Charles Kim, "Lecture Notes on Fault Detection and Location in Distribution Systems," 2010.

Source: www.mwftr.com

3. Fault Location Algorithms

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Fault Location Overview

- Traditional Methods of determining the location of a fault on T&D lines
  - Impedance Approaches (Our Focus)
  - Traveling Wave Approaches
  - Problems in Distribution Network
- Other Methods
  - Short-circuit analysis software
  - Customer calls (distribution case)
  - Line inspection
  - Fault Indicators (4)
- New Opportunities
  - Smart Sensors (6)
  - Smart Meters (6)

Impedance-Based Measurement Technique Overview

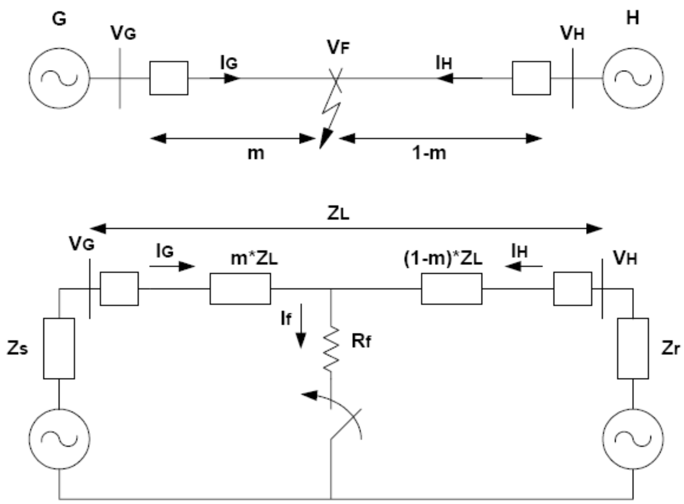
- Calculation of the fault location from the apparent impedance seen looking into the line from one end (or two ends).
- Steady-State Approach
- Phase-to-ground voltages and current in each phase must be determined.
- Fault Impedance Influence
- Loading Influence
- Ground Fault Case
  - Zero-sequence Impedance Information
  - Ground Compensation Factor

Simple Impedance Equations (with $R_f = 0$)

Fault Type	Positive-Sequence Impedance Equation ($m*Z_{1L} =$)
A – Ground	$V_A / (I_A + k*I_R)$
B – Ground	$V_B / (I_B + k*I_R)$
C- Ground	$V_C / (I_C + k*I_R)$
A-B or A-B-G	V_{AB} / I_{AB}
B-C or B-C-G	V_{BC} / I_{BC}
C-A or C-A-G	V_{CA} / I_{CA}
A-B-C	Any of the following: V_{AB}/I_{AB}, V_{BC}/I_{BC}, V_{CA}/I_{CA}

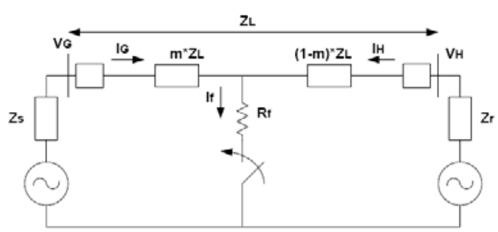
- $k=(Z_{oL} - Z_{1L})/(3 * Z_{1L})$ ground compensation factor
- Z_{oL}: zero-sequence line impedance
- m: per unit distance to fault
- I_R: Residual Current

Basic Model with System Parameters



- Simplified transmission line with two sources

Impedance (Distance) Equation



$$V_G = m \cdot Z_L \cdot I_G + R_f \cdot I_f$$

$$m = \frac{V_G - R_f \cdot I_f}{Z_L \cdot I_G}$$

$$= \frac{1}{Z_L}\left[\frac{V_G}{I_G} - R_f \cdot \frac{I_f}{I_G}\right]$$

$\frac{I_f}{I_G}$	R_f
∠ = 0	R only
∠ > 0	R and L
∠ < 0	R and C

- I_G: Line Current during fault
- I_f: Fault current through the fault resistor R_f.

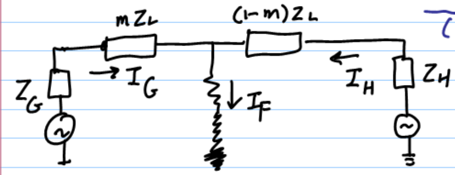
Derivation of I_f/I_G

$\Delta I_G = I_G - I_L$

Note Title 5/9/2010

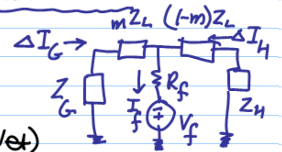
Net fault Line Component
(Superposition: subtract the normal component) ← Load

ΔI: net fault current (minus Load)



(Fault)

→ Fault (Net) only



$\Downarrow$ $\Delta I_G + \Delta I_H = I_F$

$$\left.\begin{aligned} \Delta I_G(Z_G + mZ_L) + R_f I_f &= V_f \\ \Delta I_H(Z_H + (1-m)Z_L) + I_f R_f &= V_f \end{aligned}\right\} \Rightarrow \Delta I_G(Z_G + mZ_L) = \Delta I_H(Z_H + (1-m)Z_L)$$

$$\rightarrow \Delta I_H = \frac{Z_G + mZ_L}{Z_H + (1-m)Z_L} \cdot \Delta I_G$$

Derivation Continued

ΔI_G / I_f → $\frac{\Delta I_G}{I_f} \doteq d_s$

$\frac{I_G}{I_G - I_L} = \frac{I_G}{\Delta I_L} \doteq n_s$

$d_s = |d_s| \angle \beta$

$n_s = |n_s| \angle \gamma$

$$I_F = \Delta I_G + \Delta I_H = \Delta I_G\left(1 + \frac{Z_G + mZ_L}{Z_H + (1-m)Z_L}\right) = \Delta I_G \cdot \frac{Z_G + Z_H + Z_L}{Z_H + (1-m)Z_L}$$

$$\Rightarrow \boxed{\frac{\Delta I_G}{I_F}} = \frac{Z_H + (1-m)Z_L}{Z_G + Z_H + Z_L} = d_s \quad \text{Current Distribution factor}$$

$$\boxed{\frac{I_G}{\Delta I_G}} = n_s \quad \text{Circuit Loading factor}$$

$$ZF_G = \frac{V_G}{I_G} = m \cdot Z_L + R_f \cdot \frac{1}{d_s \cdot n_s}$$

Reactive component of fault resistance

- 2 factors
  - Current distribution factor, d_s

    $$\frac{Z_H + (1-m)Z_L}{Z_G + Z_H + Z_L} = d_s$$

    - Determined by system impedances
    - Angle of d_s (β) = 0 if system is homogeneous (Same R/X ratio of lines)
  - Circuit loading factor, n_s

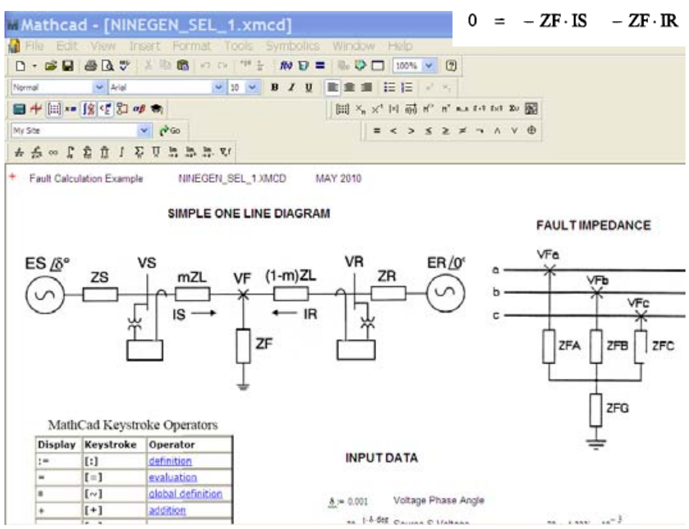
    $$\frac{I_G}{I_G - I_L} = \frac{I_G}{\Delta I_L} \doteq n_s$$

    - Determined by the load current (I_L) presence in the system
    - The angle of n_s (γ) is not zero if there is a load flow in the system
    - If I_G is much bigger than I_L, the angle will approach zero.
  - Sum of the angles ($\beta+\gamma$) determines the reactive component caused by fault resistance, R_f.

