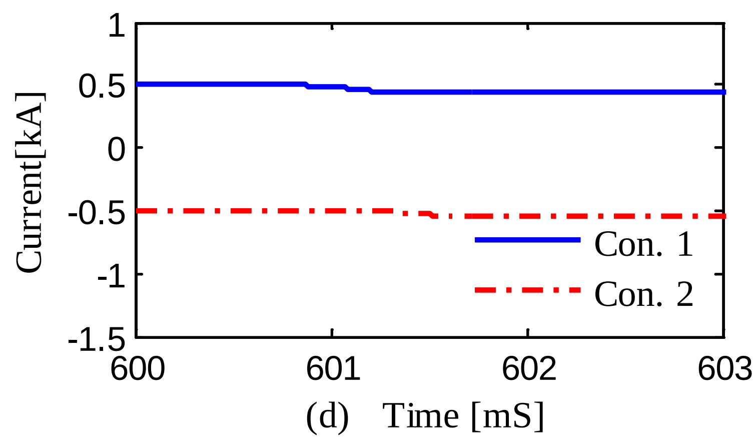
Positive pole

Negative pole



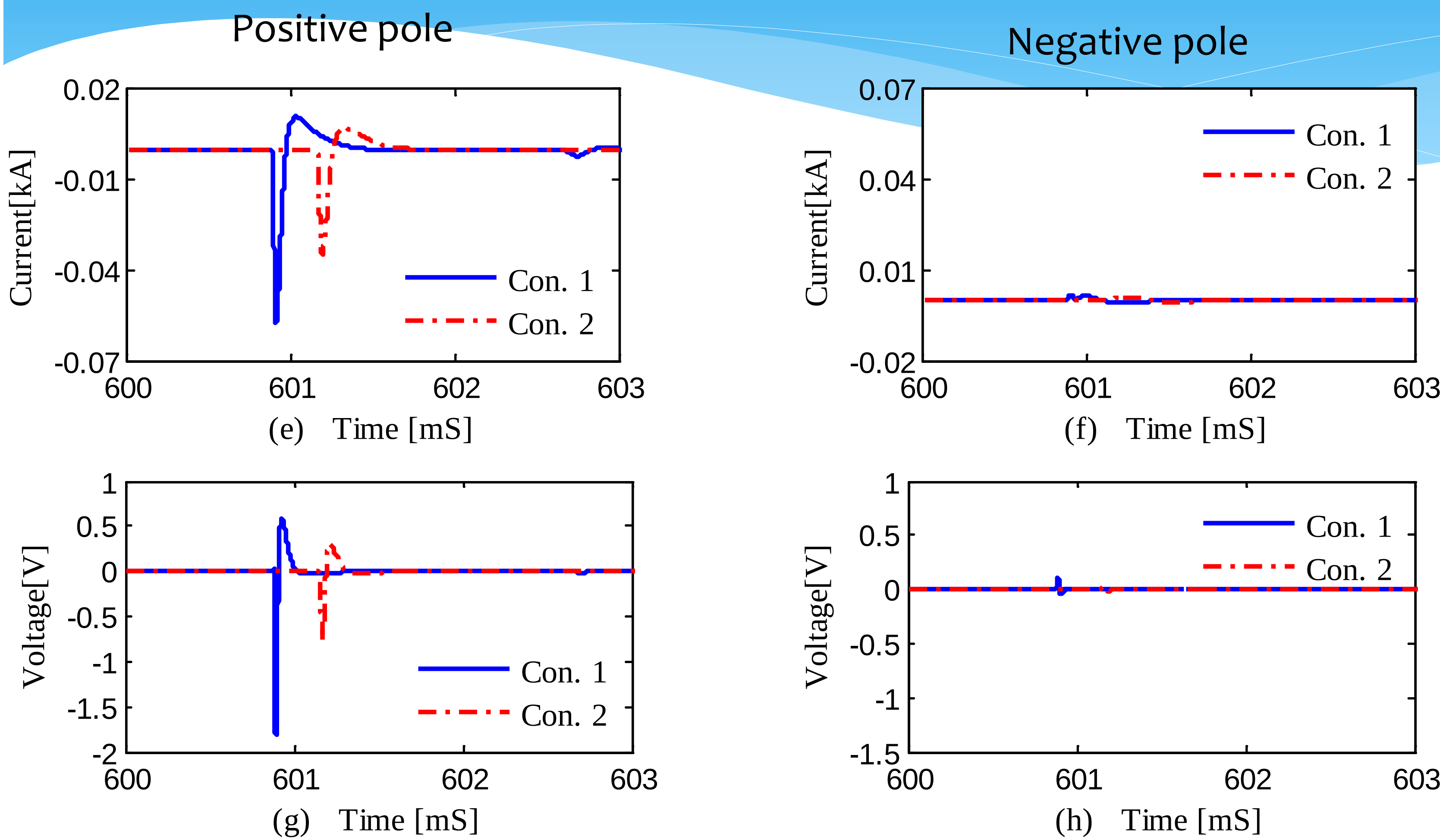






