Developments in the Line Fault Location Technology for HVDC Systems

Kasun Nanayakkara
Athula Rajapakse

MANITOBA·HVDC RESEARCH CENTRE

A collaborative research by
The University of Manitoba and
Manitoba HVDC Research Centre

UNIVERSITY OF MANITOBA

Outline

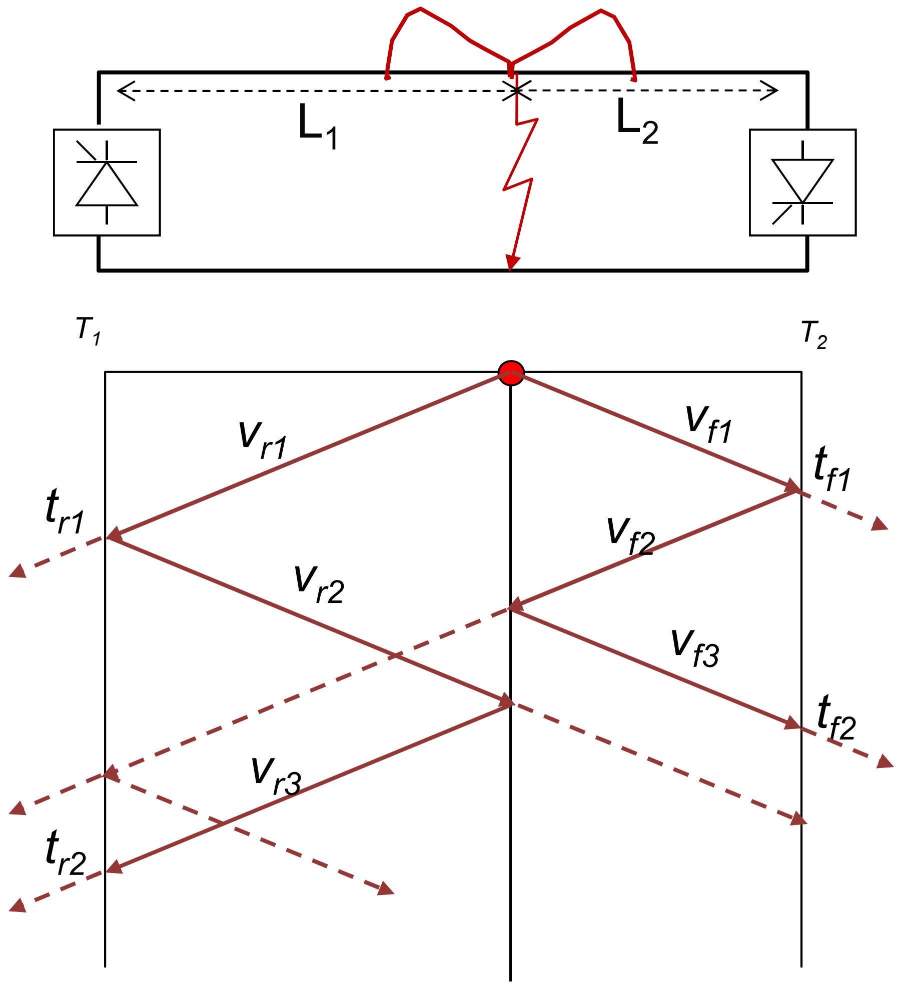
- Introduction
- Fault generated travelling wave detection
- Fault location in VSC HVDC systems
- Fault location in multi-segment HVDC systems
- Fault location in star connected multi-terminal HVDC systems
- Conclusions

Introduction

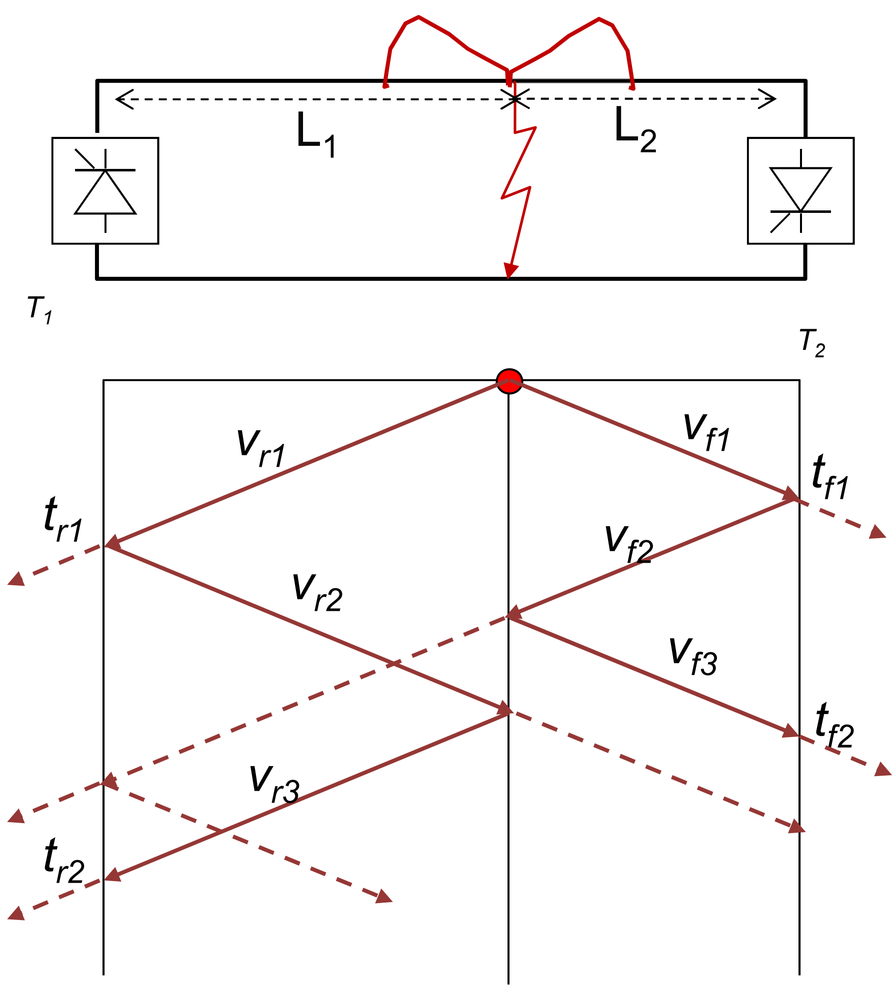
Original Picture retrieved from
http://en.wikipedia.org/wiki/File:HVDC_Crossover_North-Dakota.jpg

- High Voltage Direct Current (HVDC) technology has established as an economical solution to
  - Transmit bulk electrical power over long distances
  - Interconnect asynchronous systems
  - Transmit power through cables over long distances
- Quick location of permanent faults on HVDC transmission lines is very important
  - Involves large amount of power
  - Need quick repairs to minimize outage costs
- Fault location technology
  - Based on travelling waves generated by the fault

Travelling wave based fault location



Travelling wave based fault location methods



- Single terminal method

$$L_1 = \frac{1}{2}(t_{r2} - t_{r1}) \times v$$

- Two terminal method

$$L_1 = \frac{1}{2}\left[L + \left(t_{f1} - t_{r1}\right) \times v\right]$$

The two-terminal method :

- More reliable since only the initial surges are used
- Needs synchronized measurements

