Fault Location Principles

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Presenter

Dr. Murari Mohan Saha was born in 1947 in Bangladesh. He received B.Sc.E.E. from Bangladesh University of Technology (BUET), Dhaka in 1968 and completed M.Sc.E.E. in 1970. During 1969-1971, he was a lecturer at the E.E. dept.,BUET. In 1972 he completed M.S.E.E and in 1975 he was awarded with Ph.D. from The Technical University of Warsaw, Poland. He joined ASEA, Sweden in 1975 as a Development Engineer and currently is a Senior Research and Development Engineer at ABB AB, Västerås, Sweden. He is a Senior Member of IEEE (USA) and a Fellow of IET (UK). He is a registered European Engineer (EUR ING) and a Chartered Engineer (CEng). His areas of interest are measuring transformers, power system analysis and simulation, and digital protective relays. He holds 35 granted patents and produces more than 200 technical papers. He is the co-author of a book, entitled, " Fault location on Power Networks", published by Springer, January 2010.

Contents

- Introduction
- One-end fault location
- Two-end/Multiterminal fault location
- Fault location on distribution networks
- Conclusions
- Information about book on Fault Location

Introduction

Introduction – *What is a Fault Locator?*

- It is a device or apparatus placed at one end of a station, which displays the distance to fault (in km or in % of line) following a fault in a transmission line.
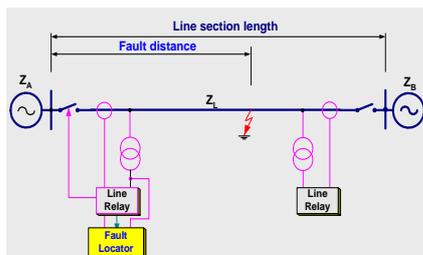
Introduction

- When a fault occurs on a line (*distribution or transmission*), it is very important for the utility to identify the fault location as quickly as possible for improving the service reliability.

- If a fault location cannot be identified quickly and this produces prolonged line outage during a period of peak load, severe economic losses may occur and reliability of service may be questioned.

- All these circumstances have raised the great importance of fault-location research studies and thus the problem has attracted widespread attention among researchers in power-system technology in recent years.

Introduction

- **Fault location** is a process aimed at locating the occurred fault with the highest possibly accuracy.

- **Fault locator** is mainly the supplementary protection equipment, which apply the fault-location algorithms for estimating the distance to fault.

- When locating faults on the line consisting of more than one section, i.e., in the case of a three-terminal or multi-terminal line, the faulted section has to be identified and a fault on this section has to be located.

Introduction

A fault-location function can be implemented into:

- microprocessor-based protective relays

- digital fault recorders (DFRs)

- stand-alone fault locators

- post-fault analysis programs

Introduction

Fault locators *versus* protective relays
– differences related to the following features:

- accuracy of fault location

- speed of determining the fault position

- speed of transmitting data from remote site

- used data window

- digital filtering of input signals and complexity of calculations

Introduction

General division of fault location techniques:

- technique based on fundamental-frequency currents and voltages – mainly on impedance measurement

- technique based on traveling-wave phenomenon

- technique based on high-frequency components of currents and voltages generated by faults

- knowledge-based approaches

- unconventional techniques (*fault indicators – installed either in substations or on towers along the line; monitoring transients of induced radiation from power-system arcing faults – using both VLF and VHF reception*)
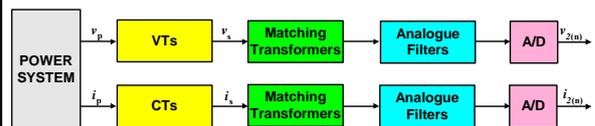
Voltage & Current Measurement Chains

Voltage & Current Measurement Chains

Voltage & Current Measurement Chains

CVT

CT

Voltage & Current Measurement Chains

CVT transformation under a–g fault on transmission line close to the relaying point