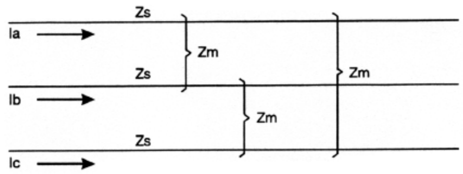
Practice with MathCad

NINEGEN_SEL_1.xmcd
Mathcad Document
1,609 KB

$$\begin{aligned} ES &= ZSS \cdot IS + 0 + VF \\ ER &= +0 + ZRR \cdot IR + VF \\ 0 &= -ZF \cdot IS - ZF \cdot IR + VF \end{aligned}$$



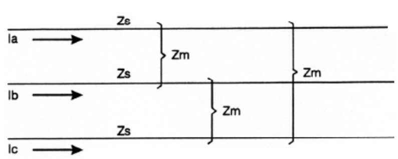
Mutual Impedance vs. Sequence Impedance



- voltage drop across the A-phase conductor is: $Va = Zs \cdot Ia + Zm \cdot (Ib + Ic)$
- for the special condition of the balanced current due to a three-phase fault where $(Ib + Ic) = -Ia$: $Va = (Zs - Zm) \cdot Ia$
  Since Va and Ia are positive-sequence quantities, the positive-sequence impedance is: $z1 = Zs - Zm$ ①
- for another special condition where the currents are equal and in phase $(Ib + Ic) = 2\,Ia$: $Va = (Zs + 2 \cdot Zm) \cdot Ia$
  In this case, Va and Ia are zero-sequence quantities; the zero-sequence impedance is: $z0 = Zs + 2 \cdot Zm$ ②

- From ① and ②, self- and mutual-impedance as functions of z0 and z1 for use in the impedance matrix
  - self-impedance: $zs(z0, z1) = \dfrac{z0 + 2 \cdot z1}{3}$
  - mutual impedance: $zm(z0, z1) = \dfrac{z0 - z1}{3}$

"k factor" from mutual impedance



- self-impedance: $zs = \dfrac{z0 + 2 \cdot z1}{3}$
- mutual impedance: $zm = \dfrac{z0 - z1}{3}$

- voltage drop across the A-phase conductor is: $Va = Zs \cdot Ia + Zm \cdot (Ib + Ic)$

$$I_r = I_a + I_b + I_c \rightarrow I_b + I_c = I_r - I_a$$

$$V_a = Z_s \cdot I_a + Z_m \cdot (I_r - I_a) = (Z_s - Z_m)\, I_a + Z_m \cdot I_r$$

$$= \left(\frac{Z0 + 2 \cdot Z1}{3} - \frac{Z_0 - Z_1}{3} \right) I_a + \frac{Z_0 - Z_1}{3} I_r \quad k_0$$

$$= Z_1 \cdot I_a + \frac{Z_0 - Z_1}{3} I_r = Z_1 \left(I_a + \frac{Z_0 - Z_1}{3 Z_1} I_r \right) = Z_1 \left(I_a + k_0 \cdot r \right)$$

Practical Approaches:
(1) Simplification & (2) Limiting errors

- **Various techniques to accommodate the two factors or to reduce the factors**
  - Fault location without using source impedance (Takagi et al)
  - Fault location using source impedance: US Patent 5839093 “System for locating faults and estimating fault resistance in distribution networks with tapped loads” Novosel et al. 1998, ABB
- **Simplification**
  - Reactance Method
  - Voltage Sag
  - Rms V and I

Reactance Method

- Measures the apparent impedance
- Determines the ratio of the measured reactance and to the reactance of the entire line, which is proportional to the distance to the fault.
- Assumptions:
  - The current through the fault resistance is in phase with the current at the measurement point
  - There is no load prior to the fault
- One of the earliest algorithms that compensate for the fault resistance by measuring only the imaginary part of the apparent line impedance

Reactance Method

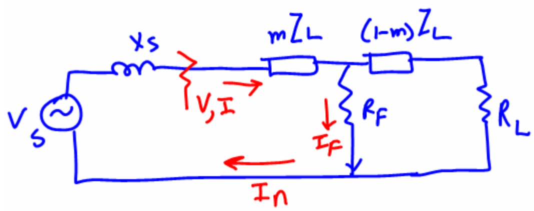
- ***m***: per-unit distance to the fault

From $Z_G = \frac{V_G}{I_G} = m \cdot Z_L + R_f \cdot \frac{I_f}{I_G}$

$$Im\left(\frac{V_G}{I_G}\right) = m \cdot Im(Z_L) + R_f \cdot \underbrace{Im\left(\frac{I_f}{I_G}\right)}_{=0 \text{ by Assumption}}$$

$$\Rightarrow m = \frac{Im(V_G/I_G)}{Im(Z_L)}$$

Reactance Method for Ground Fault Case



$$V_a = m \cdot Z_\ell \cdot (I_a + k I_p) + I_F R_F$$

$$\frac{V_a}{I_F} = \frac{m \cdot Z_\ell (I_a + k I_p)}{I_F} + R_F$$

$$R_F = \underbrace{\frac{V_a}{I_F} - \frac{m \cdot Z_\ell \cdot (I_a + k I_p)}{I_F}}_{Im = 0}$$

Further Approximation

Approximation:

$$V_a = m\cdot Z_\ell\cdot(I_a + kI_r) + I_F R_F$$

$$\angle I_F \doteq \angle I_r$$

$$V_a\cdot I_r^* = m\cdot Z_\ell\cdot(I_a+kI_r)\cdot I_r^* + \underbrace{I_F\cdot R_F\cdot I_r^*}_{\text{Real}}$$

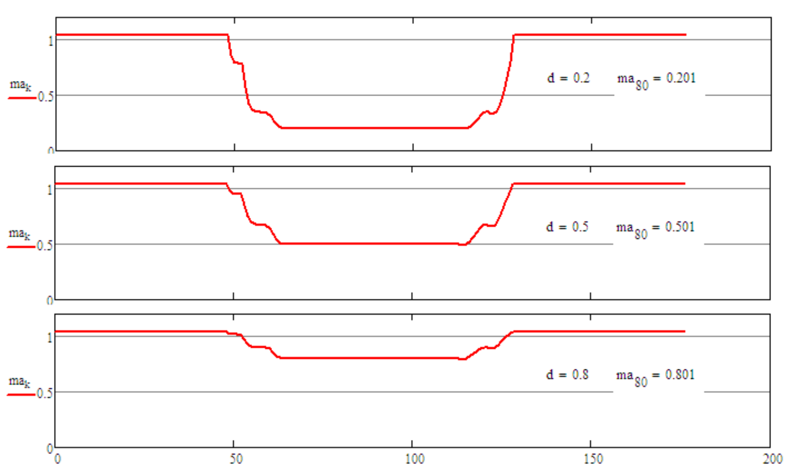
$$Im\{V_a\cdot I_r^*\} = m\cdot Im\{Z_\ell\cdot(I_a+kI_r)\cdot I_r^*\}$$

$$m = \frac{Im\{V_a\cdot I_r^*\}}{Im\{Z_\ell\cdot(I_a+kI_r)\cdot I_r^*\}}$$

NINEGEN-SEL_SRbus_X_EPRI_TAKAGI_DIFF.xmcd

Reactance Approach

$$m = \frac{Im\{Va\cdot Ir^*\}}{Im\{Z\cdot Va\cdot Ir^*\}}$$



Further Approximation

Further Approximation:

$Z_\ell \to jX_\ell$

$I_a + kI_r \to k' \cdot I_r$

$$\frac{I_r}{I_p} = \frac{3}{2+K}$$

$$I_a = \frac{2+K}{3} I_r = \frac{2+3k+1}{3} I_r = (k+1) I_r$$

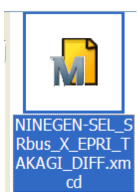
$$I_a + kI_r = (2k+1) I_r = k' I_r$$

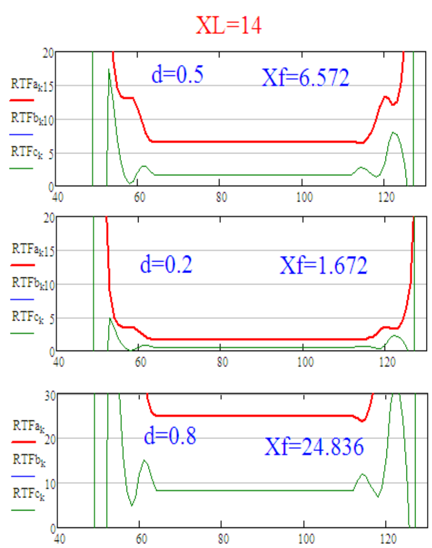
$$m \cdot X_\ell = \frac{Im\{V_a \cdot I_r^*\}}{|I_r|^2} = \frac{|V_a||I_r|}{k' \cdot |I_r|^2} \sin(\theta_{V_a} - \theta_{I_r})$$

$$X_{TF} = k \cdot \frac{|V_a|}{|I_r|} \sin(\theta_{V_a} - \theta_{I_r})$$

EPRI algorithm for ground fault.

