Locating Faults in Power Systems: An Approach based on the Wavelet Transform of Traveling Waves

ALI ABUR

Dept. of Electrical Engineering

Texas A & M University

Presented at

UNIVERSITA' DI BOLOGNA, DIPARTIMENTO DI INGEGNERIA ELETTRICA

November 2, 2004

Outline

- Fault location problem
- Fault location methods
- Traveling waves and fault location
- Why the wavelet transform?
- Applications:
  - Transmission systems
  - Distribution systems
  - Teed circuits
- Concluding remarks

Fault location problem

Determine the distance from the fault recorder to the fault point.

Motivation:

- Minimize service interruption period.
- Minimize the cost of reduced transmission capacity and reduced security margin.

Fault location methods

- Power frequency methods
  - Filter HF signals, estimate impedance to fault
  - Use discrete time equations, do parameter (for the faulted line) estimation
- Traveling wave methods

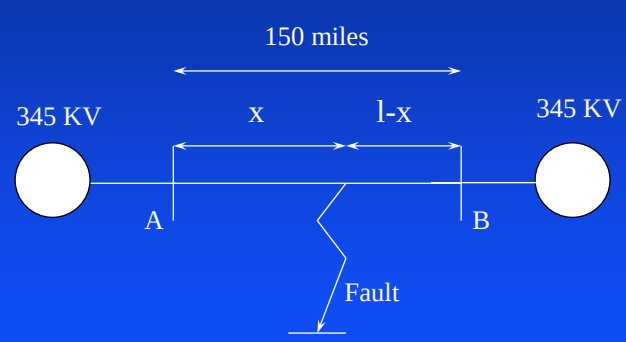
  Follow the traveling wave front and record travel time between the recorder and the fault point

Traveling waves and fault location

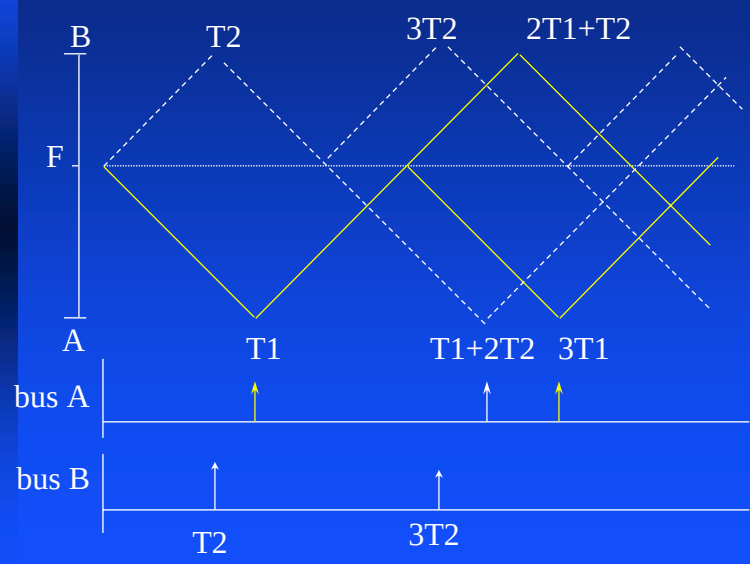
- How to identify the arrival of a traveling wave front at the recorder?
  - Do exactly the opposite of what conventional methods are doing:

    Filter LF (instead of HF)
  - Traveling wave is included in this filtered HF component
  - Find an efficient way to capture the HF component as a function of time.

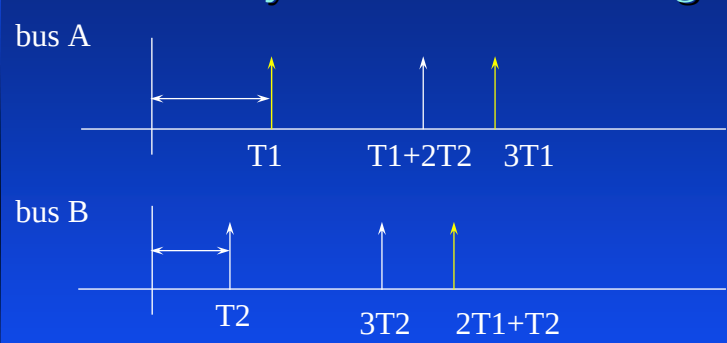
Example:
Fault at a distance "x" from bus A



Traveling waves (Bewley)