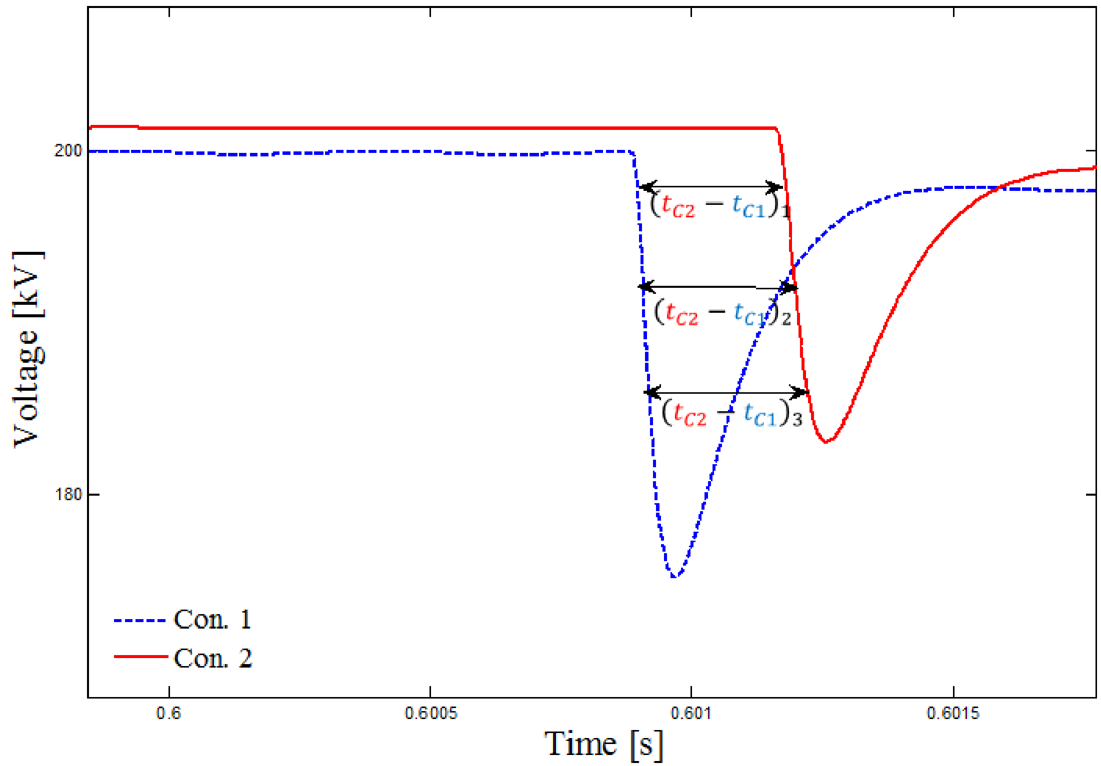
solid pole-to-ground fault on positive pole 130 km from Converter-1