Performance





Fault Location without Using Source Impedance

- Improvement
  - Elimination of load current by determining the change in current on occurrence of a fault.
  - Takagi
  - From $V_G = m \cdot Z_L \cdot I_G + R_f \cdot I_f$, $d_s = \frac{\Delta I_G}{I_f}$, $d_s = \frac{Z_H + (1-m)Z_L}{Z_G + Z_L + Z_H}$

$$V_G = m \cdot Z_L \cdot I_G + R_f \cdot \frac{\Delta I_G}{d_s}$$

$\times(\Delta I_G^*)$ both sides, and take only Imaginary parts;

$$I_m(V_G \cdot \Delta I_G^*) = m \cdot I_m[Z_L \cdot I_G \cdot \Delta I_G^*] + R_f |\Delta I_G|^2 \cdot I_m\left[\frac{1}{d_s}\right]$$

Condition: homogenous system $\rightarrow \angle d_s \doteq 0 \Rightarrow I_m\left[\frac{1}{d_s}\right] \doteq 0$

Final Equation: $$m = \frac{I_m[V_G \cdot \Delta I_G^*]}{I_m[Z_L \cdot I_G \cdot \Delta I_G^*]}$$

Takagi Method - Patent

United States Patent [19]

Takagi et al.

[11] **4,313,169**

[45] **Jan. 26, 1982**

[54] **FAULT DETECTING SYSTEM FOR LOCATING A FAULT POINT WITH A FAULT RESISTANCE SEPARATELY MEASURED**

[75] Inventors: **Toshio Takagi; Yukinari Yamakoshi,** both of Tokyo, Japan

[73] Assignee: **Tokyo Denryoku Kabushiki Kaisha,** Tokyo, Japan

[21] Appl. No.: **63,412**

[22] Filed: **Aug. 3, 1979**

[30] **Foreign Application Priority Data**

Nov. 13, 1978 [JP] Japan 53-139583

[51] **Int. Cl.**³ **G01R 31/08;** G06F 15/56

[52] **U.S. Cl.** **364/492;** 361/80; 324/52

[58] **Field of Search** 364/492; 324/52; 361/80, 81, 79

[56] **References Cited**

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3,710,239	1/1973	Nakamura	324/52
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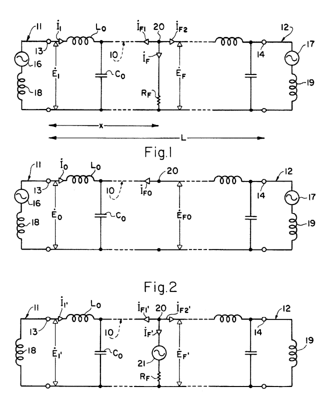
3,983,377	9/1976	Vitins	324/52 X
4,063,166	12/1977	Glavitsch et al.	324/52
4,107,778	8/1978	Nii et al.	324/52 X
4,128,805	12/1978	Lanz	324/52
4,148,087	4/1979	Phadke	324/52 X

Primary Examiner—Edward J. Wise
Attorney, Agent, or Firm—Frishauf, Holtz, Goodman & Woodward

[57] ABS

At an end (**11**) of a power detecting system monitors fault in voltage and curren the line and calculates the c location (**20**) of the fault by a line constant inherent to t the characteristic impedan stant, to thereby locate the racy by directly using the without affected by the i the fault. The system can c from the distance and thos at the end and an opposin wardly of the location of f

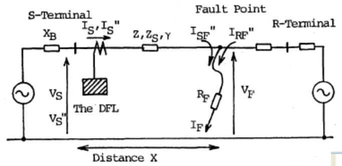
3 Claims, 7 D



Takagi Method

$$x = \frac{Im\ (V_S \cdot I_S''^*)}{Im\ (Z\ I_S \cdot I_S''^*)}$$

where
- x: distance to the fault point
- V_S: voltage of S-terminal
- I_S: current of S-terminal
- V_F: voltage of fault point
- I_F: fault current
- V_S'': voltage difference between pre-fault and after-fault voltage.
- I_S'': current difference between pre-fault and after-fault (fault component current)
- I_{SF}'': fault current from S-terminal
- Z_S: surge impedance
- Z: transmission line impedance per unit length
- γ: propagation constant
- Im: imaginary component
- *: conjugate component



$$R_F = \frac{V_a}{I_F} - \frac{m \cdot Z_\ell \cdot (I_a + k I_r)}{I_F}$$

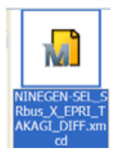
$I_m = 0$

Normal

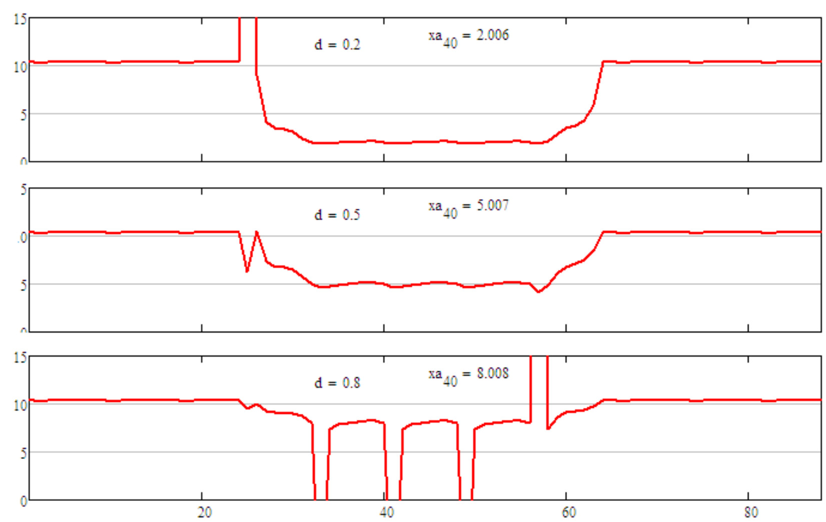
$$I_F = I_a - I_{aN}$$

$$Z_\ell \rightarrow j X_\ell$$

$$m = \frac{Im\{V_a \cdot (I_a - I_{aN})^*\}}{Im\{Z_\ell \cdot I_a \cdot (I_a - I_{aN})^*\}}$$



Takagi Approach Example



Variation of A2

- Modified method
  - Uses zero-sequence current (I_R) (instead of the net fault current)
  - Uses the angle β of the current distribution factor derived from the source impedance data
  - Accounts for non-homogeneous system
  - Reduces the reactance effect error
  - Problem with accurate correction of β.

$$m = \frac{I_m\left(V_G \cdot I_R^{*} \cdot e^{-j\beta}\right)}{I_m\left(Z_L \cdot I_G \cdot I_R^{*} \cdot e^{-j\beta}\right)}$$

Further Improvement (Modified Takagi &SEL)

$$\mathbf{Va = m \cdot Z1L \cdot (Ia + k_0 \cdot Ir) + R_F \cdot I_F}$$

$$I_F = |I_F|\, e^{jI_F}$$

$$I_r = |I_r|\, e^{jI_r} \qquad I_r^{*} = |I_r|\, e^{-jI_r}$$

$$I_F \cdot I_r^{*} = |I_F|\,|I_r|\, e^{j(I_F - I_r)}$$

$$\underbrace{I_F \cdot I_r^{*} \cdot \left\{e^{j(I_F - I_r)}\right\}^{*}}_{A} = |I_F|\,|I_r| \quad \text{Real}$$

$$V_a \cdot A = m \cdot Z1L \cdot (I_a + k_0 \cdot I_r) \cdot A + R_F \cdot |I_F|\,|I_r|$$

$$I_m\{V_a \cdot A\} = m \cdot I_m\{Z1L \cdot (I_a + k_0 \cdot I_r) \cdot A\}$$

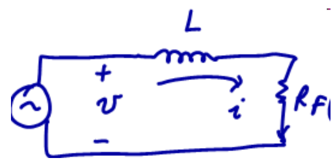
$$\rightarrow \quad m = \frac{I_m\{V_a \cdot A\}}{I_m\{Z1L \cdot (I_a + k_0 \cdot I_r) \cdot A\}}$$