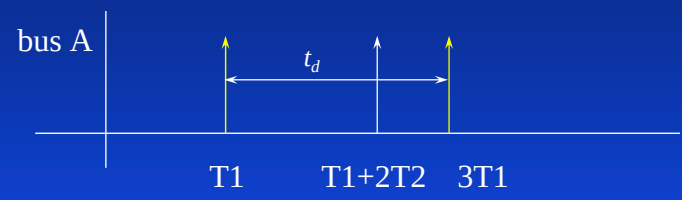
Two ended synchronized recording



$$t_d = T_1 - T_2$$

$$t_d = \frac{x}{\upsilon_m} - \frac{(l-x)}{\upsilon_m} \quad \Rightarrow \quad x = \frac{l + t_d \cdot \upsilon_m}{2}$$

Single ended recording



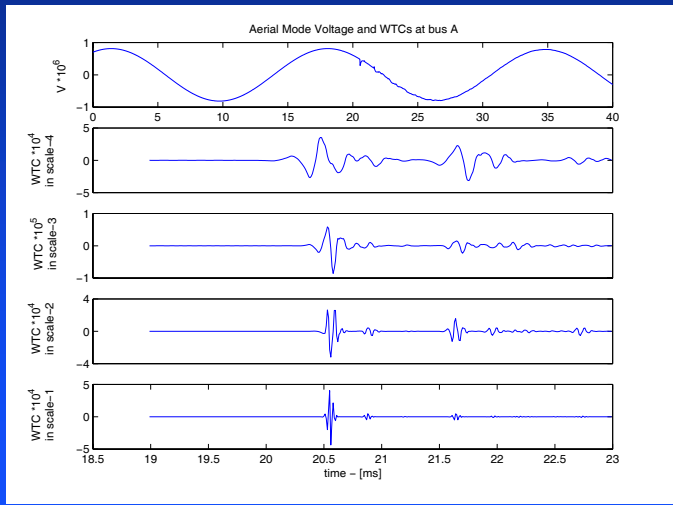
$$t_d = 2T_1$$

$$x = \frac{v_m \, t_d}{2}$$

Why the wavelet transform ?

- Allows time localization of different frequency components of a given signal.
- HF components of the fault initiated transient signal carries traveling wave information. This can be extracted as a function of time by the wavelet transform.

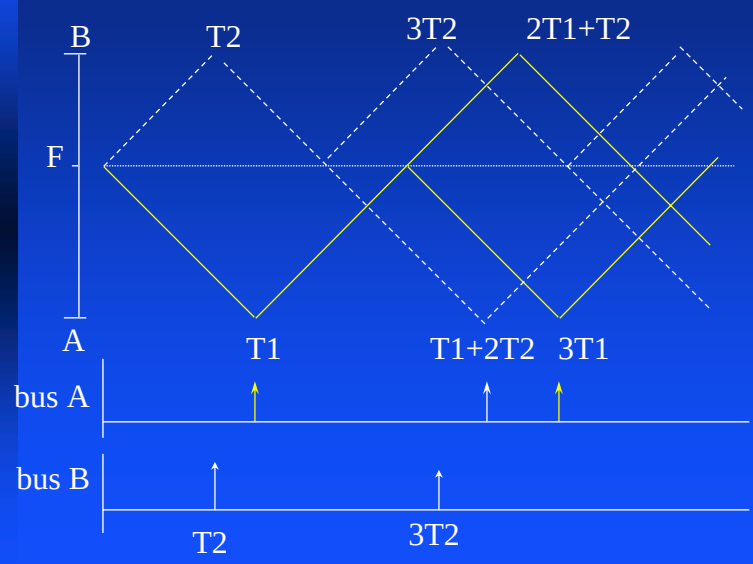
Voltage signal and its wavelet transform coefficients in 4 scales