Voltage & Current Measurement Chains

Possibility of CT saturation under unfavorable conditions: presence of d.c. component in primary current and remanent flux left in the core
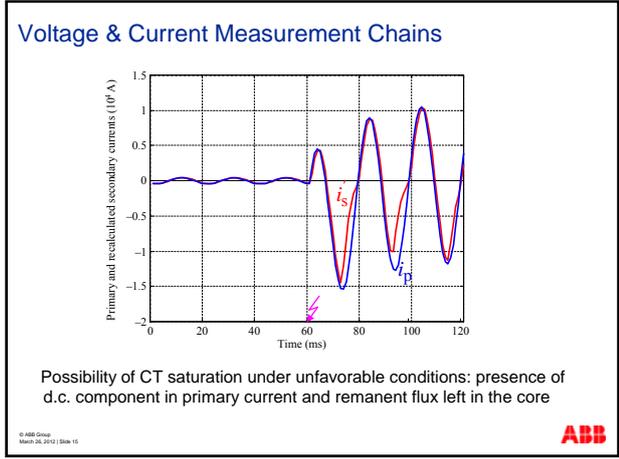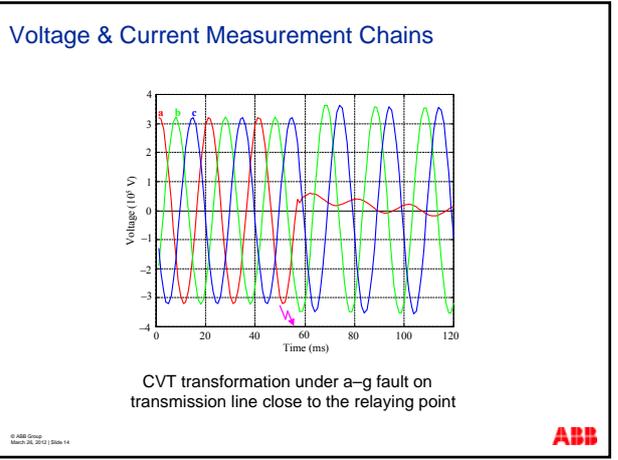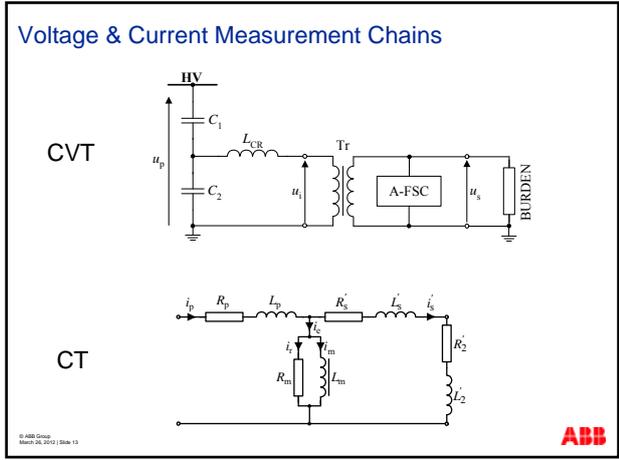
One-end Fault Location

One-end Fault Location – *Error Sources*

- Combined effect of fault resistance R_f and load for ground faults - *"reactance effect"*
- Incorrect fault-type identification
- Mutual coupling
- Line parameter uncertainty, especially zero sequence

One-end Fault Location – *Reactance Effect*

No pre-fault power flow

Pre-fault power flow from A to B

Pre-fault power flow from B to A

Slide 1

**First Stand Alone Numerical
Fault Locator on Commercial Use**

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Slide 2

One-end Fault Location Algorithm Compensating
for Remote End Infeed Effect
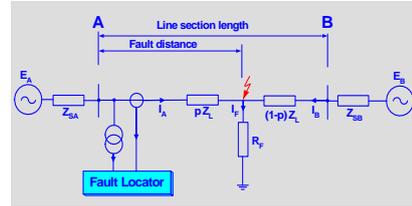
$$U_A = I_A p Z_L + I_F R_F$$

where: $I_F = \dfrac{I_{FA}}{D_A}$ $D_A = \dfrac{(1\text{-}p)Z_L + Z_{SB}}{Z_{SA} + Z_L + Z_{SB}}$

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Slide 3

One-end Fault Location Algorithm Compensating
for Remote End Infeed Effect

$$U_A = I_A p Z_L + \frac{I_{FA}}{D_A} R_F$$
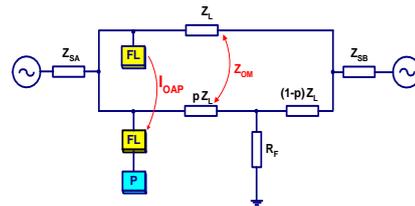
$$\boxed{p^2 - pK_1 + K_2 - K_3 R_F = 0}$$

where:

$$K_1 = \frac{U_A}{I_A Z_L} + 1 + \frac{Z_{SB}}{Z_L}$$

$$K_2 = \frac{U_A}{I_A Z_L}\left(1 + \frac{Z_{SB}}{Z_L}\right)$$

$$K_3 = \frac{I_{FA}}{I_A Z_L}\left(1 + \frac{Z_{SA} + Z_{SB}}{Z_L}\right)$$

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Slide 4

One-end Fault Location Algorithm Compensating for
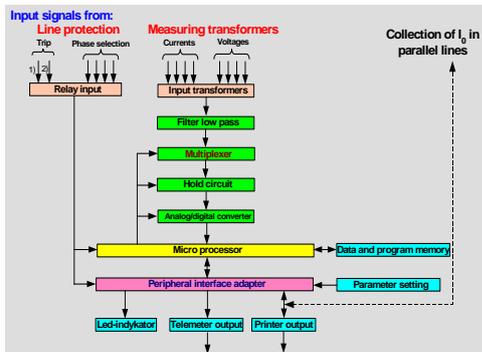Remote End Infeed Effect – *Case of Parallel Lines*

$$U_A = I_A p Z_L + \frac{I_{FA}}{D_A} R_F + Z_{OM} I_{OAP}$$

where: $D_A = \dfrac{(1\text{-}p)(Z_{SA} + Z_{SB} + Z_L) + Z_{SB}}{2Z_{SA} + 2Z_{SB} + Z_L}$

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One-end Fault Location Algorithm Compensating for
Remote End Infeed Effect – *Hardware Configuration*

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Slide 6

One-end Fault Location Algorithm Compensating for
Remote End Infeed Effect – *Field Results Experienced*

Installation	Event	Results
1 Sweden, 130 kV, 76 km	P-E fault, July 1982 67.0 km	67.6 km (error 0.8%)
2 USA, 138 kV, 23.3 km	Five staged faults on parallel lines, October 1983	Maximum error of 3% (without compensat.)
3 Spain, 400 kV, 135 km	P-E fault, March 1984 93 to 99% of line	Displayed in the range 93 to 99%
4 Italy, 380 kV, 88.5 km	P-E fault, February 1984 16% of line	16 % (no error)
5 Norway, 45 kV, 29.3 km	P-P fault, December 1984 77% of line	77% (error 0.5%)
6 Finland, 110 kV, 130 km	P-E faults, June 1985 78 to 90% of line	Displayed in the range 78 to 90% (error max 0.4%)
7 India, 400 kV, 236 km	P-E faults, December 1987 76 to 78% of line	(no error)

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Slide 1

Optimization of One-end Fault Location

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Slide 2

Optimization of One-end Fault Location
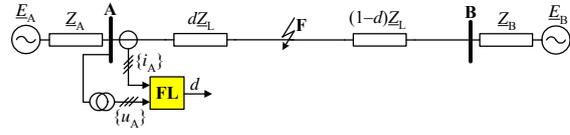
Aim:
- improving fault location accuracy by introducing compensation for shunt capacitances
- limiting influence of uncertain parameters on fault location accuracy
- to get simple formulae by applying generalized fault loop model and fault model

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Slide 3

Optimization of One-end Fault Location

Symmetrical components approach appears as very effective technique for transposed lines and fault location algorithm is formulated in terms of these components (positive-, negative- and zero-sequence)

$$\begin{bmatrix} \underline{V}_{A0} \\ \underline{V}_{A1} \\ \underline{V}_{A2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \underline{a} & \underline{a}^2 \\ 1 & \underline{a}^2 & \underline{a} \end{bmatrix} \cdot \begin{bmatrix} \underline{V}_{Aa} \\ \underline{V}_{Ab} \\ \underline{V}_{Ac} \end{bmatrix}$$

$$\underline{a} = \exp(j2\pi/3)$$

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Optimization of One-end Fault Location

Generalized fault loop model:

$$\boxed{\underline{U}_{A\_P} - d\underline{Z}_{1L}\underline{I}_{A\_P} - R_F(\underline{a}_{F1}\underline{I}_{F1} + \underline{a}_{F2}\underline{I}_{F2} + \underline{a}_{F0}\underline{I}_{F0}) = 0}$$

d, R_F – unknown distance to fault (p.u.) and fault resistance

$\underline{U}_{A\_P}$, $\underline{I}_{A\_P}$ – fault loop voltage and current (*dependent on fault type*)

$\underline{Z}_{1L}$ – line impedance for the positive-sequence

$\underline{I}_{F1}, \underline{I}_{F2}, \underline{I}_{F0}$ – symmetrical components of the ttotal fault current

$\underline{a}_{F1}, \underline{a}_{F2}, \underline{a}_{F0}$ – weighting coefficients (*dependent on fault type*)

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Optimization of One-end Fault Location

Fault loop voltage and current (*in terms of symmetrical components*):

Fault loop voltage:
$$\boxed{\underline{U}_{A\_P} = \underline{a}_1\underline{U}_{A1} + \underline{a}_2\underline{U}_{A2} + \underline{a}_0 U_{A0}}$$