NINEGEN-SEL_SRbus_Modified_Takagi.xmcd

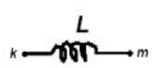
Differential Equation Approach

- *L* calculation from sampled data of *v* and *I*
  - *Time domain Approach*
  - *Extraction of R and X*
- Different ways of dealing Derivative *(d/dt) for computing from sampled data*
  - Numerical Analysis of Derivative
  - Conversion of the equation into integral, then trapezoidal rule
  - Discretized element model

$$v(t)=R*i(t)+L\frac{di(t)}{dt}$$



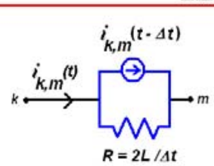
Discretized Model of Elements – EMTP approach



$$v_k - v_m = L\frac{di_{k,m}}{dt}$$

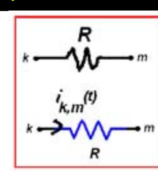
$$i_{k,m}(t) = i_{k,m}(t-\Delta t) + \frac{1}{L}\int_{t-\Delta t}^{t}(v_k - v_m)dt$$

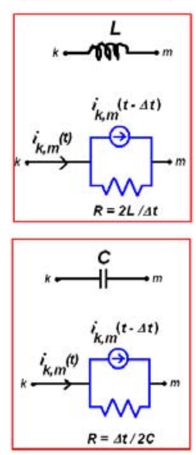
$$i_{k,m}(t) = I_{k,m}(t-\Delta t) + \frac{\Delta t}{2L}\left[v_k(t) - v_m(t)\right]$$



$$I_{k,m}(t-\Delta t) = i_{k,m}(t-\Delta t) - \frac{\Delta t}{2L}\left[v_k(t-\Delta t) - v_m(t-\Delta t)\right]$$

Discretization Error: $(\Delta t)^3$





Trapezoidal Approximation

$$v(t) = R \cdot i(t) + L \cdot \frac{di(t)}{dt}$$

$$\int_{t_0}^{t} v(t)\,dt = R\int_{t_0}^{t} i(t)\,dt + L\left[i(t_1) - i(t_0)\right]$$

$$\int_{t_1}^{t_2} v(t)\,dt = R\int_{t_1}^{t_2} i(t)\,dt + L\left[i(t_2) - i(t_1)\right]$$

$$\int_{t_0}^{t_1} v(t)\,dt = \frac{\Delta t}{2}\left[v(t_1) + v(t_0)\right]$$

$$\int_{t_1}^{t_2} v(t)\,dt = \frac{\Delta t}{2}\left[v(t_2) + v(t_1)\right]$$

$$\frac{\Delta t}{2}\left[v(t_1) + v(t_0)\right] = R \cdot \frac{\Delta t}{2}\left[i(t_1) + i(t_0)\right] + L\left[i(t_1) - i(t_0)\right]$$

$$\frac{\Delta t}{2}\left[v(t_2) + v(t_1)\right] = R \cdot \frac{\Delta t}{2}\left[i(t_2) + i(t_1)\right] + L\left[i(t_2) - i(t_1)\right]$$

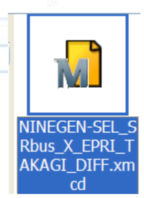
$$\begin{bmatrix} \frac{\Delta t}{2}\left[I_{k+1} + I_k\right] & \left[I_{k+1} - I_k\right] \\ \frac{\Delta t}{2}\left[I_{k+2} + I_{k+1}\right] & \left[I_{k+2} - I_{k+1}\right] \end{bmatrix} \begin{bmatrix} R \\ L \end{bmatrix} = \begin{bmatrix} \frac{\Delta t}{2}\left[V_{k+1} + V_k\right] \\ \frac{\Delta t}{2}\left[V_{k+2} + V_{k+1}\right] \end{bmatrix}$$

- Source: Arum G. Phadke and James S. Thorp, ''Computer relaying for power systems'', RSP.Ltd August 1994, pp.118-131

Final Form and Practice with MathCad

$$R = \frac{(V_{k+1} + V_k)\cdot(I_{k+2} - I_{k+1}) - (V_{k+2} + V_{k+1})(I_{k+1} - I_k)}{(I_{k+1} + I_k)\cdot(I_{k+2} - I_{k+1}) - (I_{k+2} + I_{k+1})\cdot(I_{k+1} - I_k)}$$

$$X = (f\pi\Delta t)\cdot\frac{(I_{k+1} + I_k)(V_{k+2} + V_{k+1}) - (I_{k+2} + I_{k+1})(V_{k+1} + V_k)}{(I_{k+1} + I_k)(I_{k+2} - I_{k+1}) - (I_{k+2} + I_{k+1})(I_{k+1} - I_k)}$$

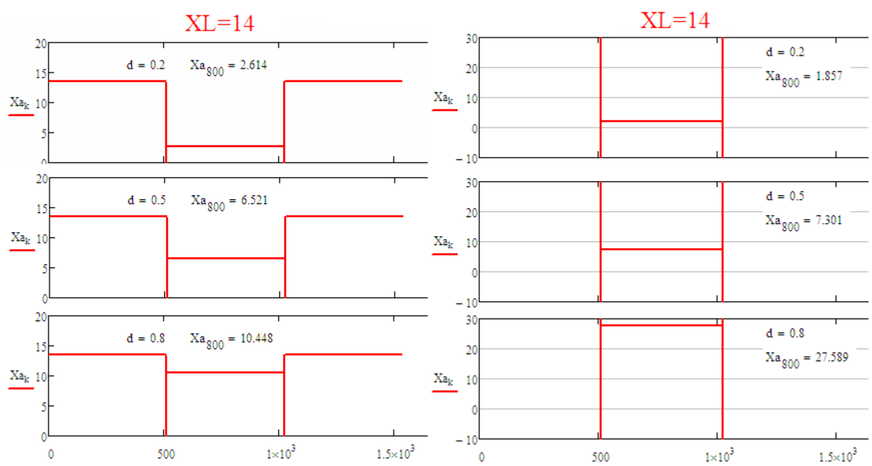


Differential Equation Approach on SEL

$$v(t) = R*i(t) + L\frac{di(t)}{dt}$$

$i(t) \rightarrow i_a(t) + k*Ir$

$i(t) \rightarrow k'*Ir$

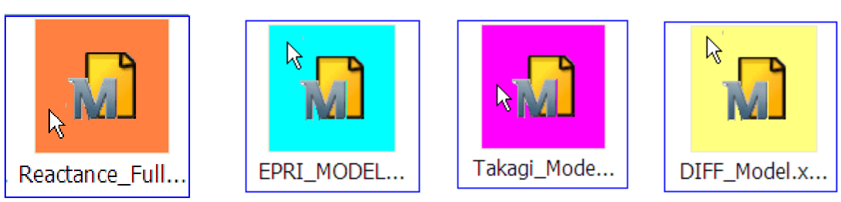


Fault Location with Actual Data

* Data Given/tested by Dan Sabin **

* Last two columns DE (distance by SABIN) and LL (Line length in X) *

SubstationBus	MMDDYY-HHMM	FT	True Distance (X)	Calculated Dist (X)	Line Length (in X)	Line
CreelmanS	102205-031724	CG	2.2	2.83	5.13	CR973
CreelmanS	102205-031731	CG	2.2	2.26	5.13	CR973
CreelmanS	121005-031342	AG	2.09	1.97	5.13	CR973
CreelmanS	121005-031348	AG	2.09	2.1	5.13	CR973
CreelmanS	121005-031433	AG	2.09	2.09	5.13	CR973
CreelmanN	012606-114830	AG	4.2	4.4	10.4	CR237
CreelmanN	022706-222122	BG	1	1.27	10.4	CR237
CreelmanN	121706-225239	BG	4.4	3.79	8	CR972
CreelmanN	121706-225244	BG	4.4	3.86	8	CR972



Fault location using Source Impedance

United States Patent [19]

Novosel et al.