Surge Capacitor currents and Rogowski coil Voltages



solid pole-to-ground fault on positive pole 130 km from Converter-1

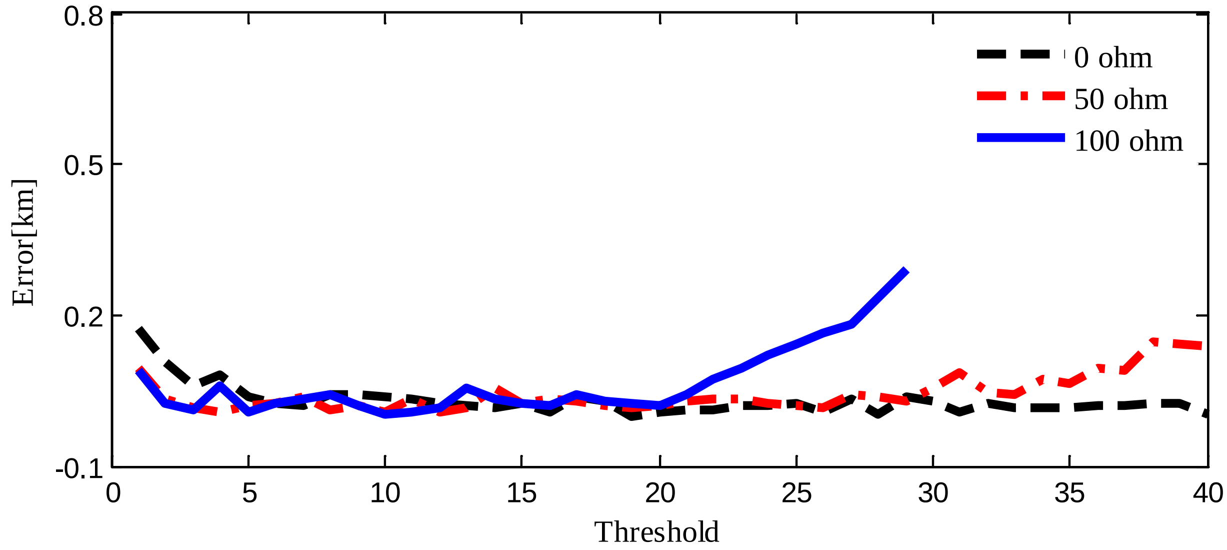
Threshold setting



Threshold setting

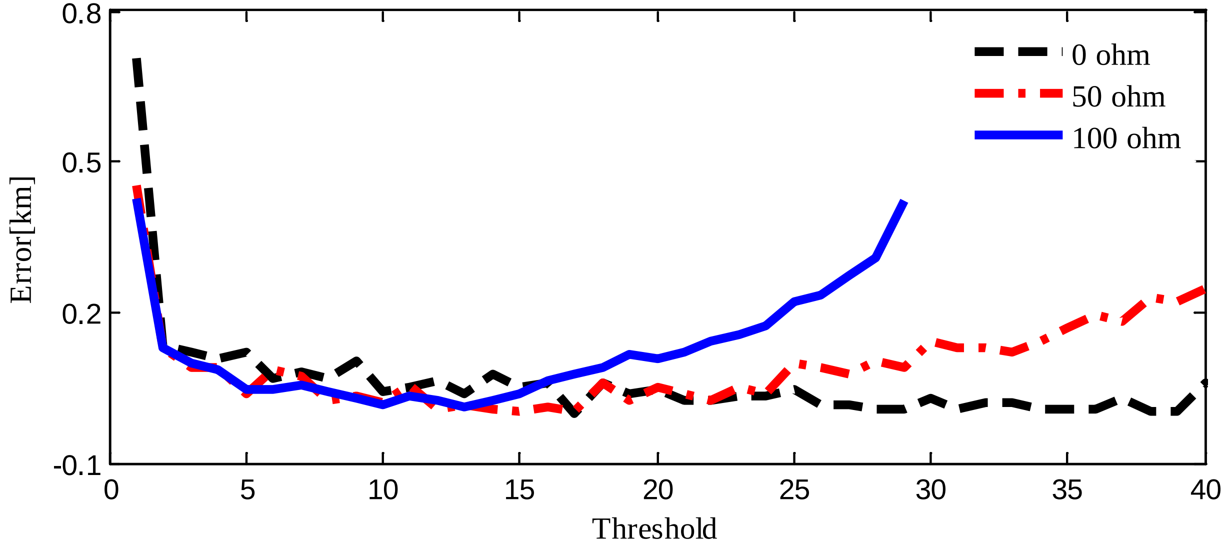
Actual fault location (km)	Fault location errors (km)			
	visual inspection	Threshold 1	Threshold 10	Threshold 25
30	0.233	0.209	-0.209	0.097
50	0.721	0.707	0.326	0.123
130	0.578	0.567	0.453	0.193
160	-0.476	-0.394	-0.172	-0.115
230	-0.327	-0.286	-0.019	0.106
260	-0.863	-0.807	-0.424	-0.165