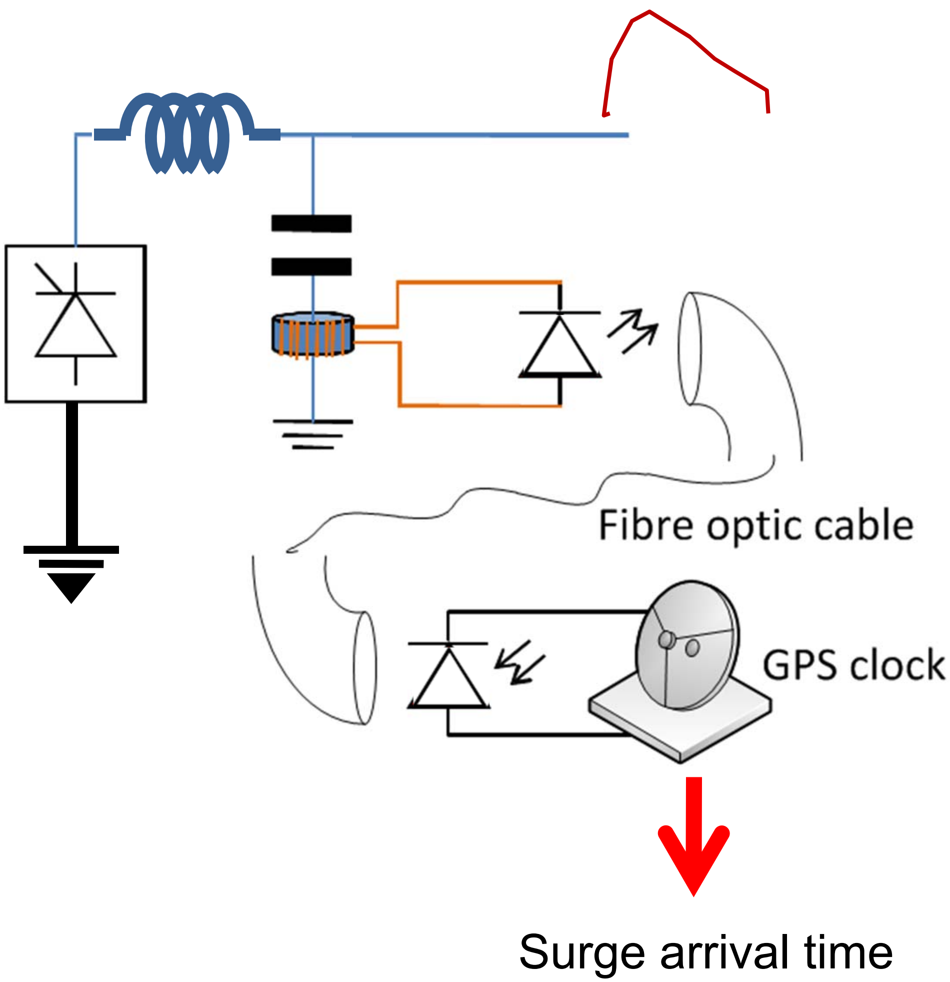
Fault location in HVDC transmission lines

- Fault location: $L_1 = \frac{1}{2}[L + (t_{f1} - t_{r1}) \times v]$
- Accuracy depends largely on accuracy of the surge arrival time measurement
  - In overhead lines, waves travel close to speed of light (299 792 458 m/s)
  - 1µs error in Δt could cause up to 300 m error in distance
- Potential signals for detecting the arrival of travelling waves
  - Terminal voltage of DC line
  - Current through the surge capacitor
  - DC line current ?

Fault location in HVDC transmission lines

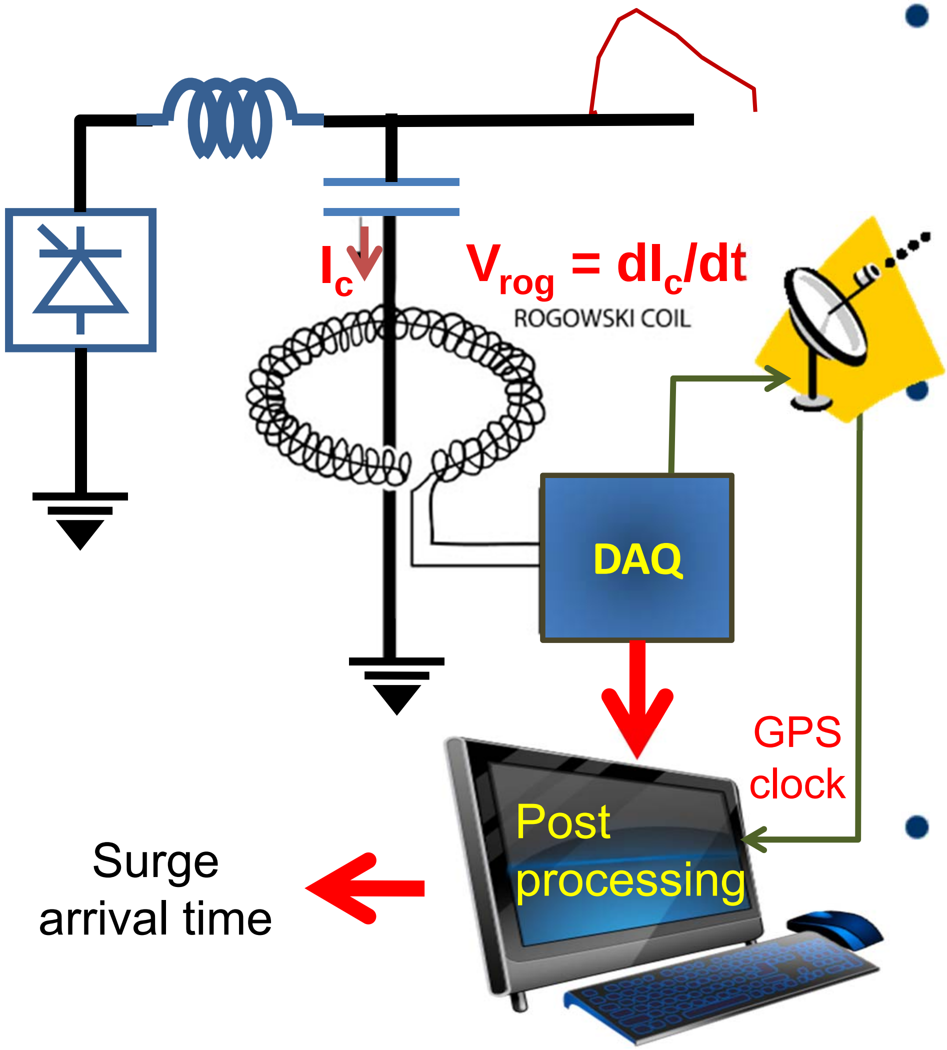
- **Manitoba HVDC Research Centre** is a commercial HVDC Line Fault Locator manufacture
  - Expects a growth in the demand for fault locators
  - Foresees challenges due to emerging changes in the nature of the HVDC transmission systems
- Major challenges
  - Long transmission lines (> 1000 km) and cables (> 200 km)
  - VSC based HVDC systems
  - HVDC systems with multiple transmission segments
  - Multi-Terminal HVDC (MTHVDC) schemes and DC grids
- Initiated a collaborative research project with MHI and University of Manitoba