[11] **Patent Number:** **5,839,093**

[45] **Date of Patent:** **Nov. 17, 1998**

[54] **SYSTEM FOR LOCATING FAULTS AND ESTIMATING FAULT RESISTANCE IN DISTRIBUTION NETWORKS WITH TAPPED LOADS**

[75] Inventors: **Damir Novosel**, Cary; **David Hart**, Raleigh; **Yi Hu**, Cary, all of N.C.; **Jorma Myllymaki**, Tampere, Finland

[73] Assignee: **ABB Transmit Oy**, Vaasa, Finland

[21] Appl. No.: **777,623**

[22] Filed: **Dec. 31, 1996**

[51] **Int. Cl.**[6] **H02H 3/26**

[52] **U.S. Cl.** **702/59**; 702/58; 364/528.27; 364/528.28; 364/528.29; 361/65; 361/63; 361/79; 361/80; 324/525

[58] **Field of Search** 364/492, 480–483, 364/550, 551.01, 555, 579, 580, 802, 528.27–528.29, 807, 823, 838; 324/512, 522, 521, 525,

4,499,417	2/1985	Wright et al.	324/533
4,559,491	12/1985	Saha	324/522
4,841,405	6/1989	Udren	361/80
4,857,854	8/1989	Matsushima	324/512
4,906,937	3/1990	Wikström et al.	324/523
4,996,624	2/1991	Schweitzer et al.	361/63
5,072,403	12/1991	Johns	
5,428,549	6/1995	Chen	
5,455,776	10/1995	Novos	
5,661,664	8/1997	Novos	

Primary Examiner—Emanuel

Assistant Examiner—Hal D.

[57] ABST

Both fault location and fault r lated by the present method system takes into account the load flow, thereby calculating consideration the current flo network as well as the effect method calculates fault locatio

The impedances Z_s AND Z_{load} are calculated by using Equations 9 and 7 respectively. Complex Equation 22 has two unknowns, m and R_F. This equation can be separated into real and imaginary parts. By eliminating R_F, m is given by:

$$m = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (26)$$

where:

$$a = 1$$

$$b = -\left(Re(k_1) - \frac{Im(k_1) \times Re(k_3)}{Im(k_3)}\right) \quad (27)$$

$$c = Re(k_2) - \frac{Im(k_2) \times Re(k_3)}{Im(k_3)}$$

The inventors have ascertained that the proper solution for m is given by:

$$m = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \quad (28)$$

Once an accurate value for m is obtained, the fault resistance R_f may be accurately obtained by solving for the imaginary part of equation (22) as follows:

$$R_f = -m \times \frac{Im(k_1)}{Im(k_3)} + \frac{Im(k_2)}{Im(k_3)} \quad (29)$$

- The current distribution factor, d_s, is a function of the source impedance, line impedance, and the unknown fault location.
- If the source impedance is known, fault location can be estimated without the assumption related with the distribution factor.

Quadratic Equation Derivation

$(Z_H \to Z_{load})$

From $d_s = \frac{\Delta I_G}{I_f} = \frac{Z_H + (1-m) Z_L}{Z_s + Z_H + Z_L}$

&

$$V_G = m Z_L \cdot I_G + R_f \cdot \frac{\Delta I_G}{d_s}$$

$$= m Z_L I_G + R_f \cdot \Delta I_G \cdot \frac{Z_s + Z_H + Z_L}{Z_H + (1-m) Z_L}$$

$$V_G (Z_H + Z_L - m \cdot Z_L) = m (Z_H + Z_L - m \cdot Z_L) \cdot Z_L \cdot I_G + R_f \cdot \Delta I_G \cdot (Z_s + Z_H + Z_L)$$

$$I_G \cdot Z_L^2 \cdot m^2 - \left[(Z_H + Z_L) \cdot Z_L \cdot I_G + V_G \cdot Z_L\right] m + V_G (Z_H + Z_L) - R_f \cdot \Delta I_G (Z_s + Z_H + Z_L) = 0$$

Continued

$$m^2 - k_1 \cdot m + k_2 - k_3 \cdot R_f = 0$$

where, $k_1 = \frac{V_G}{I_G \cdot Z_L} + \frac{Z_H}{Z_L} + 1$

$$k_2 = \frac{V_G}{I_G \cdot Z_L} \cdot \left[\frac{Z_H}{Z_L} + 1 \right],$$

$$k_3 = \frac{\Delta I_G}{I_G \cdot Z_L} \left[\frac{Z_S + Z_H}{Z_L} + 1 \right]$$

$$Z_S = \frac{V_{FS}}{I_{FS}} - Z_L$$

$$Z_H = \frac{V_{HS}}{I_{HS}} - Z_L$$

Unknowns : m and R_f

① R_f ← by Imaginary part only

$$R_f = -m \cdot \frac{Im(k_1)}{Im(k_3)} + \frac{Im(k_2)}{Im(k_3)}$$

Continued-

ASSIGNMENT

Mathcad

② m : quadratic solution

$$m = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$a = 1$

$$b = -\left[Re(k_1) - \frac{Im(k_1) \cdot Re(k_3)}{Im(k_3)} \right]$$

$$c = -Re(k_2) - \frac{Im(k_2) \cdot Re(k_3)}{Im(k_3)}$$

- Problem
  - Source Impedance in program must be the same as the actual source impedance of a network

Factors affecting the accuracy of the fault estimation

- The combined effect of the load current and fault resistance (reactance effect)
- Influence of zero-sequence mutual effect on the components
- Uncertainty about the zero-sequence impedance
  - Difficult to obtain an accurate zero-sequence impedance (Z_{oL}) for line
  - The value is affected by soil resistivity, which can be difficult to measure, and may be changeable.
  - A 20% error in the Z_{oL} can introduce a 15% error in fault calculation
  - The impedance is not uniformly distributed along the line length (100 to 1 variation in earth resistivity produces about 2 to 1 change in Z_o)

Other Factors of Error

- Insufficient accuracy of the line model (un-transposed lines are represented as being transposed and charging capacitance is not considered)
- Presence of shunt reactors and capacitors
- Load flow unbalance
- Measurement errors, CT/PT errors
- Low resolution or sampling rate at measurement station

Two-Terminal Data Methods

- Advantages
  - More accurate than one-terminal methods
  - Able to minimize or eliminate the effects of fault resistance, loading, and charging current.
  - Positive Sequence components are used instead of zero-sequence, eliminating the adverse effect of zero-sequence components
- Drawback
  - The data from both ends must be collected at one location
- Required Equipment
  - Measuring devices for 3-phase voltages and currents at each end with time stamping.
  - Communication equipment
  - Central computer for collection of data and calculation of fault location

Some other Fault Location Methods

United States Patent [19] — **Saha**
[11] **Patent Number: 4,559,491**
[45] **Date of Patent: Dec. 17, 1985**

[54] **METHOD AND DEVICE FOR LOCATING A FAULT POINT ON A THREE-PHASE POWER TRANSMISSION LINE**
[75] Inventor: **Murari M. Saha**, Västerås, Sweden
[73] Assignee: **ASEA Aktiebolag**, Västerås, Sweden

Godard, Electrical Utility Load Forecasting, Feb. 1956, AIEE, p. 1428.
Stevens et al., Frequency Modulated Fault Locator for Power Lines, Dec. 1971, pp. 1760–1768.
Humpage et al., Measuring Accuracy of Distance Protection with Particular Reference to Earth–Fault Con-

(12) **United States Patent** — **Saha et al.**
(10) **Patent No.: US 6,483,435 B2**
(45) **Date of Patent: Nov. 19, 2002**

(54) METHOD AND DEVICE OF FAULT LOCATION FOR DISTRIBUTION NETWORKS
(75) Inventors: **Murari Saha**, Vasteras (SE); **Eugeniusz Rosolowski**, Warsa
(73) Assignee: **ABB AB**, Vasteras (SE)

WO WO 99/46609 9/1999

United States Patent [19] — **Nii et al.**
[11] **4,107,778**
[45] **Aug. 15, 1978**

[54] **DIGITAL FAULT-LOCATION CALCULATION SYSTEM**
[75] Inventors: **Yoshiji Nii**, Kawaguchi; **Takayuki Matsuda**, Tokyo; **Yoichi Yamazaki**; **Haruo Nohara**, both of Hitachi, all of Japan
[73] Assignees: **Hitachi, Ltd.; The Tokyo Electric Power Co., Inc.**, both of Japan
[21] Appl. No.: **768,841**

3,758,763	9/1973	Nohara et al.	235/151.31
3,885,199	5/1975	Nohara et al.	235/151.31 X
3,931,502	1/1976	Kohlas	235/151.31
3,983,377	9/1976	Vitins	235/151.31
3,984,737	10/1976	Okamura et al.	361/80

Primary Examiner—Edward J. Wise
Attorney, Agent, or Firm—Craig & Antonelli

[57] **ABSTRACT**

Provided is a digital fault-location calculation system

More

ASSIGNMENT

(19) **United States**
(12) **Patent Application Publication**
Premerlani et al.