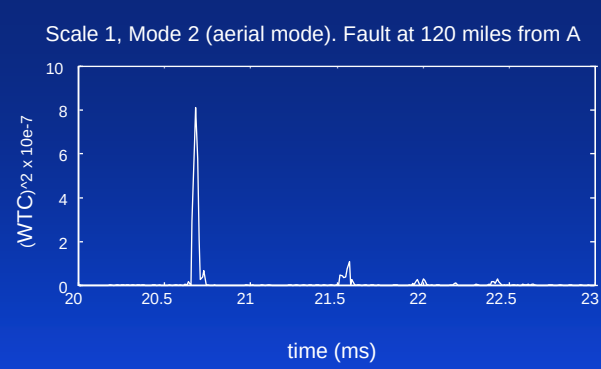


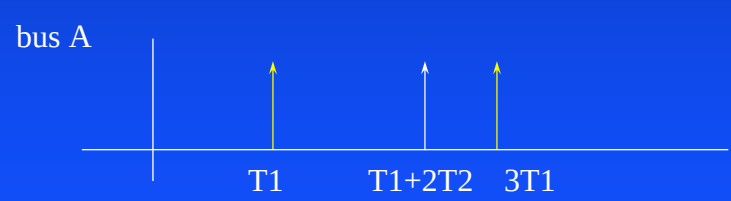
Fault Location Using Traveling Waves and DWT

- Record voltage signals during the fault
- Apply modal transformation (Clarke's [T] is used here) to obtain modal components of the transient voltage signals
- Apply discrete wavelet transform to the aerial and ground mode voltages
- Process modal voltages to estimate the location of the fault

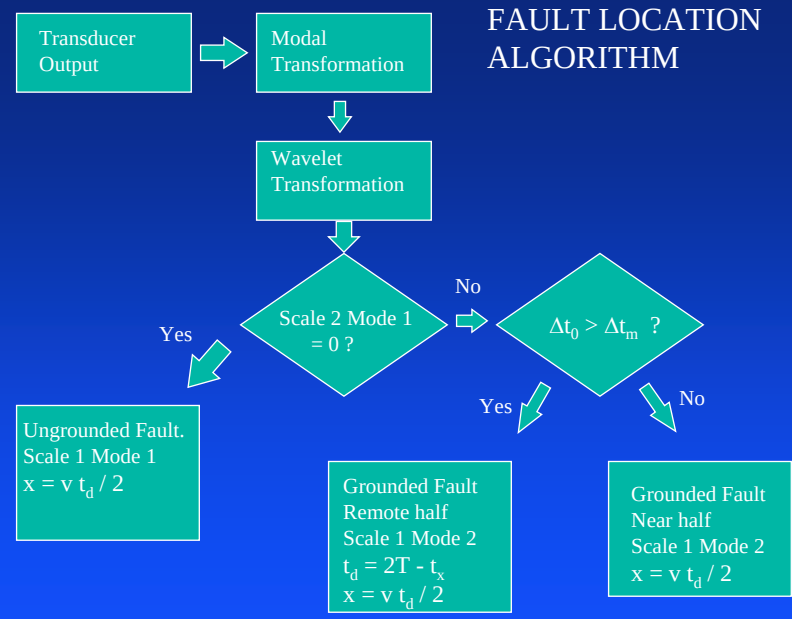
Traveling waves (Bewley)