Wave-front detection in existing LFL



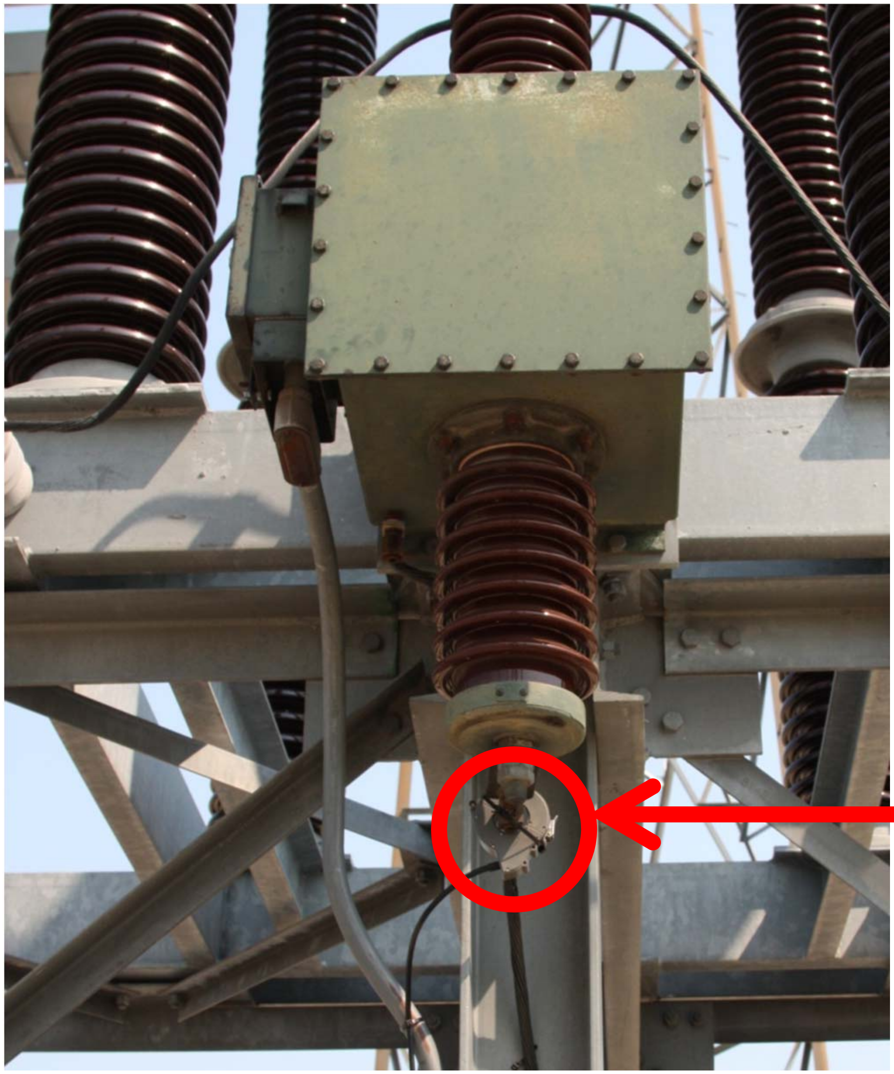
- Detection signal:
  - Surge capacitor current
- Analog detector
  - LED/optical sensor
  - GPS based time stamping

New proposal for wave-front detection



- Capturing waveforms
  - Possibility of post processing to obtain more accurate surge arrival times
  - Wavelet transform
- Rogowski coil as transducer?
  - Zero output at steady state - ideal
  - Bandwidth limitations, noise levels, and output voltage levels are concerns
- DAQ hardware requirements?
  - Sampling frequency
  - Bit resolution
  - Voltage range

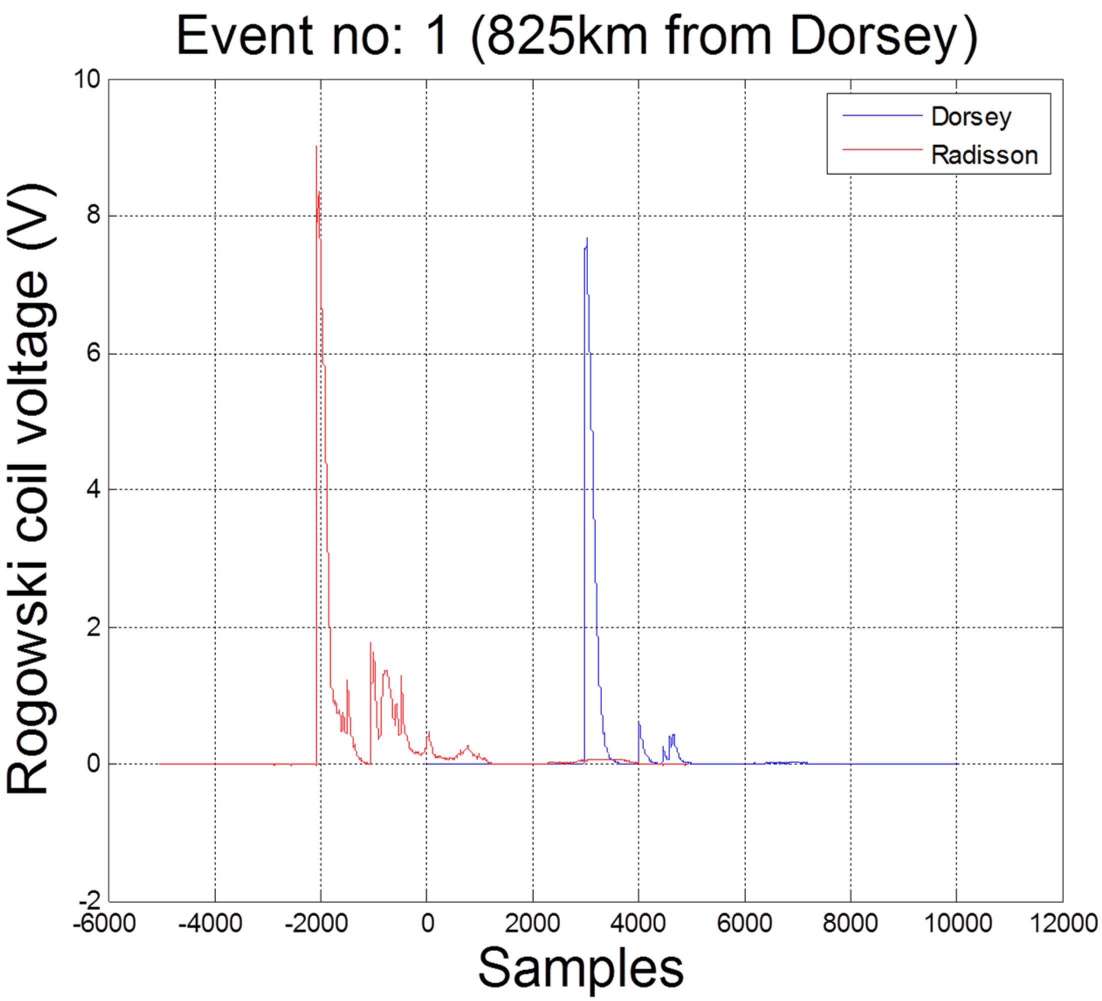
Experimental wave-front capturing unit



- Test units were installed at Dorsey and Radisson converter stations
- Data were recorded between 23rd of July 2012 and 4th of September 2012

Rogowski coil

Captured waveforms



2MHz sampling frequency

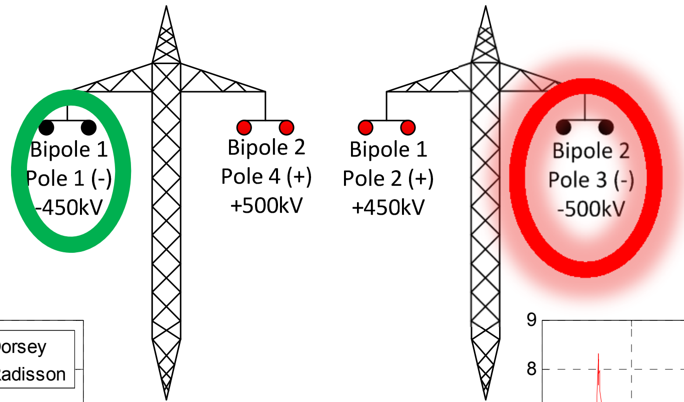
- $\Delta t = 0.5\mu s$
- GPS clock accuracy ± 150ns

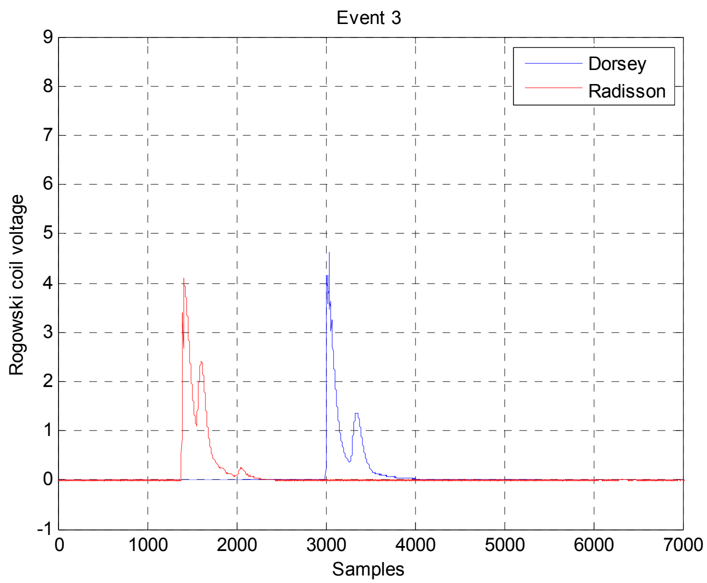
Event 1- 23/07/2012, 22:56:36 :