(10) **Pub. No.: US 2008/0150544 A1**
(43) **Pub. Date: Jun. 26, 2008**

(54) **MULTI-ENDED FAULT LOCATION SYSTEM**

(76) Inventors: **William J. Premerlani**, Scotia, NY (US); **Bogdan Z. Kasztenny**, Markham (CA); **Mark G. Adamiak**, Paoli, PA (US)

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(22) Filed: **Dec. 22, 2006**

Publication Classification

(51) **Int. Cl.**
G01R 31/08 (2006.01)

(52) **U.S. Cl.** **324/521**; 324/522

United States Patent [19]
Yang

[11] **Patent Number: 5,773,980**
[45] **Date of Patent: Jun. 30, 1998**

[54] **ONE-TERMINAL FAULT LOCATION SYSTEM THAT CORRECTS FOR FAULT RESISTANCE EFFECTS**

[75] Inventor: **Lifeng Yang**, Coral Springs, Fla.

[73] Assignee: **ABB Power T&D Company, Inc.**, Raleigh, N.C.

4,812,995	3/1989	Girgis et al.	324/512 X
4,906,937	3/1990	Wikstrom et al.	324/522
5,428,549	6/1995	Chen	364/483
5,455,776	10/1995	Novosel	364/492
5,661,664	8/1997	Novoel et al.	364/492

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Elmore, Walter, "Evolution of Distance Relaying Principles," 48th Annual Conference for Protective Relay Engineers, Texas A&M University, College Station, Texas, Apr. 3–5, 1995.

(19) **United States**
(12) **Patent Application Publication**
Wahlroos et al.

(10) **Pub. No.: US 2008/0297163 A1**
(43) **Pub. Date: Dec. 4, 2008**

(54) **METHOD FOR DETERMINING LOCATION OF PHASE-TO-EARTH FAULT**

(75) Inventors: **Ari Wahlroos**, Vaasa (FI); **Janne Altonen**, Toijala (FI)

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(51) **Int. Cl.**
G01R 31/08
(52) **U.S. Cl.** ....
(57)

A method and appa... phase-to-earth fault c... tric network, compri... fault current and loa...

(19) **United States**
(12) **Patent Application Publication**
Wahlroos et al.

(10) **Pub. No.: US 2009/0267611 A1**
(43) **Pub. Date: Oct. 29, 2009**

(54) **APPARATUS AND METHOD FOR DETERMINING LOCATION OF PHASE-TO-PHASE FAULT OR THREE-PHASE FAULT**

(75) Inventors: **Ari Wahlroos**, Vaasa (FI); **Janne Altonen**, Toijala (FI)

Publication Classification

(51) **Int. Cl.**
G01R 31/08 (2006.01)

(52) **U.S. Cl.** **324/522**

(57) **ABSTRACT**

More

ASSIGNMENT

(19) **United States**
(12) **Patent Application Publication**
Tremblay et al.

(10) **Pub. No.: US 2010/0102824 A1**
(43) **Pub. Date: Apr. 29, 2010**

(54) **ELECTRICAL NETWORK FAULT LOCATION BY DISTRIBUTED VOLTAGE MEASUREMENTS**

(76) Inventors: **Mario Tremblay**, Varennes (CA); **Ryszard Pater**, Saint-Laurent (CA); **Francisc Zavoda**, Montreal (CA); **Mario Germain**, Saint-Roch-de-Richelieu (CA)

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(30) **Foreign Application Priority Data**

Apr. 18, 2007 (CA) 2,585,820

Publication Classification

(51) **Int. Cl.**
G01R 31/08 (2006.01)

(52) **U.S. Cl.** **324/522**

(57) **ABSTRACT**

A method of locating a fault on an electrical network energized by a source uses a form of triangulation of voltage measurements at least three different locations on the network, with at least one of the locations situated upstream from the fault with respect to the source. Voltage phasors corre-

(19) **United States**
(12) **Patent Application Publication**
Lubkeman et al.

(10) **Pub. No.: US 2003/0085715 A1**
(43) **Pub. Date: May 8, 2003**

(54) **SYSTEM AND METHOD FOR LOCATING A FAULT ON UNGROUNDED AND HIGH-IMPEDANCE GROUNDED POWER SYSTEMS**

(76) Inventors: **David Lubkeman**, Raleigh, NC (US); **Michael J. Gorman**, Fitchburg, WI (US); **David G. Hart**, Raleigh, NC (US)

Publication Classification

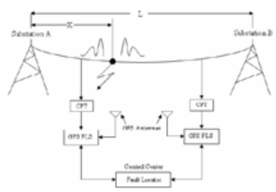
(51) **Int. Cl.[7]** **G01R 31/14**
(52) **U.S. Cl.** **324/509**

(57) **ABSTRACT**

A fault is located in a power distribution system having a line frequency. The power distribution system includes a plurality of phases, at least one feeder, and each feeder

Traveling Wave Approach

- Transient Wave Arrival Time
- Transient Wave Frequency Analysis
- Features
  - High sampling of data
  - Transient Frequency correlation to fault distance
  - More suitable for long distance faults



Overview of High Frequency/Traveling Wave Methods

- Reflection and transmission of fault generated traveling wave on the faulted point
- Accurate but more complex and expensive in implementation
- Added equipment
  - GPS system
  - Fault transient detectors and diagnosis software
- Difficulties in the configuration an location of fault transient detectors due to complex distribution network

Traveling Wave Method

- Correlation of Incident and reflected waveform.
- Single-ended and double-ended approaches
- Big problem in multiple discontinuity (reflection points) in networks
- Variations
  - High frequency signals measured at the substation (with Wavelet analysis) F. H, Magnago and A. Abur (1999) A new fault location technique for radial distribution systems based on high frequency signals. Proc of IEEE PES Summer Meeting, 1:426-431

Summated Voltage and Current Wave

- In a total ***n*** lines, with the same value Zo, connected to a common bus bar, the summated waves on the line carrying the incident wave is:

$$\text{Summated Voltage Wave} = \frac{2}{n}$$

$$\text{Summated Current Wave} = 2 - \frac{2}{n}$$

- As the number of lines connected to a bus bar increases
  - The summated voltage will tend to zero
  - The summated current wave will double
- Observation of current waves (via CT) may be preferable
- But both have been applied.

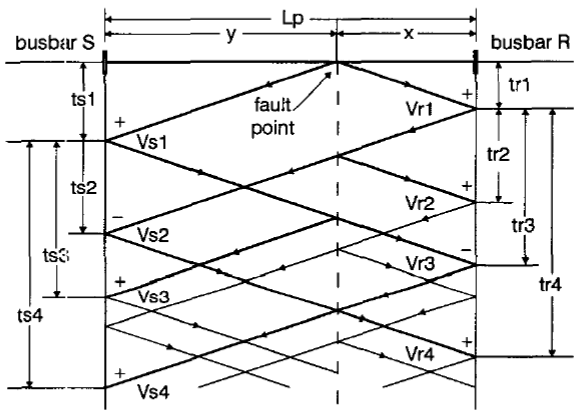
Accuracy Limitation

- Assumption
  - The light speed: $3*10^8$ m/s
  - Discontinuities in electrical system produces wave reflections
  - Two terminal method allow timing from the initiation of the fault, hence reflected waves are not used.
- Accuracy
  - 300 meters even for long lines
  - Wave detection error due to interpretation of the transient is a major source of error. Many transients and/or reflected transients appear at the same time.
  - One terminal method needs to be more sophisticated – signature analysis required.