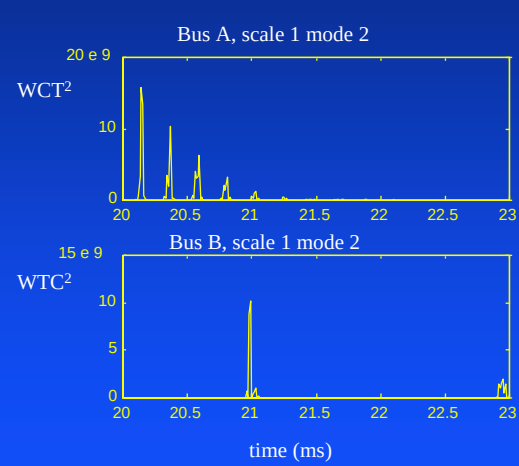




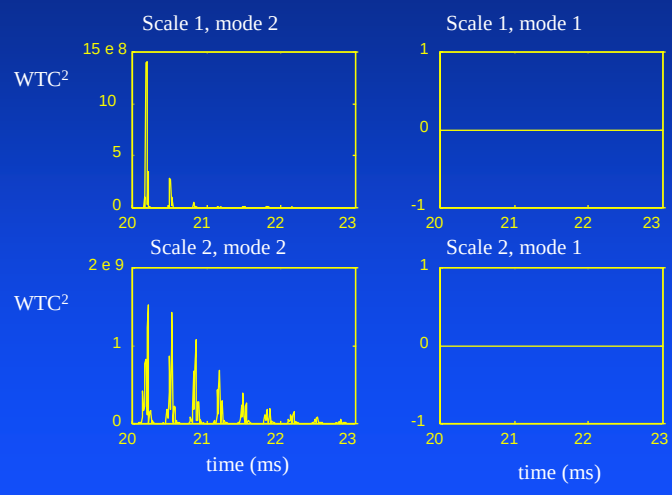
FAULT LOCATION ALGORITHM



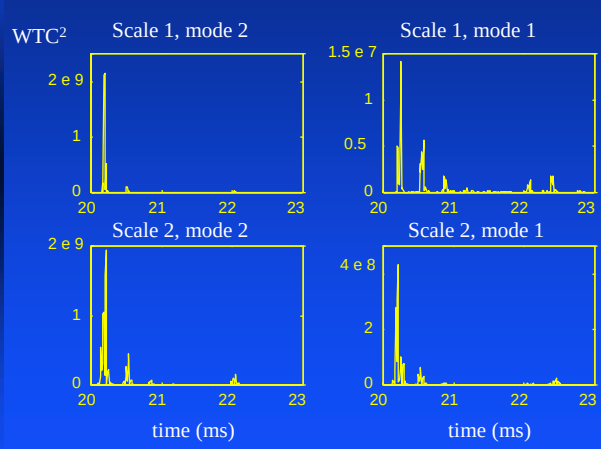
Three phase fault at 20 miles from A



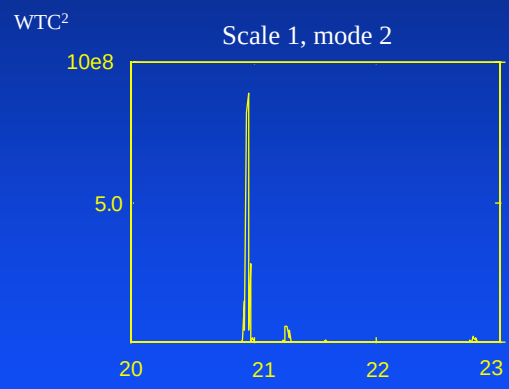
Phase to phase fault at 30 miles from A



Phase to ground fault at 30 miles from A



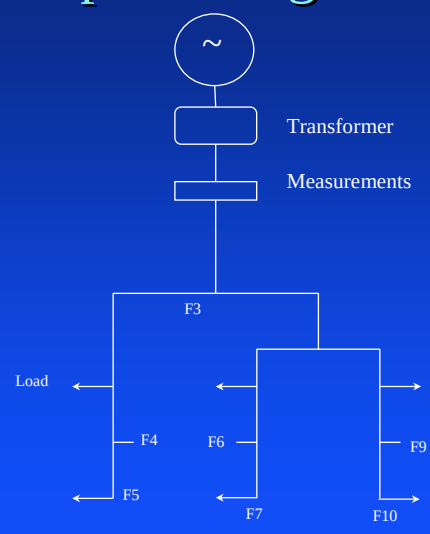
Phase to ground fault at 170 miles from A



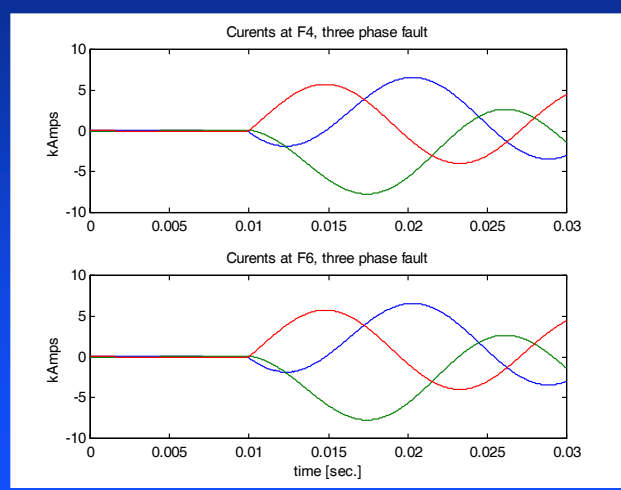
Distribution Systems

- Radial
- Several laterals
- V-I recorded at the substation only
- Multiple fault locations may yield identical recordings at power frequency

Example configuration:



Fault signals for faults at F4 and F6:



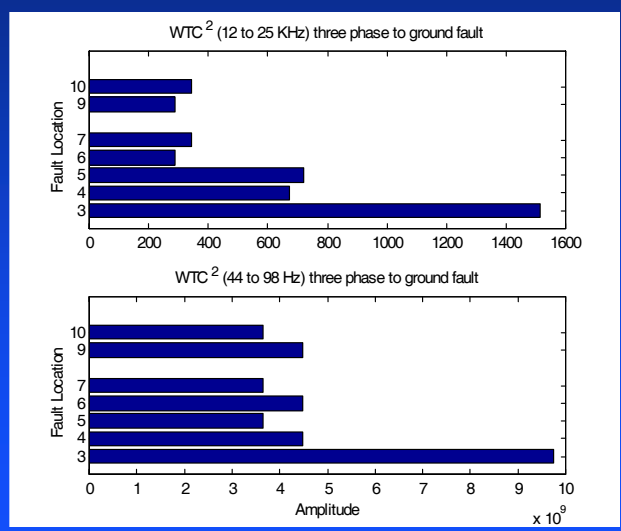
Discriminator:

Define a discriminator "s" as:

$$s = \left[WTC_i^T \cdot WTC_i \right]$$

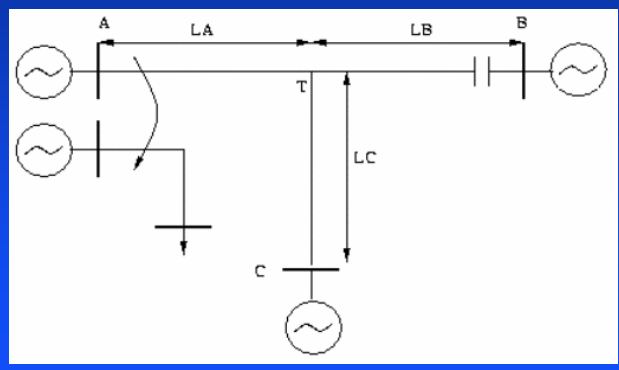
Note:
s is NOT the same even for faults at equal distance from the substation, as long as fault paths have different junction characteristics.

Plot of "s" for two scales:



Fault Location in Teed Circuits

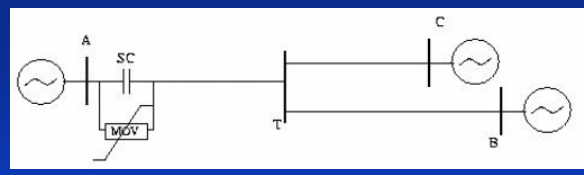
- ✓ MOV protected SC
- ✓ Coupled line sections



Fault Location in Teed Circuits

- Measurements at each bus are fully synchronized
  - ✓ Faulted branch is determined
  - ✓ Double ended fault location algorithm is used [Magnago&Abur'98]
- ✓ Measurements are not synchronized
  - ✓ Faulted branch is determined
  - ✓ Modified single ended fault location algorithm is used [Magnago&Abur'99]