- Temp flashover possibly caused by smoke
- No lightning anywhere near
- There was a fire about 11 miles away from the estimated location

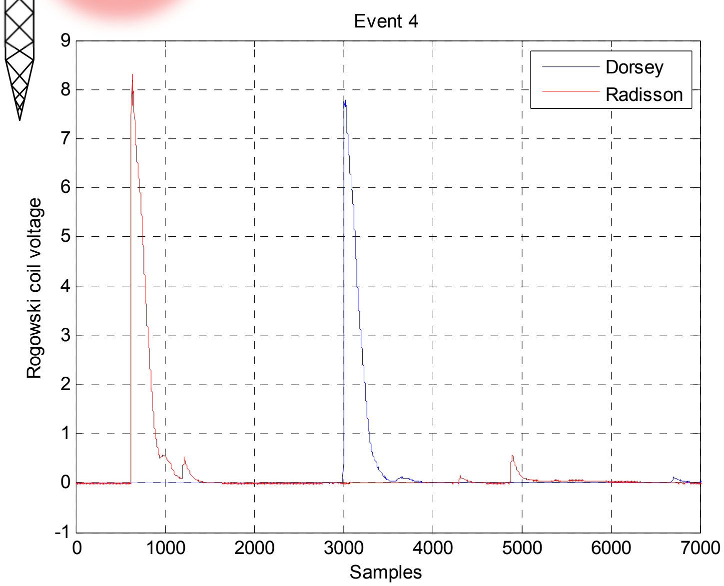
Existing	Rog. coil	**Δt (nano Sec)**
826.25	826.16	646.0057

Possible fault in pole 3





Pole 3 event



Pole 1 event

- Faults on bipole-2 can be detected through the measurements on bipole-1 using induce transients

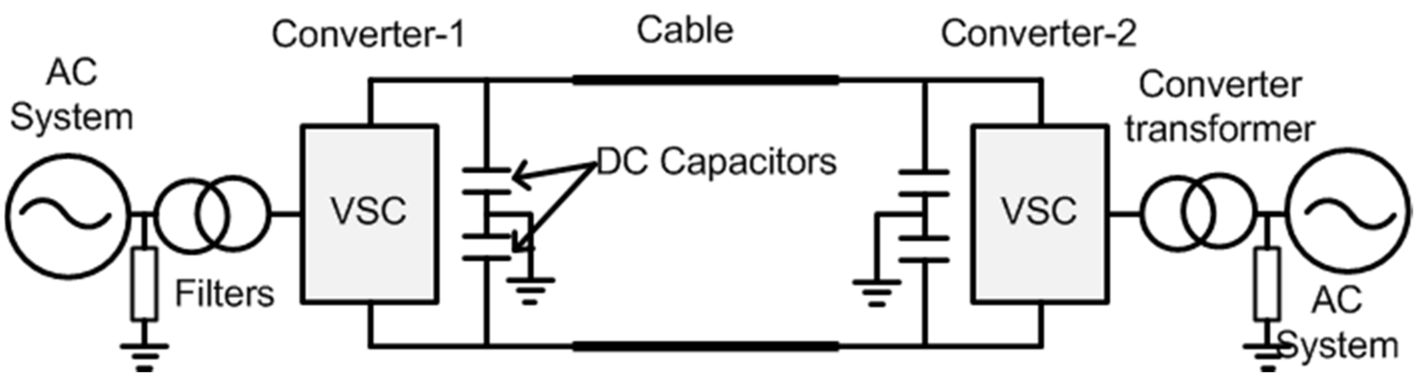
Comparison of results

- Calculated values in km from Radisson using time differences and propagation velocity of 299792.458 km/s

Evt No	Date	Hr	Min	Sec	Δt Existing LFL	Δt Wavelet LFL	Difference in Δt (nS)	Fault location (km) Radisson Existing LFL	Fault location (km) Radisson Wavelet LFL	Difference in fault loc (m)
3	26/07/2012	13	29	18	0.000806	0.000807	-692.9884999	326.2836498	326.1797734	-103.8763629
4	26/07/2012	14	10	17	0.001187	0.001188	-1134.0194	269.1581969	268.9882117	-169.9852317
5	26/07/2012	14	56	11	0.000924	0.000926	-1593.0237	308.5359363	308.297148	-238.7882453
6	26/07/2012	15	28	21	0.001181	0.001181	-366.9691	270.1025432	270.0475359	-55.00728425

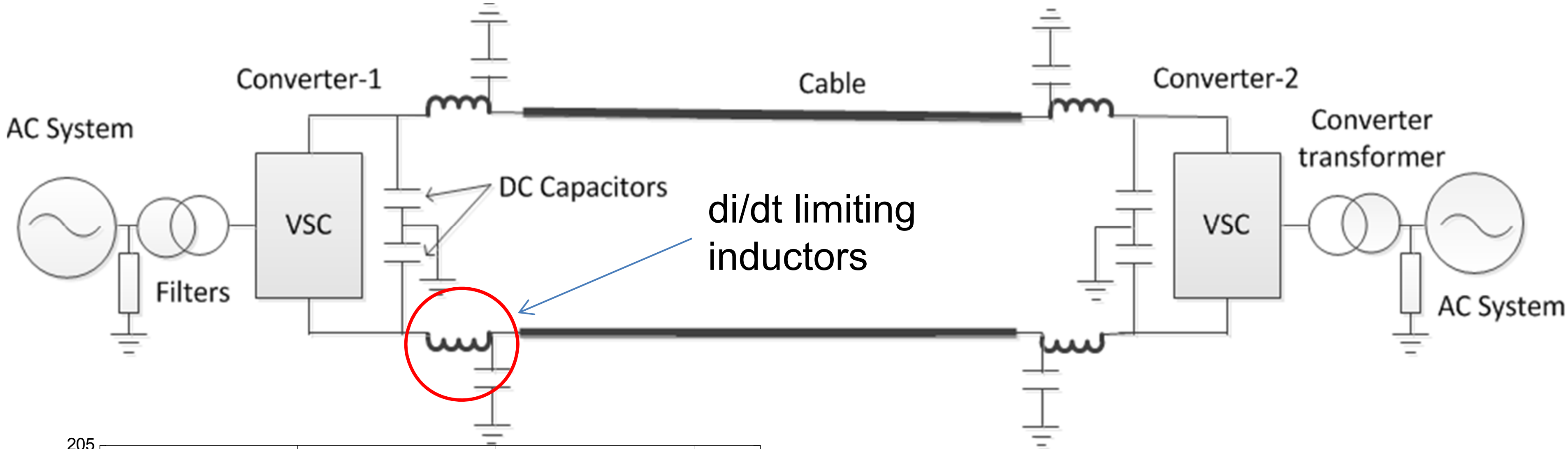
- Rogowski coil measurements of the surge capacitor current can be successfully used for determining surge arrival times
  - Post-processing of waveforms using wavelet transform can improve the accuracy under difficult conditions