Traveling Wave Method Modes

- Type A (single-ended) mode
  - Flashover at the fault point launches two waves that travel in opposite directions away from the fault
  - The effective impedances at the line terminals are assumed to be lower than the line surge impedance so that significant reflections are produced which then travel back along the faulty line to the fault point.
  - If the fault arc still exists, and also presents an effective resistance lower than the surge impedance of the line, then any waves arriving at the fault will be almost totally reflected back to the line terminals.
- Type D (two-ended) mode
  - Difference in the times of first arrival of the two fault generated waves at both line terminals are determined.
  - Reflections from other discontinuities, branches, tapped loads, cable sections become unimportant.
- Type E (Single-Ended Circuit Breaker Transient) mode
  - Uses the transients created when a line is re-energized by closing a circuit breaker (close to the Impulse Current Method of fault location widely used on underground cables)

Loss Free Overhead Line



- Detection Device at S

$$x = \frac{v * tr2}{2}$$

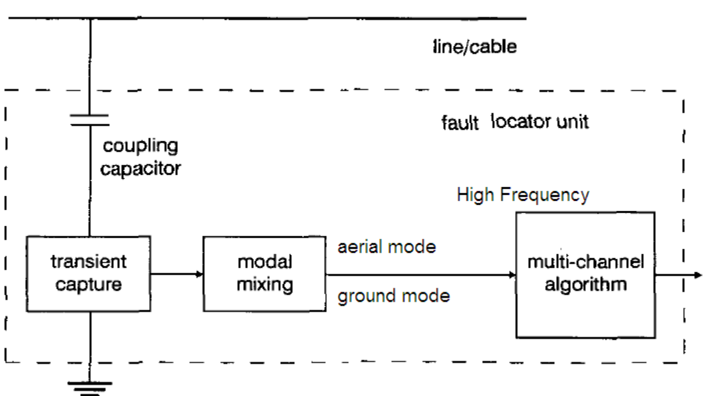
- Detection Device at R

$$x = \frac{v * ts2}{2}$$

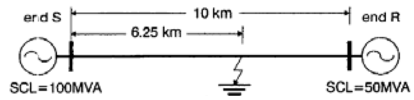
$$y = Lp - \frac{v * ts2}{2}$$

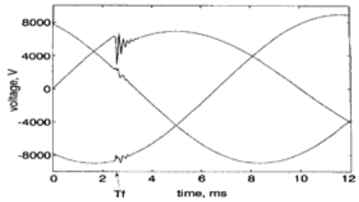
The distinction between the reflected wave from the fault point and that from the remote bus bar is vital.

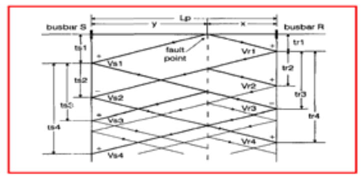
Example Fault Locator

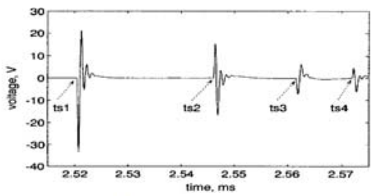


Test 1





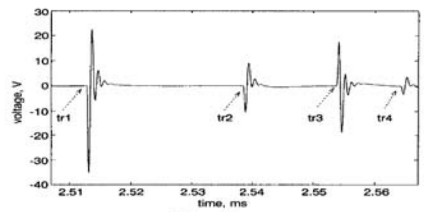




@Bus S

$$x = \frac{v * ts2}{2}$$

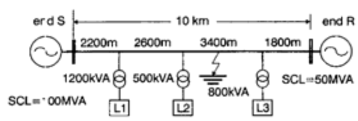
$$y = Lp - \frac{v * ts2}{2}$$

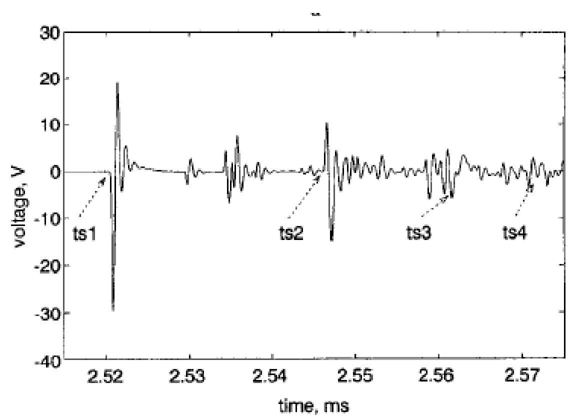


@Bus R

$$x = \frac{v * tr2}{2}$$

Test 2 (with load)





Can we apply the algorithms to Distribution Systems Faults?

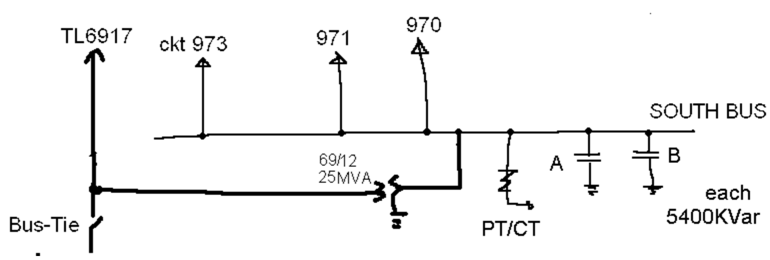
- Numerous factors affecting the algorithms in distribution networks
  - Conductor size change
  - Multiple feeder taps and laterals
  - Inaccurate models and system data and dynamic configuration
  - Effects of fault impedance
  - Different Grounding Methods
    - Solid grounding
    - Ungrounded Network
    - Peterson's coil
    - Resistance Grounded

Distribution Network Topology

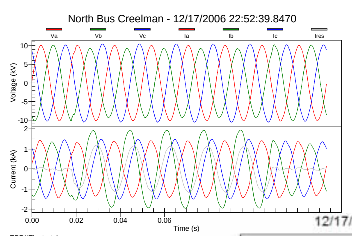
- Heterogeneous Feeders
  - Different size and length of cables
  - Presence of overhead and underground lines
  - Presence of single, double, and three-phase loads
  - Presence of laterals along the main feeder
  - Presence of load taps along the main feeder and laterals.
- Cause of estimation error in fault locations
- Model
  - Lumped parameter model
  - Symmetrical components on phasor-based algorithms
- Single line to ground fault is most common
- Different values of fault resistance

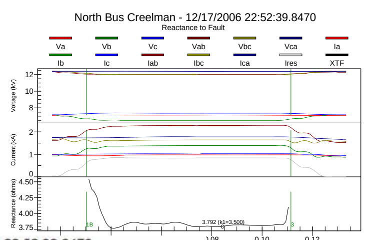
Fault Location at SDG&E

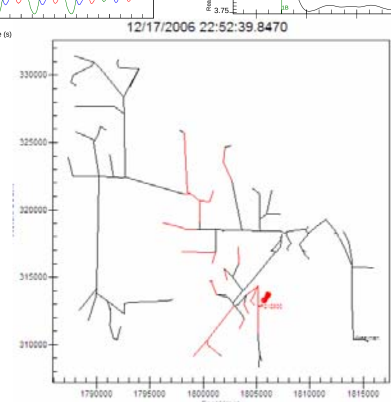
- Fault Location Efforts
  - Data Measurement (“PQNode”) at 36 Substations
  - Data Analysis using PQView
  - Algorithm (“reactance approach”) Programmed by EPRI
  - Off-line Evaluation for a few Substation Circuits



Fault Location – EPRI Example

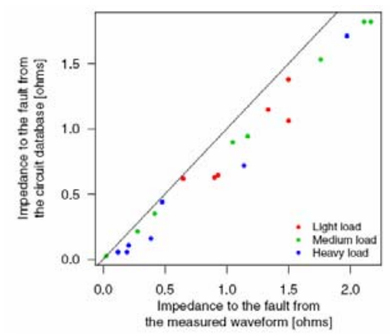






Strength and Weakness of the Current Approach

- Current approach
  - Simple and Effective
  - Load dependency
    - Overreaching & Under-reaching Problem