Threshold setting and fault resistance



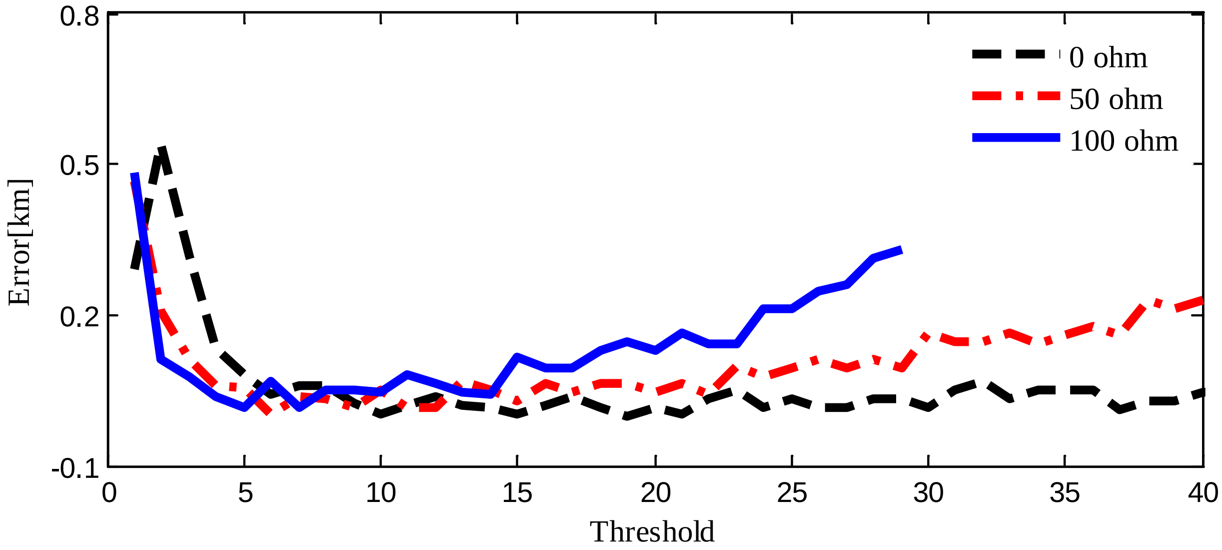
Solid fault 30km the Converter -1

Threshold setting and fault resistance



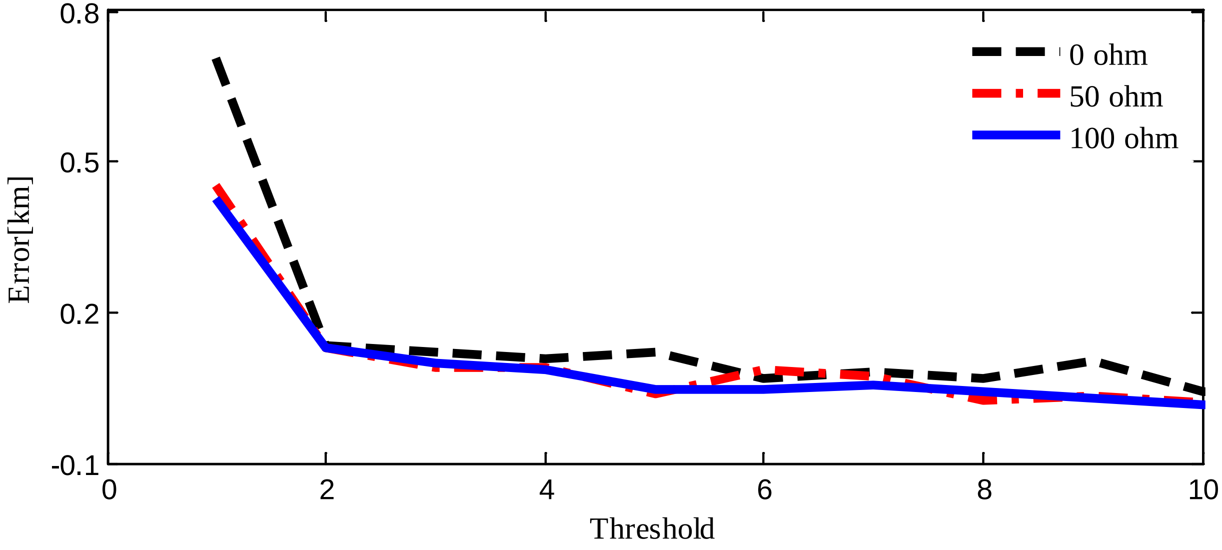
Solid fault 50km the Converter -1

Threshold setting and fault resistance



Solid fault 220km the Converter -1

Threshold setting and fault resistance/low Thresholds



Solid fault 220km the Converter -1

Possibilities of improving the accuracy

- Modal Transform
  - Remove the coupling between conductors.

- Filtering
  - Selecting frequency band.

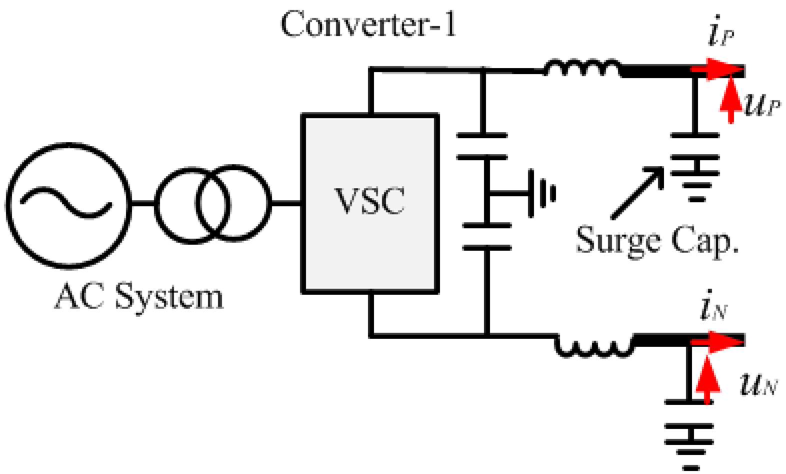
Modal transform

$$\begin{bmatrix} u_{m0} \\ u_{m1} \end{bmatrix} = T.\begin{bmatrix} u_N \\ u_P \end{bmatrix} \qquad \begin{bmatrix} i_{m0} \\ i_{m1} \end{bmatrix} = T.\begin{bmatrix} i_N \\ i_P \end{bmatrix}$$

$$T = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$\begin{bmatrix} k\ddot{u}_{m0} \\ k\ddot{u}_{m1} \end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}.\begin{bmatrix} k\ddot{u}_N \\ k\ddot{u}_P \end{bmatrix}$$

$$\begin{bmatrix} v_{rm0} \\ v_{rm1} \end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}.\begin{bmatrix} v_{rN} \\ v_{rP} \end{bmatrix}$$



Fault Location errors /Modal transform

Actual fault location (km)	Fault location error (*km*)		
	No M.Trans.	Mode '0'	Mode '1'
30	0.209	0.172	0.209
50	0.707	0.707	0.707
130	0.567	0.567	0.567
160	-0.394	-0.467	-0.431
230	-0.286	-0.286	-0.286
260	-0.807	-0.807	-0.807