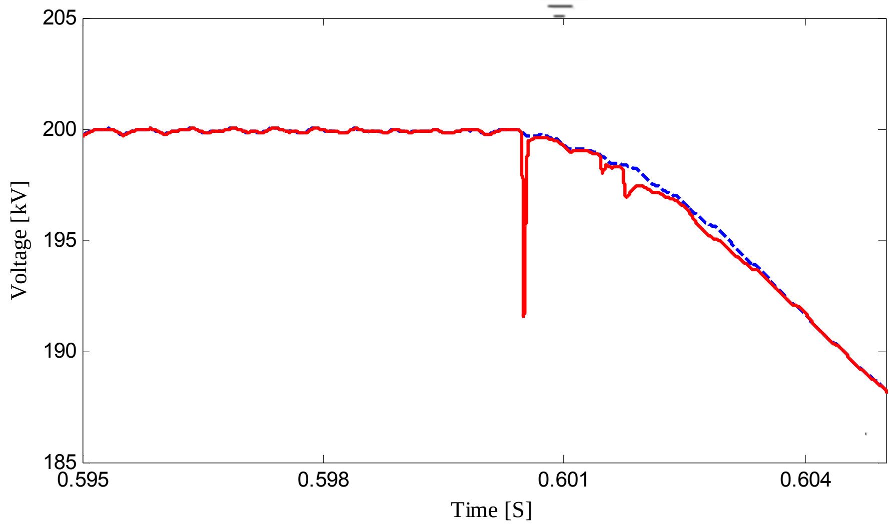
Fault location in VSC HVDC systems



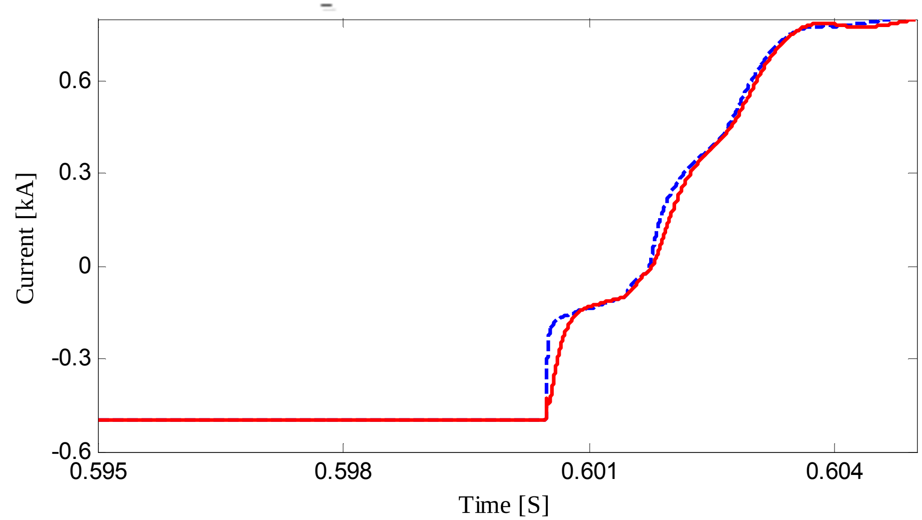
- Fault location in VSC HVDC schemes with long cable connections (> 100 km) is challenging
  - Large DC capacitance at the converter terminal
  - Absence of large smoothing inductor
  - Need to understand limitations and develop solutions