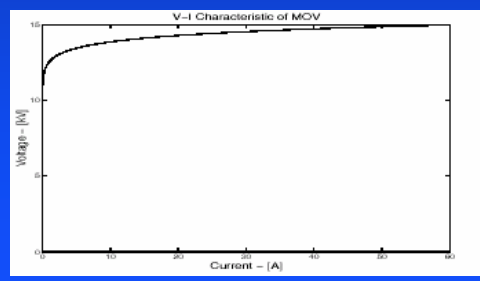
w/ MOV Protected SC

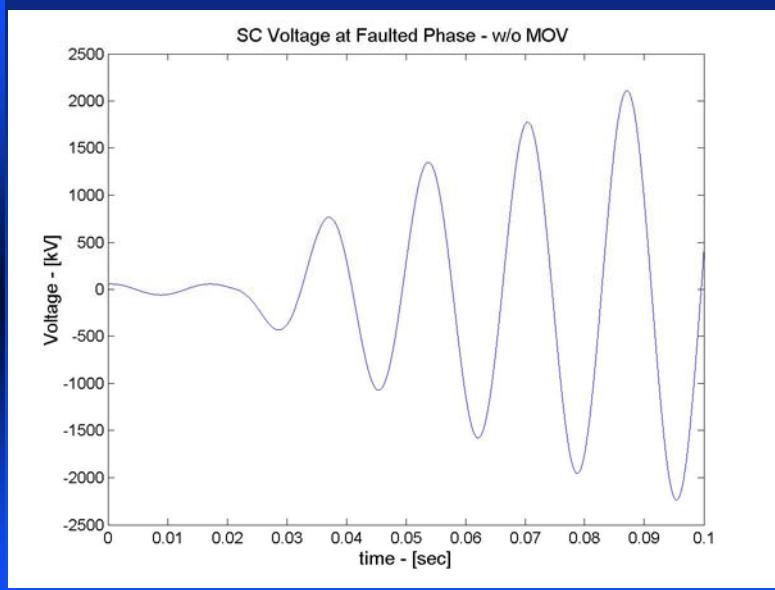


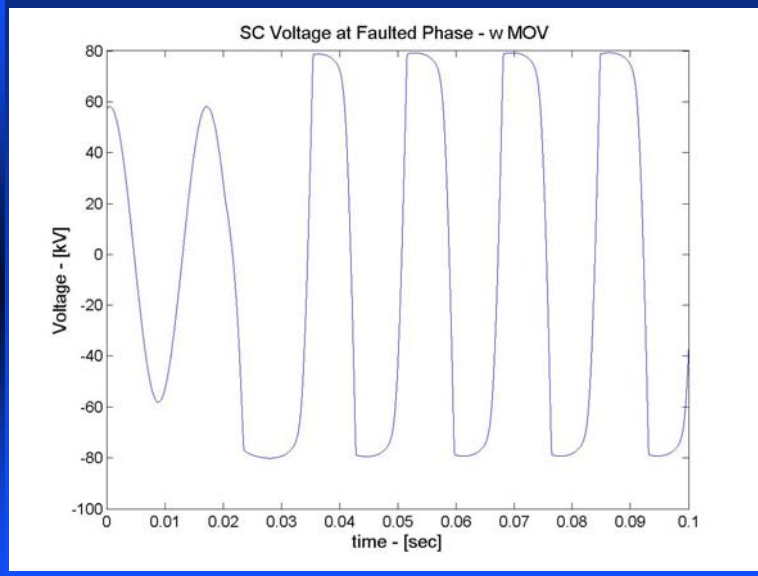
- MOV has a nonlinear characteristic
- When voltage approaches the protection level MOV conducts
- The voltage across

the SC is limited at V_{ref}

$$i = I \cdot \left(\frac{V}{V_{ref}}\right)^q$$

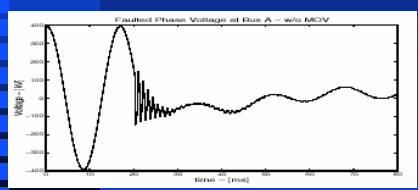




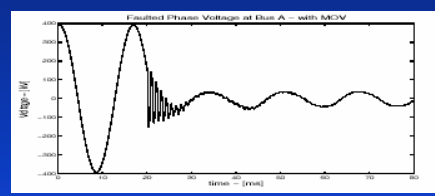


w/ MOV Protected SC

The transient voltage wave is recorded at bus A :

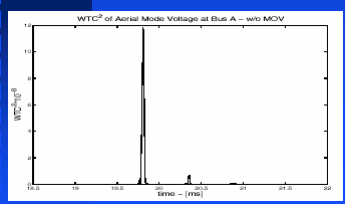


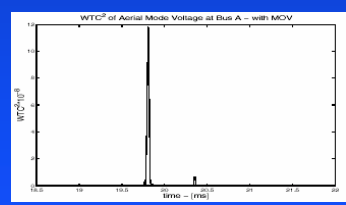
w/o MOV



w/ MOV

The DWT of the voltage signals :





w/ MOV Protected SC

- Grounded fault
  - If $\Delta t_0 < \Delta t_m$ ➔ first half,

$$x = \frac{v \times \Delta t}{2}, \Delta t = t_2 - t_1$$

  - Else ➔ second half,

$$x = \frac{v \times \Delta t}{2}, \Delta t = t_3 - t_1$$

- Ungrounded fault ➡ No remote end reflections

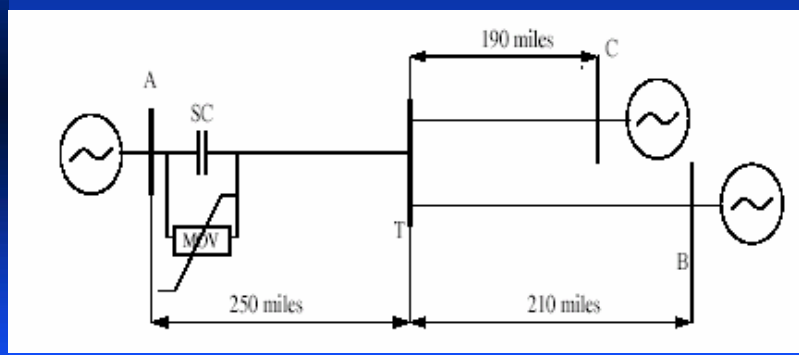
$$x = \frac{v \times \Delta t}{2}, \Delta t = t_2 - t_1$$

Return

Simulation results: w/ MOV Protected SC

The series compensation rate is 40 %.