Fault loop current – single line:
$$\boxed{\underline{I}_{A\_P} = \underline{a}_1\underline{I}_{A1} + \underline{a}_2\underline{I}_{A2} + \underline{a}_0 \frac{\underline{Z}_{0L}}{\underline{Z}_{1L}}\underline{I}_{A0}}$$

Fault loop current – parallel lines:
$$\boxed{\underline{I}_{A\_P} = \underline{a}_1\underline{I}_{AI1} + \underline{a}_2\underline{I}_{AI2} + \underline{a}_0\left(\frac{\underline{Z}_{0LI}}{\underline{Z}_{1LI}}\underline{I}_{AI0} + \frac{\underline{Z}_{0m}}{\underline{Z}_{1LI}}\underline{I}_{AII0}\right)}$$

$\underline{a}_1, \underline{a}_2, \underline{a}_0$ – share coefficients (*dependent on fault type*)

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Slide 6

Optimization of One-end Fault Location

Total fault current can be expressed as the weighted sum of its symmetrical components:

$$\boxed{\underline{I}_F = \underline{a}_{F0}\underline{I}_{F0} + \underline{a}_{F1}\underline{I}_{F1} + \underline{a}_{F2}\underline{I}_{F2}}$$

$\underline{a}_{F0}, \underline{a}_{F1}, \underline{a}_{F2}$ – weighting coefficients (complex numbers), dependent on fault type and the assumed priority for using particular symmetrical components,

$\underline{I}_{F0}, \underline{I}_{F1}, \underline{I}_{F2}$ – zero-, positive- and negative-sequence components of total fault current, which are to be calculated or estimated

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Optimization of One-end Fault Location

Fault location formula:

$$\underline{A}_2 d^2 + \underline{A}_1 d + \underline{A}_0 + \underline{A}_{00} R_F = 0$$

After resolving into real/imag parts the unknowns: d, R_F are determined

$\underline{A}_2 = \underline{K}_1 \underline{Z}_{1L}$

$\underline{A}_1 = \underline{L}_1 \underline{Z}_{1L} - \underline{K}_1 \underline{Z}_{A\_P}$

$\underline{A}_0 = -L_1 \underline{Z}_{A\_P}$

$\underline{A}_{00} = \dfrac{(\underline{a}_{F1}\Delta \underline{I}_{A1} + \underline{a}_{F2}\underline{I}_{A2})\underline{M}_1}{\underline{I}_{A\_P}}$

Optimization of One-end Fault Location

Compensation for shunt capacitances of the line:

$$\underline{U}_{A\_P} - d_{(n)}\underline{Z}_{1L}\left(\underline{a}_1\underline{A}^{sh}_{1(n-1)}\underline{I}^{comp}_{A1} + \underline{a}_2\underline{A}^{sh}_{2(n-1)}\underline{I}^{comp}_{A2} + \underline{a}_0\underline{A}^{sh}_{0(n-1)}\dfrac{\underline{Z}_{0L}}{\underline{Z}_{1L}}\underline{I}^{comp}_{A0}\right) - R_{F(a)}(\underline{a}_{F1}\underline{I}^{comp}_{F1} + \underline{a}_{F2}\underline{I}^{comp}_{F2} + \underline{a}_{F0}\underline{I}^{comp}_{F0}) = 0$$

$\underline{I}^{comp}_{A1} = \underline{I}_{A1} - 0.5 d_{(n-1)}\ell\underline{Y}'_{1L}\underline{A}^{th}_{1(n-1)}\underline{U}_{A1}$
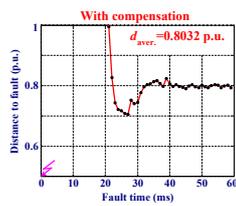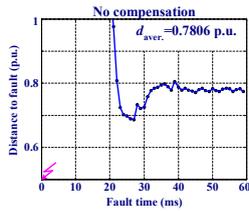
$\underline{I}^{comp}_{A2} = \underline{I}_{A2} - 0.5 d_{(n-1)}\ell\underline{Y}'_{2L}\underline{A}^{th}_{2(n-1)}\underline{U}_{A2}$

$\underline{I}^{comp}_{A0} = \underline{I}_{A0} - 0.5 d_{(n-1)}\ell\underline{Y}'_{0L}\underline{A}^{th}_{0(n-1)}\underline{U}_{A0}$

Optimization of One-end Fault Location

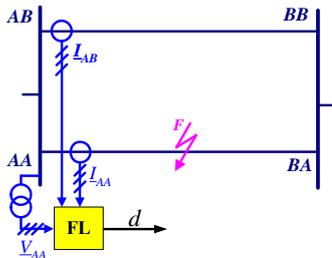Example: 400kV, 300km line; a-g fault, d=0.8 pu, R_F=10 Ω