Measurements in the presence of dI/dt limiting reactor



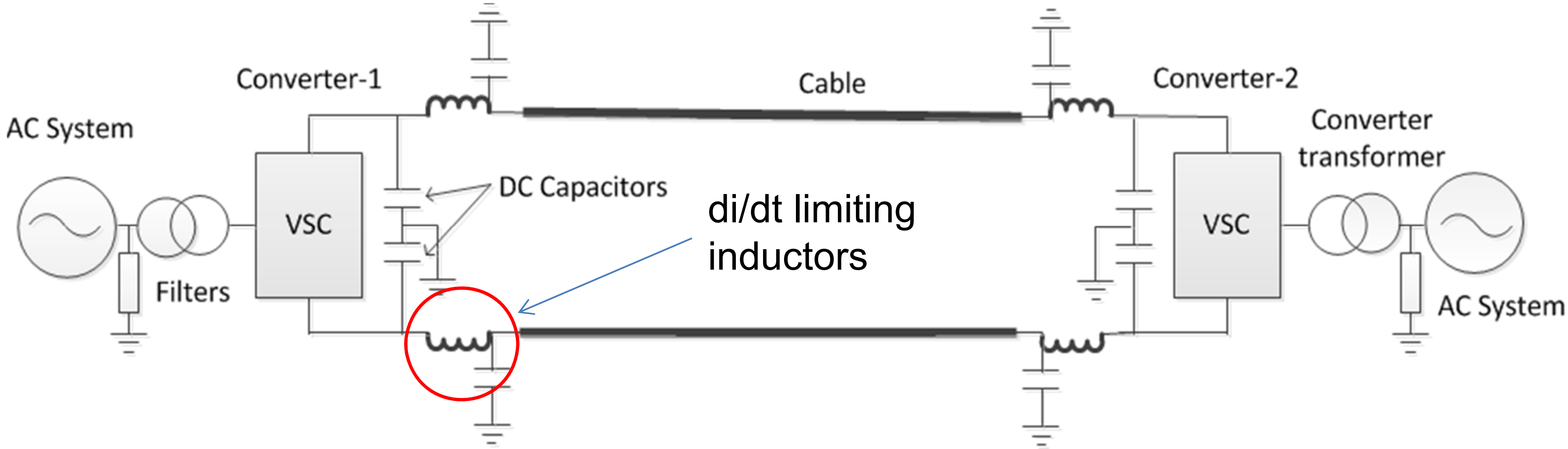


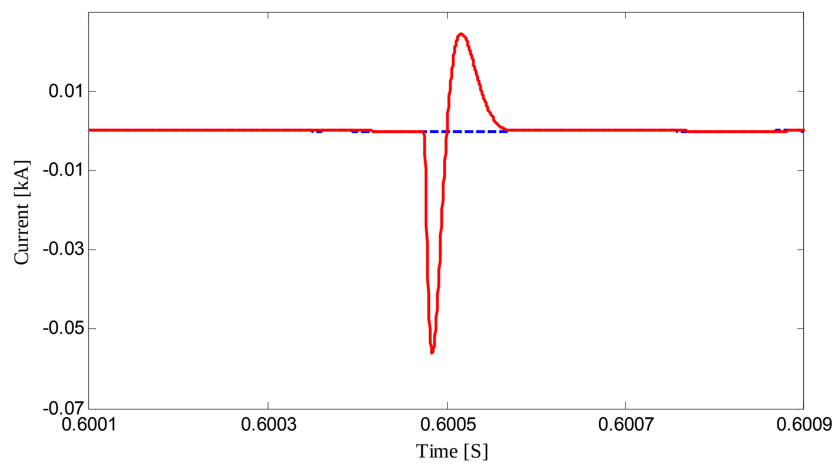
Terminal voltage



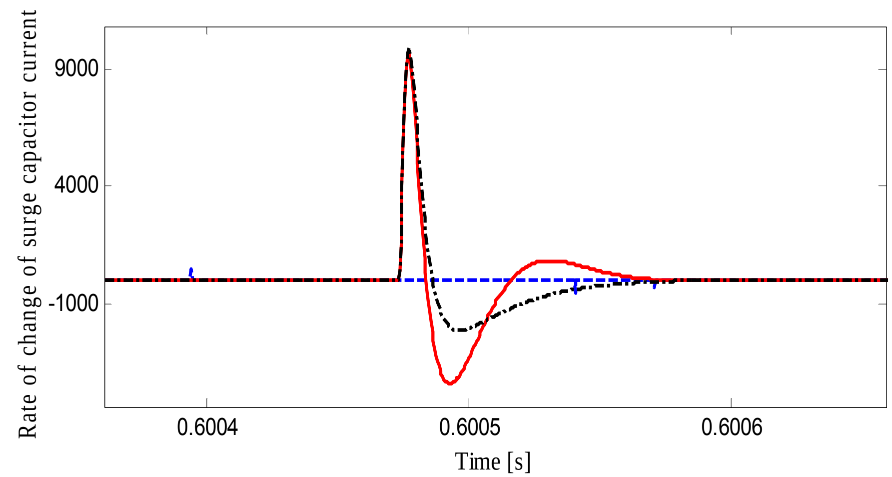
Series Current change

Measurements in the presence of dI/dt limiting reactor



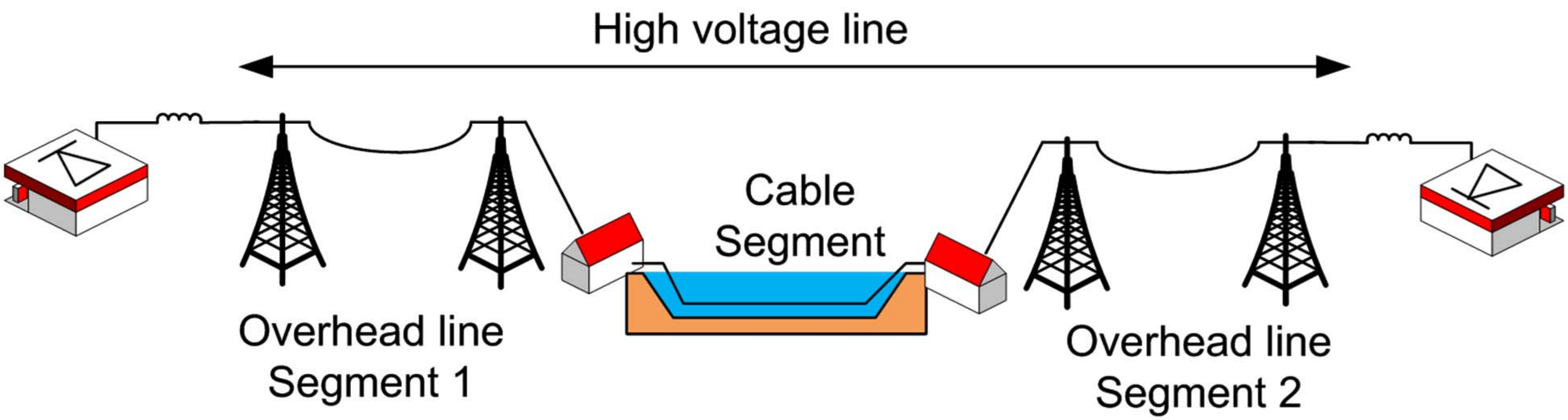


Surge cap. current



Rate of change of the surge cap. current

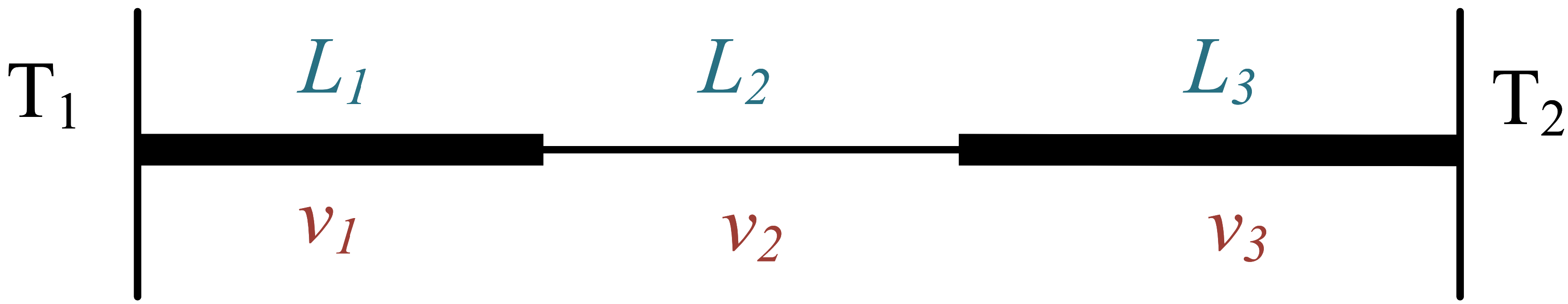
Fault location in multi-segment HVDC lines



- HVDC transmission systems are often used to transport electricity across water bodies
- Fault location in HVDC systems with multi-segments is generally achieved with the help of **repeater stations**

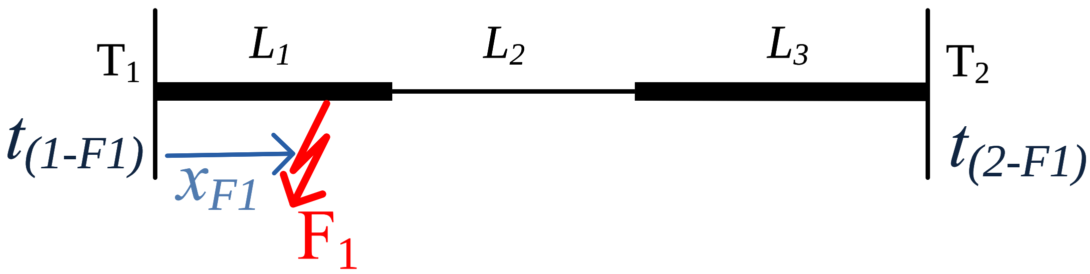
Novel fault location algorithm

- Use only the measurements at the converter terminals.
  - Eliminates duplicate fault location hardware for each line section
  - Substantial economics benefits



Novel fault location algorithm

- Case of a fault in segment 1 (F_1)



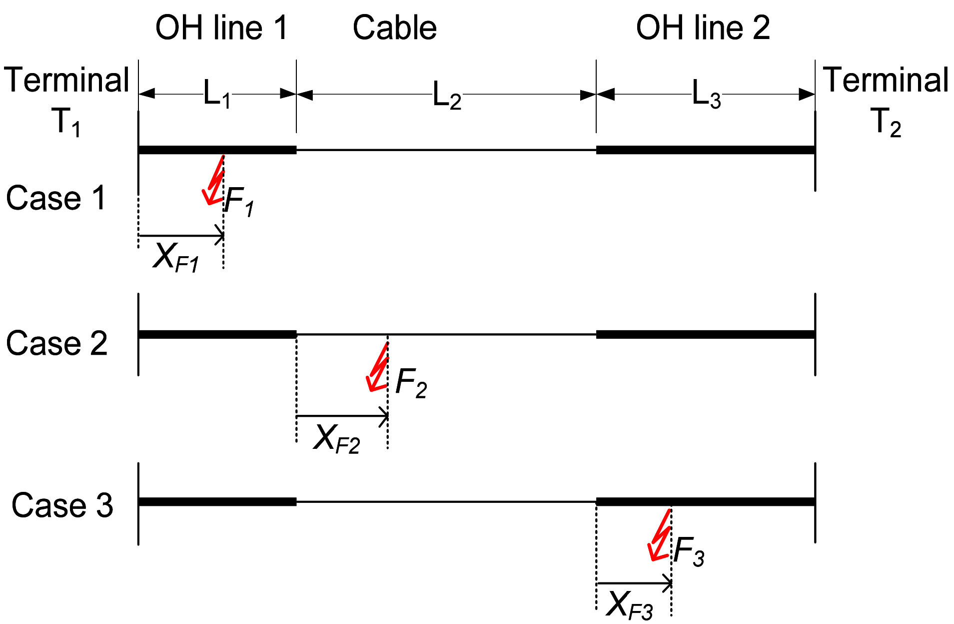
T_1 surge arrival time= $t_{1-F1} = \frac{x_{F1}}{v_1}$

T_2 surge arrival time= $t_{2-F1} = \left(\frac{L_1 - x_{F1}}{v_1}\right) + \frac{L_2}{v_2} + \frac{L_3}{v_3}$

Surge arrival time difference = $\Delta t_{12-F1} = t_{1-F1} - t_{2-F1} = \frac{2 \cdot x_{F1}}{v_1} - \frac{L_1}{v_1} - \frac{L_2}{v_2} - \frac{L_3}{v_3}$