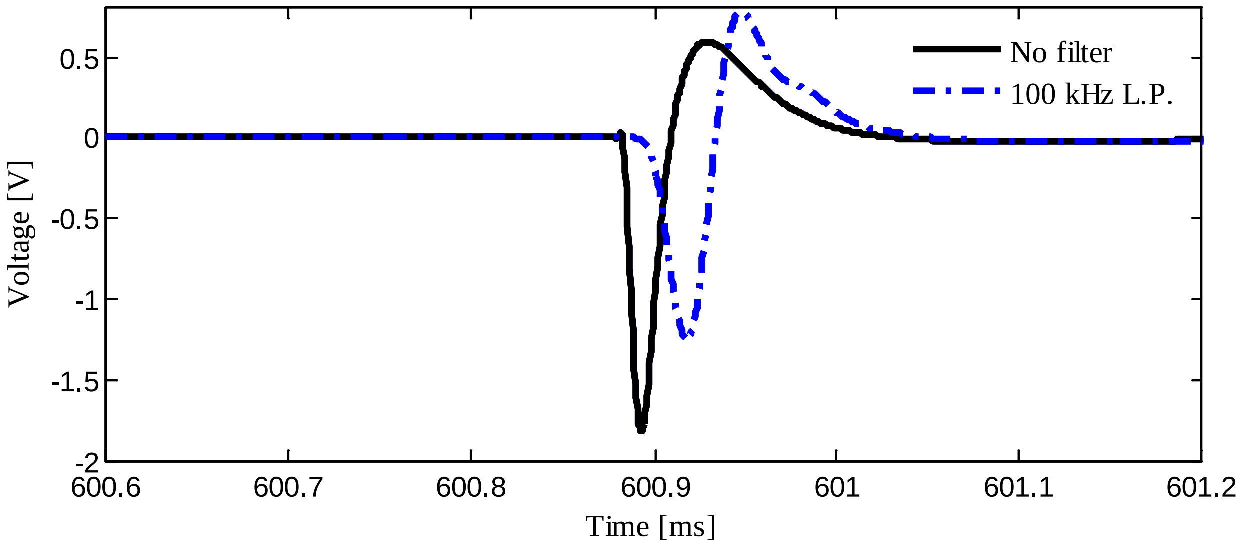
Solid-Fault

Fault Location errors /Modal transform

Actual fault location (km)	Fault location error (km)		
	No M.Trans.	Mode ‘0’	Mode ‘1’
30	-0.088	-0.119	-0.095
50	0.427	0.402	0.452
130	0.474	0.432	0.479
160	-0.182	-0.179	-0.404
230	-0.100	-0.080	-0.120
260	-0.499	-0.508	-0.527

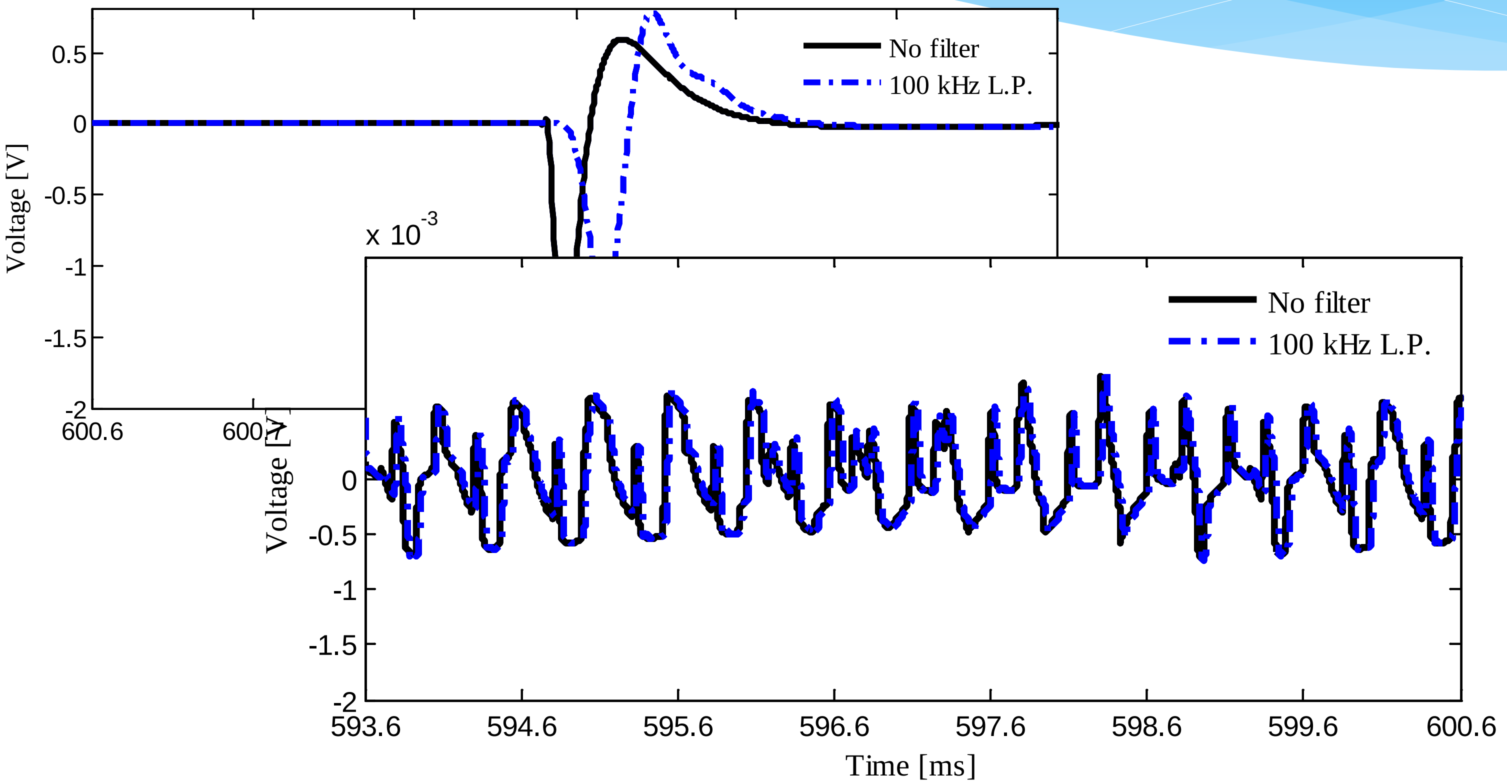
100Ω Fault resistance

filtered and unfiltered Rogowski coil voltages



Solid P-G fault 130 km away from the Converter-1.

Line Fault Location Performance



Solid P-G fault 130 km away from the Converter-1.