ELECTRIC POWER RESEARCH INSTITUTE

Distribution Fault Location

Field Data and Analysis

1012438 Final Report, December, 2006

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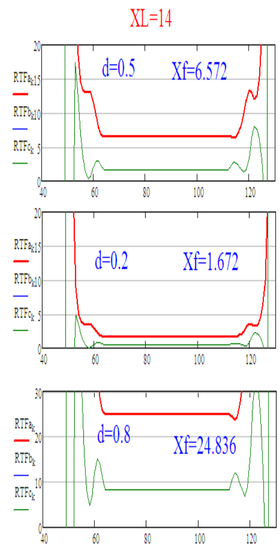
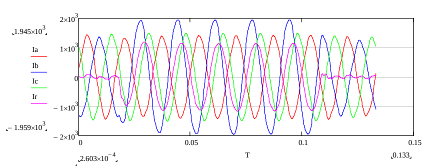
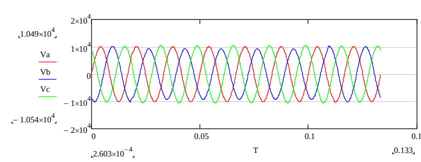
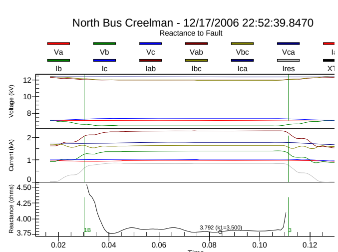
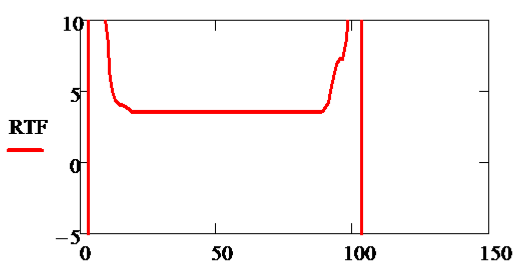


Reproduction of EPRI Approach





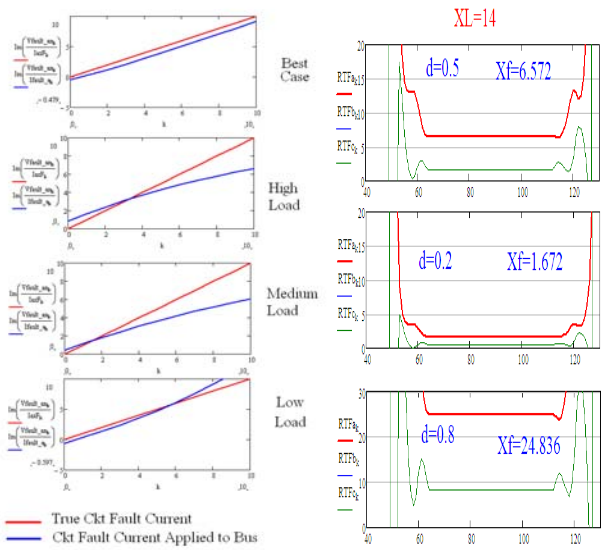




$$X = k\frac{V}{Ir}\sin\theta$$

Strength and Weakness of the Current Approach

- Current approach
  - Simple and Effective
  - Load dependency
    - Overreaching & Under-reaching Problem
  - Minimum Data Length Requirement --- at least 2 cycles of faulted data are needed.



Simpler Approach

- RMS current Only
  - Fault Current Calculation at each every node
  - Look-up Table

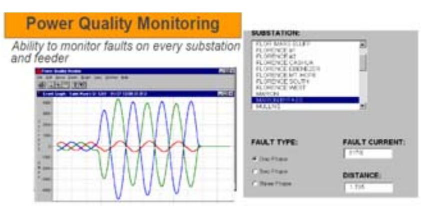
$$d = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

$$a = Z_l^2$$

$$b = 2R_l R_{src} + 2X_l X_{src}$$

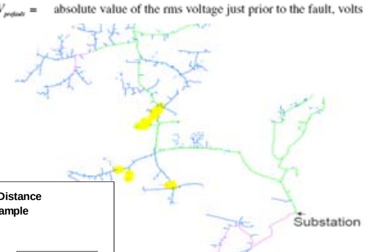
$$c = Z_{src}^2 - \left(\frac{V_{prefault}}{I_{fault}}\right)^2$$

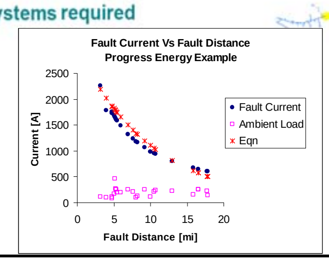
R_{src} = source resistance, ohms
X_{src} = source reactance, ohms
Z_{src} = absolute value of the source impedance, ohms
R_l = line resistance, ohms per unit distance
X_l = line reactance, ohms per unit distance
Z_l = absolute value of the line impedance, ohms per unit distance
I_{fault} = absolute value of the rms current during the fault, amperes
$V_{prefault}$ = absolute value of the rms voltage just prior to the fault, volts



Interfaces to many different systems required

- Feeder Monitoring System FMS
- DIS mapping
- FMS Fault Locator
- Distribution feeder models (CYME)





Characterization of Specific Fault

- Voltage-Dip Energy Index (E_{dip})
  - Characterization of specific fault
  - Integration of the drop in signal energy over the duration of an event.
  - V(t): RMS voltage over time
  - V_{nom}: Rated voltage

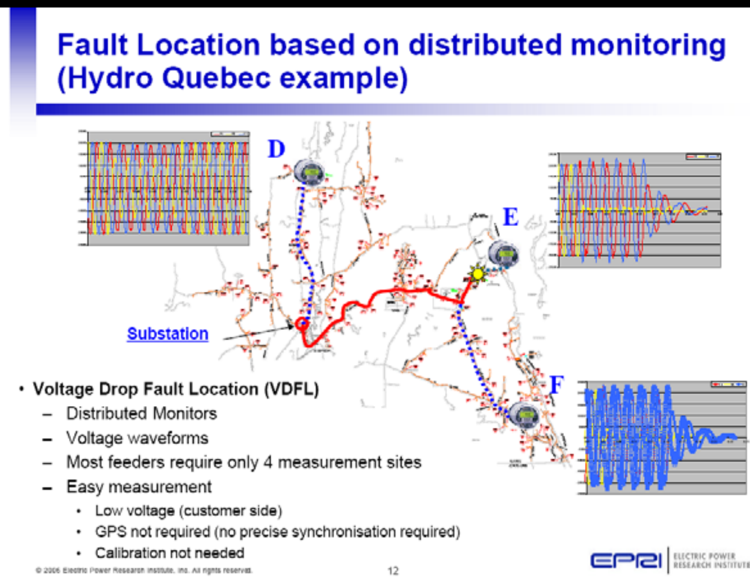
$$E_{dip} = \int_0^T \left(1 - \left[\frac{V(t)}{V_{nom}}\right]^2\right) dt$$

Fault Location by RMS current – main tool

- Determine the average of RMS current during the fault (initial and steady-state portions) duration
- Determine the current index: I_{index}
  - p: predicted value
  - Exp: experimental value
- Compare the current index at several nodes determined by DSFL (by fault current & recloser, etc ?)
- Pick the location where the current index is minimum (i.e., the least error location between model vs actual)

$$\bar{I}_{rms} = \frac{1}{t_f}\int_0^{t_f} I_{rms}\, dt \qquad I_{index} = \sqrt{\left|\frac{1}{2}\sum_k \left[1 - \left(\frac{I^{p}_{rms}}{I^{exp}_{rms}}\right)^2\right]\right|}$$

Example



Other Methods

- Distributed Devices
  – Voltage Sensor matrix
  – Voltage magnitude and phase angle table of all sections and nodes in the network
  – Measured data vs. historical fault data.
- Hybrid Methods
  – Fault distance calculation & Distributed Device Method
- Fault Indicator Methods
- Use of Smart Meters and Smart Grid Communication Infrastructure

References

- L. Nastac and A. Thatte, "Distribution Systems Fault Locator" Electrical Infrastructure Technology, Training and Assessment Program, DOE Technical Report under Cooperative Agreement DE-FC02-04CH11241, September 30, 2006
- L. Nastac, "Advanced Fault Analysis Software (or AFAS) for Distribution Power Systems," Center for Grid Modernization Program, DOE Technical Report under Cooperative Agreement DE-FC02-05CH11298, July 31, 2007.
- Numerous US patents and patent publications