Distance to fault from T1 = $x_{F1} = \left(\Delta t_{12-F1} + \frac{L_1}{v_1} + \frac{L_2}{v_2} + \frac{L_3}{v_3}\right) \times \frac{v_1}{2}$

Novel fault location algorithm

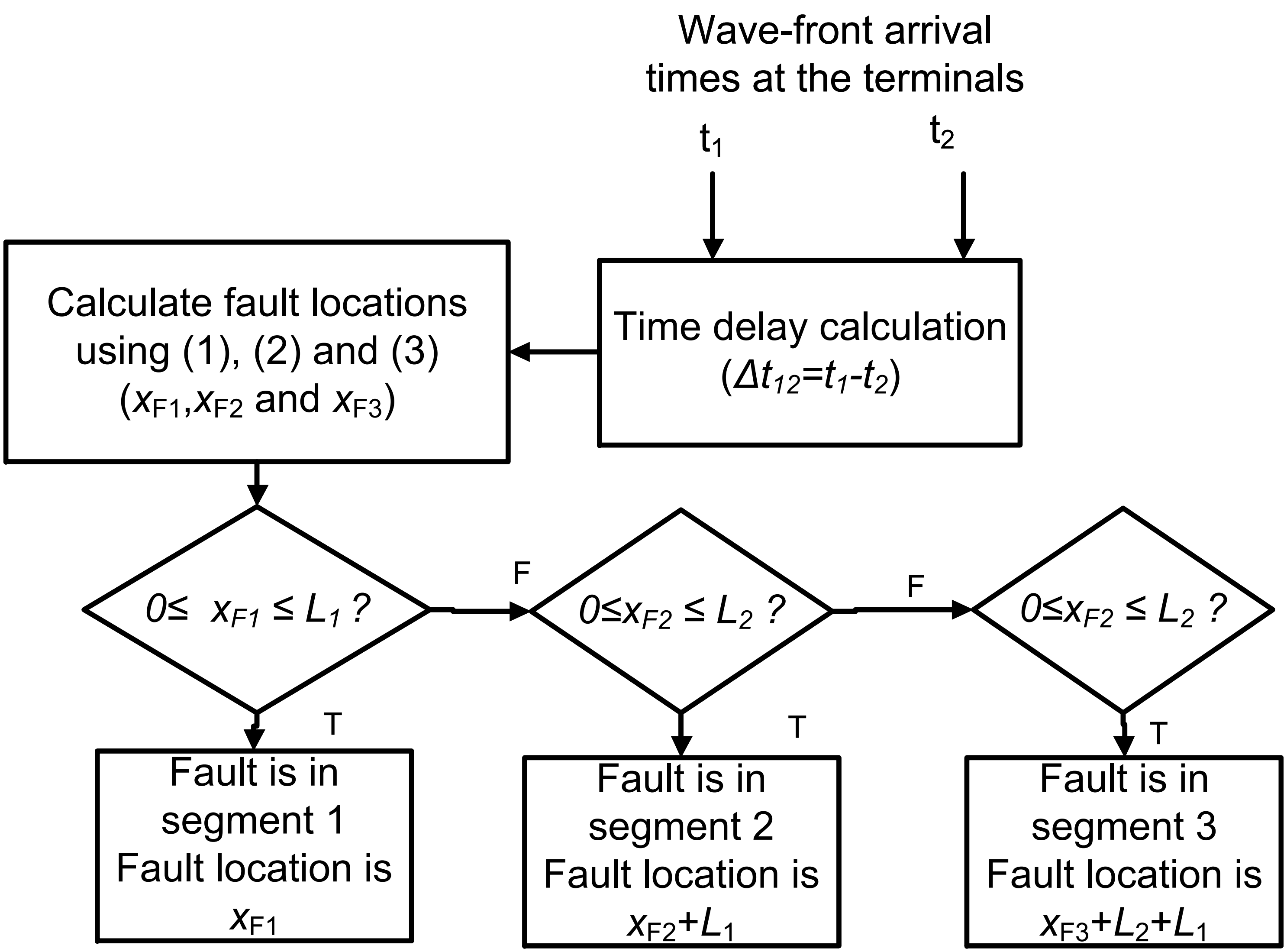


$$x_{F1} = \left(\Delta t_{12-F1} + \frac{L_1}{v_1} + \frac{L_2}{v_2} + \frac{L_3}{v_3}\right) \times \frac{v_1}{2} \rightarrow (1)$$

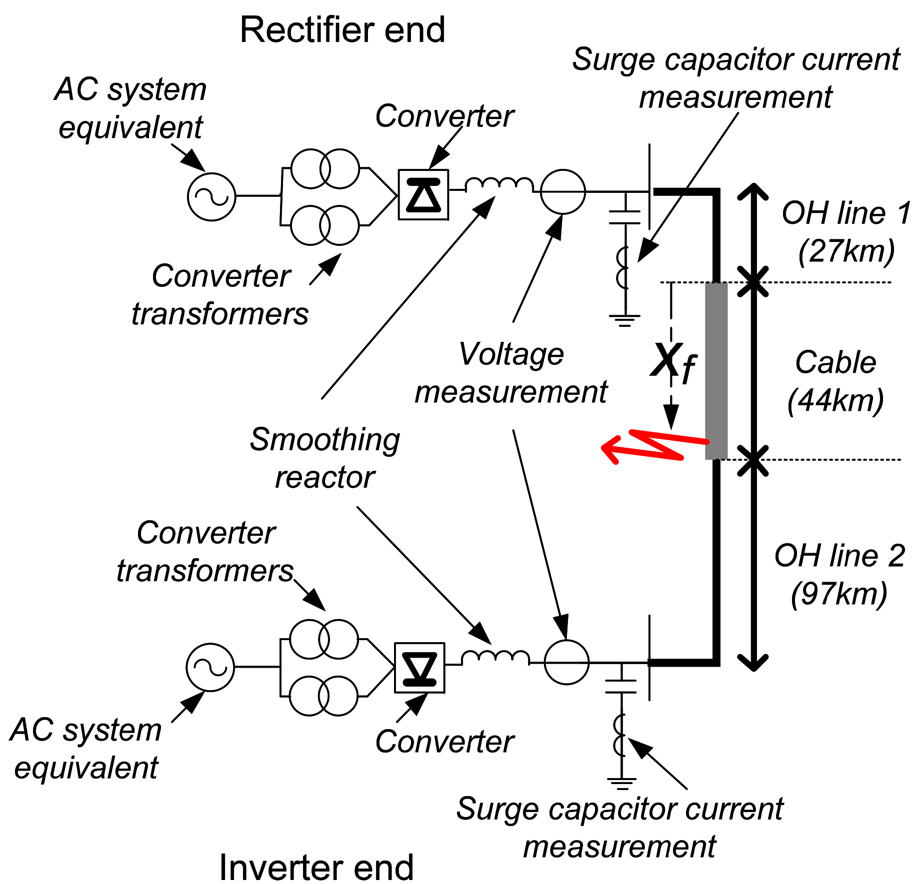
$$x_{F2} = \left(\Delta t_{12-F2} - \frac{L_1}{v_1} + \frac{L_2}{v_2} + \frac{L_3}{v_3}\right) \times \frac{v_2}{2} \rightarrow (2)$$

$$x_{F3} = \left(\Delta t_{12-F3} - \frac{L_1}{v_1} - \frac{L_2}{v_2} + \frac{L_3}{v_3}\right) \times \frac{v_3}{2} \rightarrow (3)$$

Identification of the faulty segment



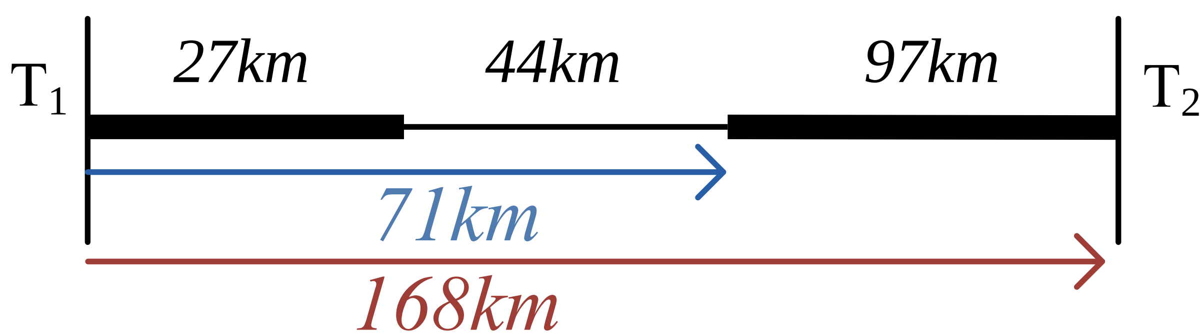
Simulated case study to validate the method



- Test network was built in PSCAD/EMTDC and the fault location algorithm was implemented in MATLAB.
- Wavelet coefficients of the surge capacitor current/voltage was used to determine the surge arrival times.