The MOV parameters are I = 60 A, q = 23, V_{ref} = 15 kV

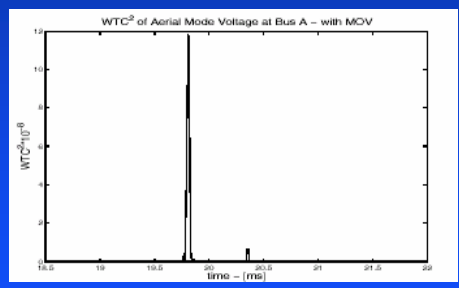


Single line to ground fault 50 miles away from bus A

- First determine the faulted branch
- Locate the faulted section

Finally, determine the arrival times of the WTC^2 peaks:

$t_1 = 20.30$ ms $\qquad t_2 = 20.85$ ms



$$x_f = v \,.\, \Delta t / 2 \;,$$

$$\Delta t = t_2 - t_1 = 0.55 \text{ ms}$$

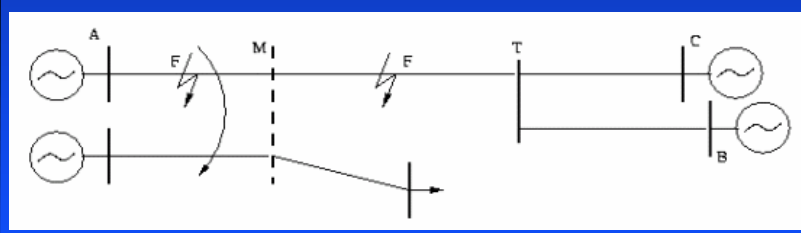
$$\Delta x_f = 51.07 \text{ miles}$$

w/ Coupled Line Section:

The end point of the coupled section behaves like a discontinuity.

Fault location procedure will be different depending on if:

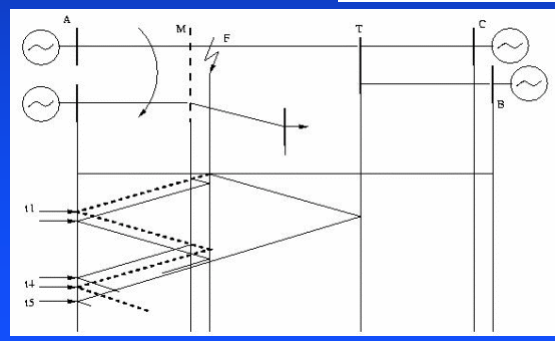
- Fault occurs within the coupled section, A - M
- Fault occurs outside the coupled section, M - T



w/ Coupled Line Section

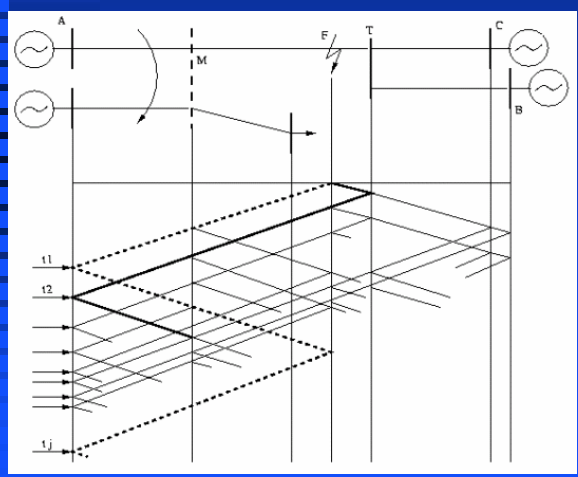
- If the fault is in the coupled section A-M:
  - ✓ Use the previously described algorithm
- If the fault is outside the coupled section M-T, then:

  If it is in the first half, use: $x = \frac{v \times \Delta t}{2}, \Delta t = t_4 - t_1$



w/ Coupled Line Section

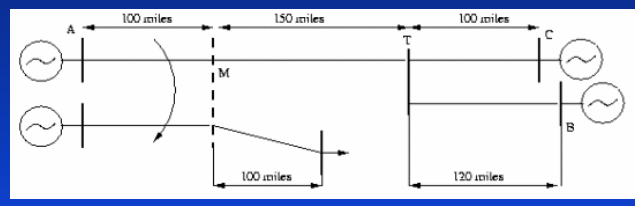
If in the second half, the arrival time of the reflected wave will be delayed as the location of the fault moves closer to T.