Fault location with filtered signals (Threshold-1/Solid fault)

Actual fault location (km)	Fault location error (km)					
	No filter	1MHz	500 kHz	100kHz	50kHz	10kHz
30	0.172	0.161	0.112	-0.095	0.071	0.159
50	0.707	0.641	0.576	0.163	0.114	-1.63
130	0.567	0.510	0.452	-0.004	0.030	-1.121
160	-0.394	-0.31	-0.190	-0.089	-0.015	1.164
230	-0.286	-0.278	-0.197	-0.203	-0.011	52.462
260	-0.807	-0.731	-0.619	-0.216	-0.129	67.948

Fault location with filtered signals (Threshold-1/100 Ω)

Actual fault location (km)	Fault location error (km)					
	No filter	1MHz	500 kHz	100kHz	50kHz	10kHz
30	-0.088	-0.136	-0.117	0.058	0.140	0.804
50	0.427	0.362	0.359	0.206	0.129	-2.195
130	0.474	0.38	0.182	-0.003	0.011	-1.51
160	-0.182	-0.172	-0.164	-0.071	0.012	1.723
230	-0.100	-0.056	-0.068	-0.135	0.064	53.374
260	-0.499	-0.424	-0.414	-0.204	-0.152	68.969

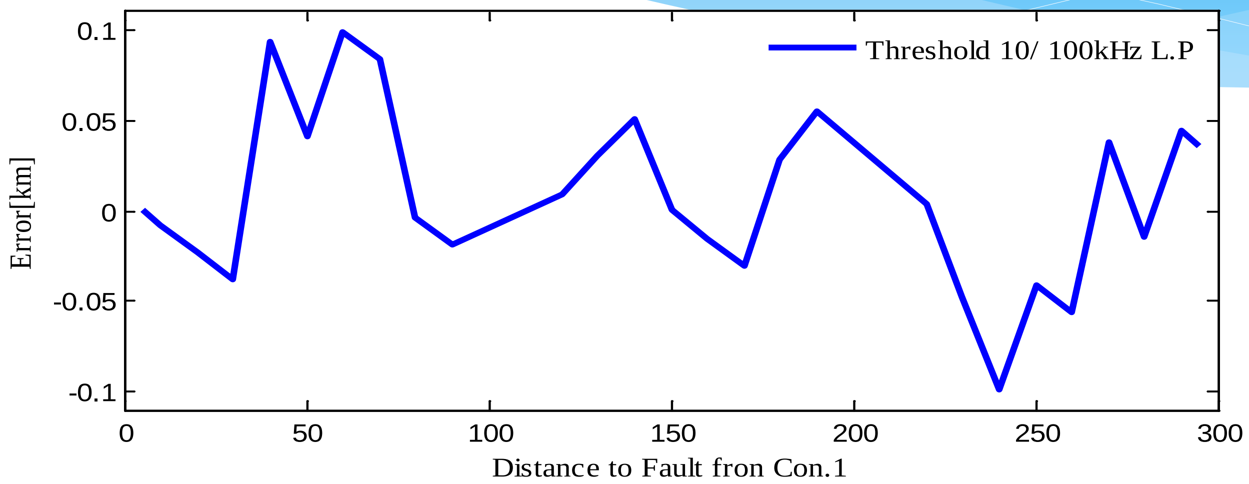
Fault location with filtered signals (Threshold-10/Solid fault)

Actual fault location (km)	Fault location error (km)					
	No filter	1MHz	500 kHz	100kHz	50kHz	10kHz
30	-0.209	-0.221	-0.165	-0.038	0.040	0.373
50	0.326	0.297	0.258	0.041	0.057	-0.057
130	0.453	0.176	0.015	0.03	0.019	-0.305
160	-0.172	-0.125	-0.117	-0.015	0.009	0.03
230	-0.019	-0.011	-0.024	-0.048	0.034	-0.039
260	-0.424	-0.349	-0.302	-0.056	-0.012	-0.333

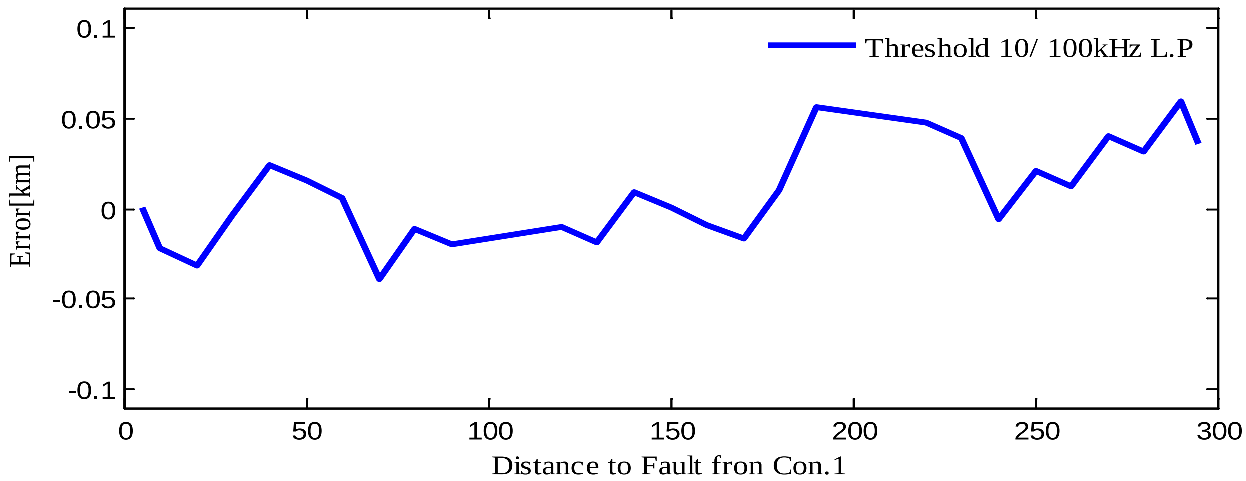
Fault location with filtered signals (Threshold-10/100 Ω)