Sample of simulation results

Actual fault location (km) [measured from the rectifier end]		5	26	49	70	91	167
Calculated values using equations 1,2 and 3	x_{F1} (Valid Range: 0 to 27)	5.07	25.97	71.26	113.57	135.51	211.22
	x_{F2} (Valid Range: 0 to 44)	-10.88	-0.51	21.95	42.94	53.82	91.38
	x_{F3}(Valid Range: 0 to 97)	-111.14	-90.15	-44.65	-2.14	19.89	95.94
Predicted fault location (km)		(x_{F1}) 5.07	(x_{F1}) 25.97	(27+x_{F2}) 48.95	(27+x_{F2}) 69.94	(27+44+x_{F3}) 90.89	(27+44+x_{F3}) 166.94



Multi-terminal HVDC systems

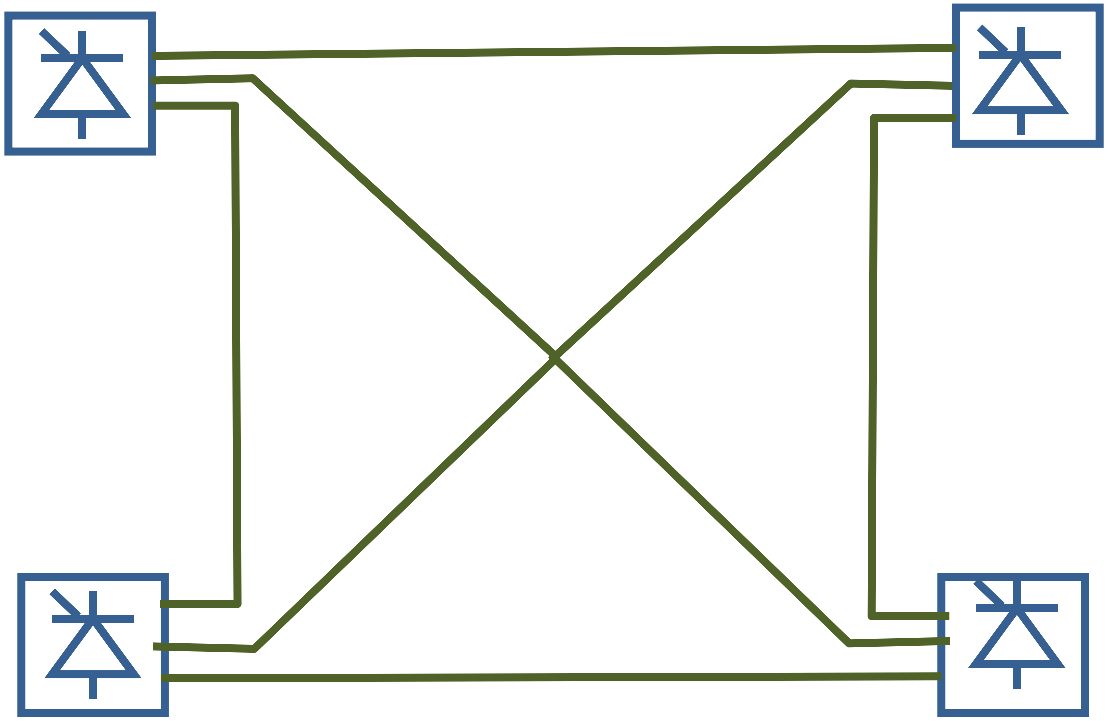
- MTHVDC systems have more than two converter stations connected to a common HVDC transmission system
  - Interconnection of off-shore wind farms
  - Underground urban sub-transmission systems
  - Shipboard power supplies
  - Interconnection of on shore renewable generation systems

(a) The Lillgrund offshore wind farm in Sweden

(b) Waldpolenz Solar Park in Waldpolenz, Germany

Fault location in MTHVDC systems

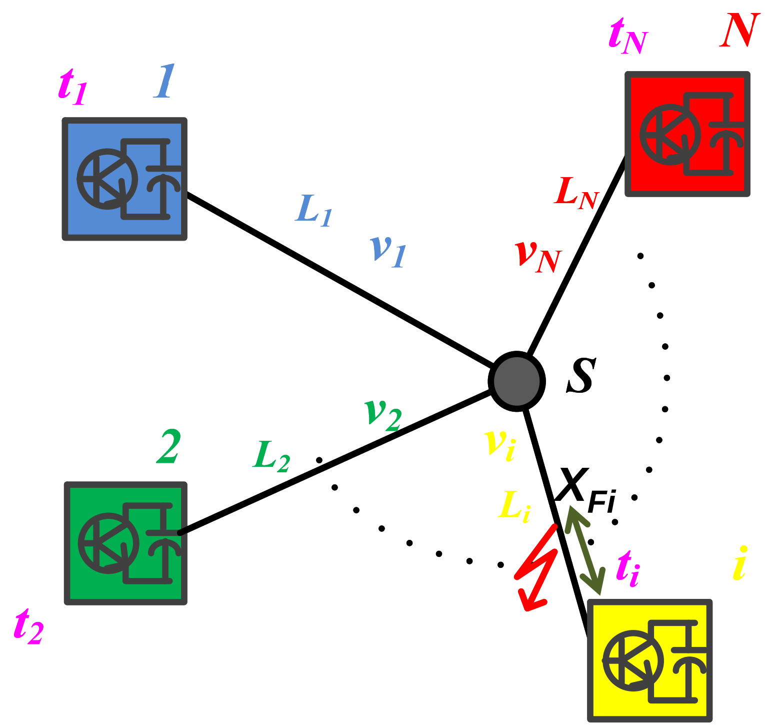
- Possible different topologies
  - point to point
  - Ring
  - Star
  - Mixed



New fault location algorithm star networks

- Use only the measurements at the converter terminals.

- Determine faulted line segment
  - Assume fault is on segment *i*
  - Calculate N-1 fault location estimations considering different pairs of converter stations
  - If the estimations are consistent, the fault is on segment *i*
  - Otherwise go to next segment; repeat the procedure until faulted line segment is found



- Determine exact location
  - Average of the N-1 estimations for the faulted line segment

Conclusions

- Through this collaborative research project, we developed solutions for a number of challenging HVDC fault location problems
  1. New fault generated surge arrival time measurement scheme
  2. Wavelet based post-processing for more accurate surge arrival time determination
  3. New algorithm for fault location in multi-segment HVDC schemes using only terminal measurements
  4. Surge detection in VSC based HVDC schemes
  5. New algorithm for fault location in star connected multi-terminal HVDC schemes

Acknowledgements

- Manitoba HVDC Research Centre staff
  - Randy W. Wachal
  - Jean-Sebastien Stoezel
  - Warren Erickson
- Manitoba Hydro Technical Staff at Dorsey and Radisson stations
- Financial support
  - Research grant from Manitoba Hydro
  - Collaborative R&D grant from NSERC
  - UoM Graduate Fellowship from University of Manitoba
  - Manitoba Graduate Fellowship from the Government of Manitoba

Thank you