- ✓ The largest magnitude WTC^2 peak after the first two WTC^2 peaks, belongs to the backward traveling wave.
- ✓ Hence, use:

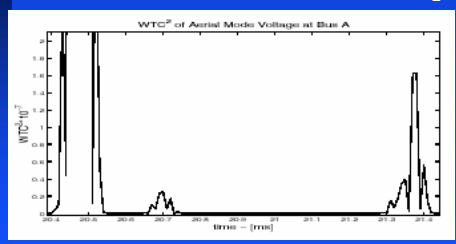
$$x = \frac{v \times \Delta t}{2}, \Delta t = t_j - t_1$$

Simulation results: w/ Coupled Line Section



Fault is inside the coupled section 80 miles away from bus A

The arrival times of the WTC^2 peaks: $t_1 = 20.48$ ms and $t_3 = 21.36$ ms



$$x_f = v \,.\, \Delta t / 2$$

$$\Delta t = t_3 - t_1 = 0.88 \text{ ms}$$

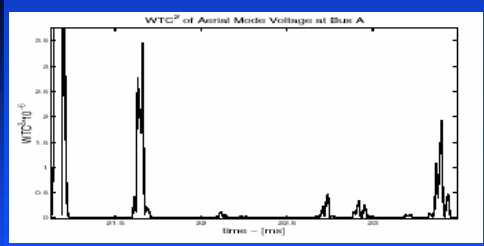
$$\Delta x_f = 81.72 \text{ miles}$$

Simulation results: continued..

The fault is inside the second half of the uncoupled section, 205 miles away from bus A:

In this case, the peak with the largest magnitude after the first two peaks is the 8th peak.

The arrival times of the WTC^2 peaks: $t_1 = 21.17$ ms and $t_8 = 23.39$ ms



$$x_f = v \,.\, \Delta t / 2$$

$$\Delta t = t_8 - t_1 = 2.22 \text{ ms}$$

$$\Delta x_f = 206.16 \text{ miles}$$

Concluding Remarks

- Traveling wave methods have inherent advantages over parameter estimation methods.
- They remain insensitive to fault impedance (which is typically unknown).
- Challenge in traveling wave methods is to capture the arrival time of the waves.
- Wavelet transform is an effective way to address this challenge.

Concluding Remarks...

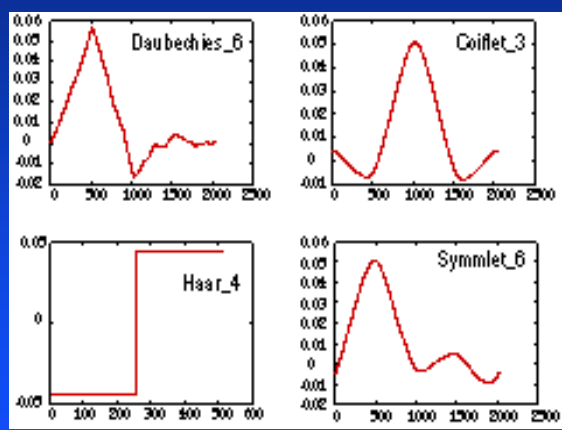
- The lowest scale wavelet coefficients are used to determine the fault location.
- The method is shown to be equally suitable for mutually coupled tower geometries and series capacitor compensated lines.
- The method can be used both synchronized and non-synchronized signals recorded at a single or multiple terminals of lines

Wavelet transform

- Continuous Wavelet transform

$$WT_{(f,a,b)} = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f_{(t)} \Psi_{\left(\frac{t-b}{a}\right)} dt$$

- Discrete Wavelet transform

$$DWT_{(f,m,n)} = \frac{1}{\sqrt{a_0^{\,m}}} \sum_k f_{(k)} \Psi_{\left(\frac{n-ka_0^{\,m}}{a_0^{\,m}}\right)}$$

Wavelet Transform