Actual fault location (km)	Fault location error (km)					
	No filter	1MHz	500 kHz	100kHz	50kHz	10kHz
30	0.031	-0.016	0.069	-0.004	0.051	2.354
50	-0.016	-0.044	-0.021	0.015	0.012	-7.37
130	0.011	0.028	-0.019	-0.019	0.002	-2.04
160	-0.097	-0.050	-0.045	-0.009	0.035	0.816
230	0.028	0.035	0.003	0.039	0.133	6.053
260	-0.008	0.030	0.013	0.012	0.094	-2.886

Fault location errors with cable connection

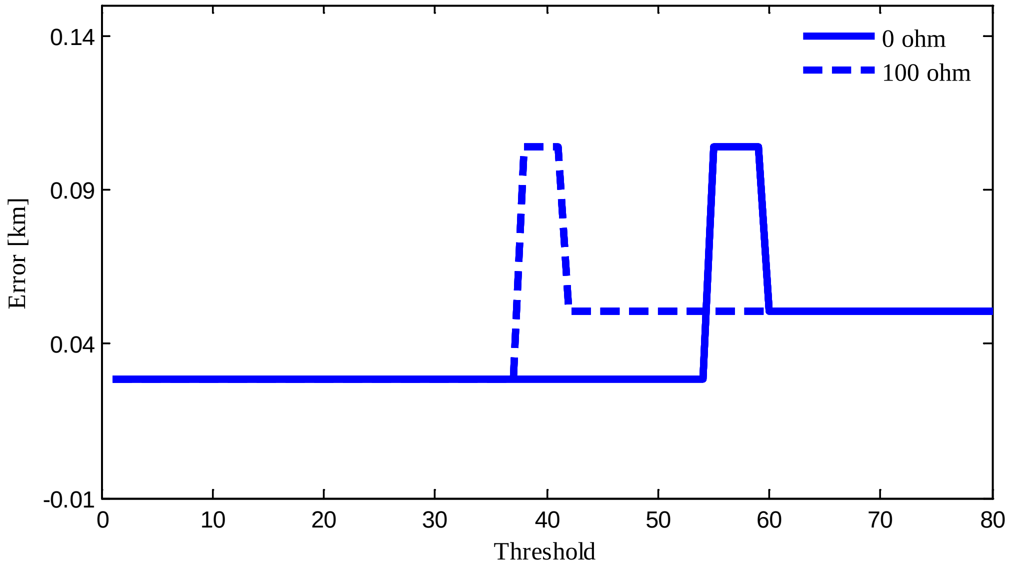


Solid fault



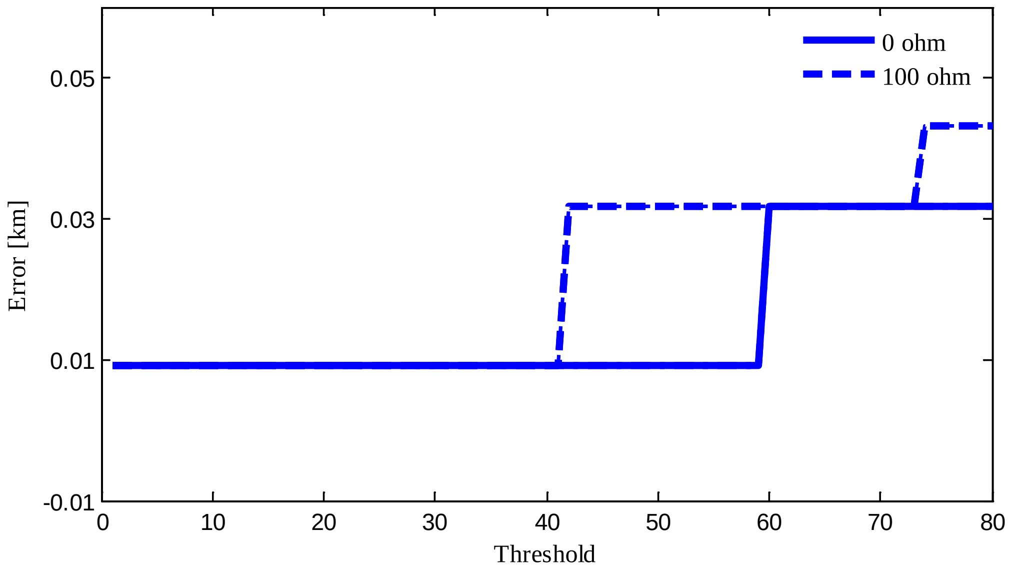
100Ω fault resistance

VSC HVDC scheme with overhead lines



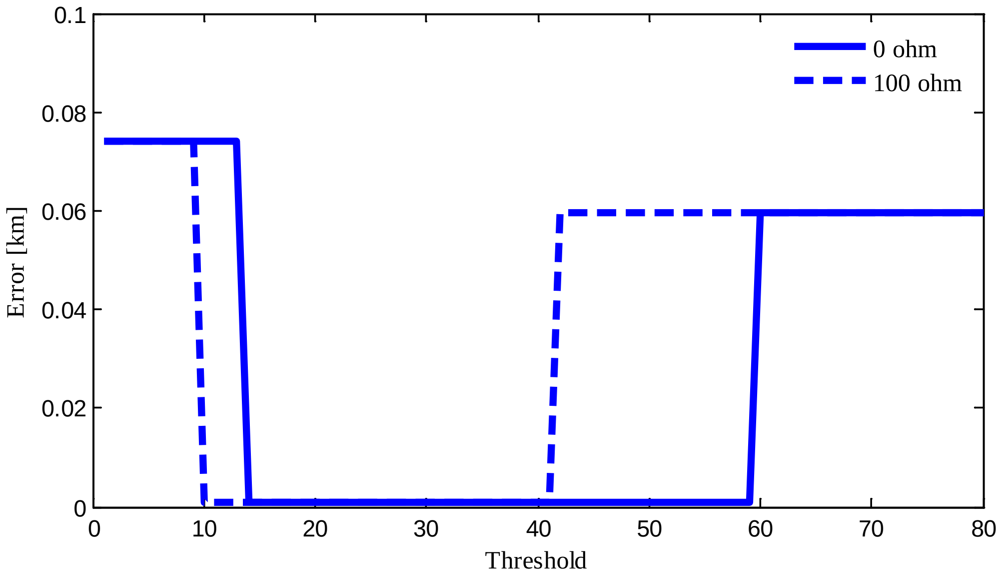
Solid fault 300km the Converter -1

VSC HVDC scheme with overhead lines



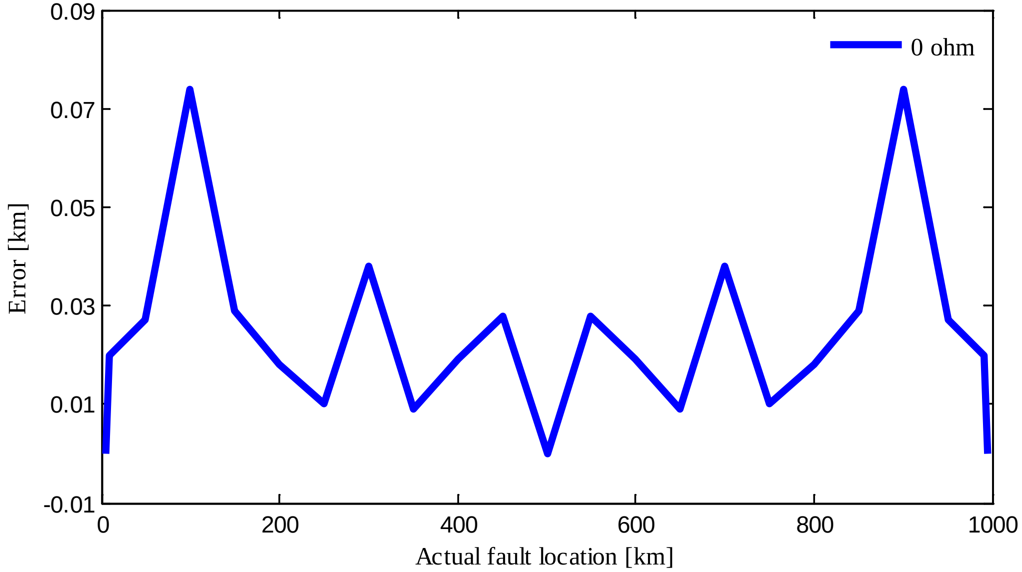
Solid fault 600km the Converter -1

VSC HVDC scheme with overhead lines

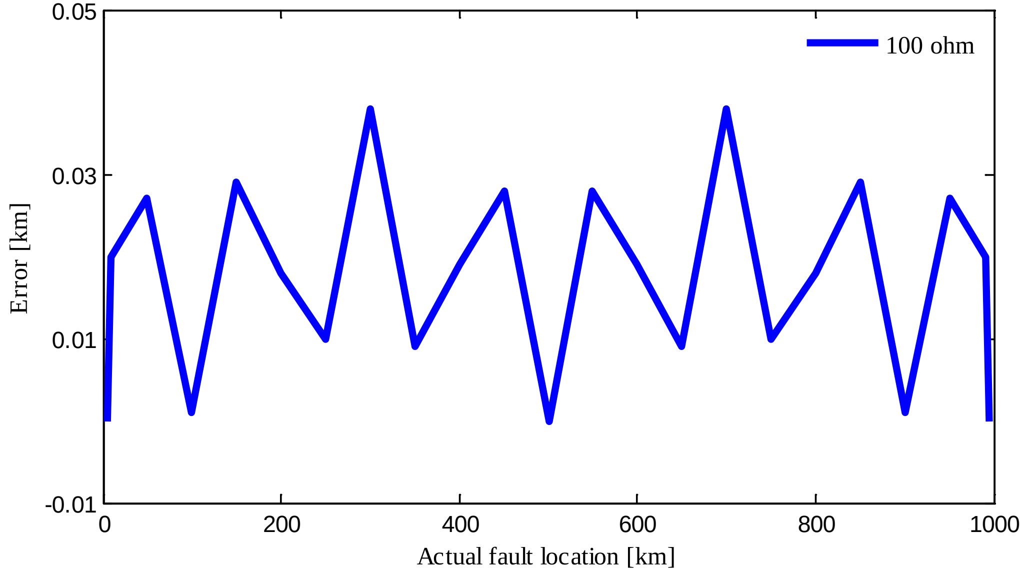


Solid fault 100km the Converter -1

Fault location errors with overhead line



Fault location errors with overhead line



Remarks

- Simulation results indicated that there is an optimum range of threshold settings.

- Accuracy improved by filtering the signal from Rogowski coil with a low pass filter with a cut-off frequency of 50-100 kHz.

Conclusions

- Proposed termination enables successful detection of travelling waves in VSC HVDC schemes.
- Fault location accuracy can be improved by filtering and selecting a optimum threshold setting.
- Fault location accuracy of ± 250 m for a 1000 km overhead line or 300 km long cable in a VSC HVDC system with the proposed method.