Due to compensation the error decreases from 1.94% to 0.32%

Fault Location on Parallel Lines with measurements at one-end

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Fault Location on Parallel Lines under Availability of Complete Measurements at One End

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Fault Location on Parallel Lines under Availability of Complete Measurements at One End

- Traditional one-end FLs for parallel lines apply the following standard input signals:
  - phase voltages
  - phase currents from the faulted line
  - zero-sequence current from the healthy line (to compensate for the mutual coupling)

- Limitationss of the traditional one-end FLs:
  - pre-fault measurements are required
  - remote source impedance data has to be provided
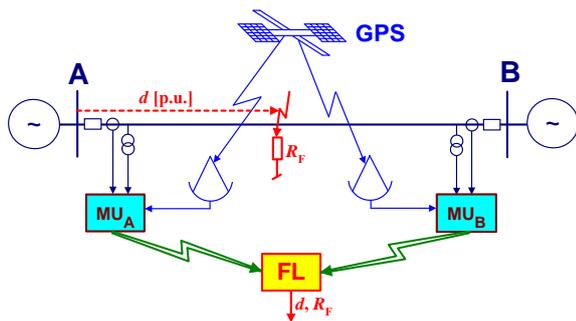
Two-end Fault Location

Two-end Fault Location

- One-terminal methods have some limitations due to necessity of taking simplifying assumptions

- Two-Terminal methods give better results but require communications
  - Methods using Global Positioning Satellites (GPS)
    - synchronized phasors from both ends
  - Methods requiring time-tagging of events
    - no synchronized phasors
- Low-speed communications needed for two-end fault location
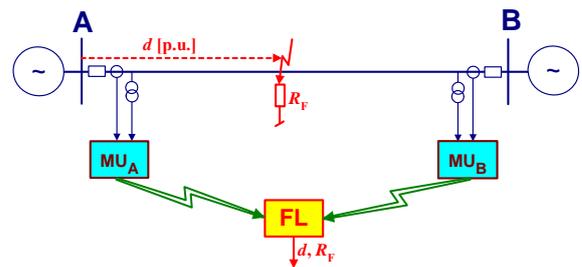- Analyze data from two ends at a third, more convenient site

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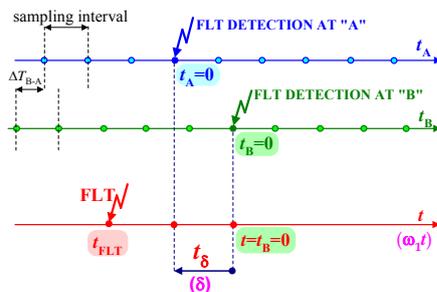## Two-end Fault Location – *Synchronized Measurements*

Two-end Fault Location – *Unsynchronized Measurements*

Two-end Fault Location – *Unsynchronized Measurements*

Need for phase alignment:

Two-end Fault Location – *use of incomplete measurements*

- Use of incomplete two-end measurements:

- two-end currents and one-end voltage ($2 \times I + 1 \times V$)

- one-end current and two-end voltages ($1 \times I + 2 \times V$)

- two-end voltages ($2 \times V$)

- two-end currents ($2 \times I$)

Two-end Fault Location – *use of:* 2x*I* +1x*V*

- Fault location (FL) function added to current differential relay
- Use of two-end synchronised measurements of three-phase currents and additionally providing the local three-phase voltage
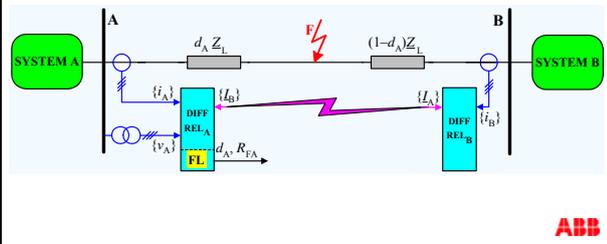
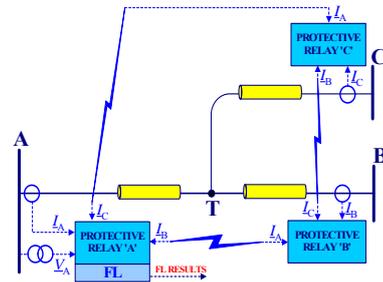## Two-end Fault Location – *use of:* 1x*I* +2x*V*

Immunity of fault location to saturation of CTs at one line side is assured by rejecting currents from saturated CTs
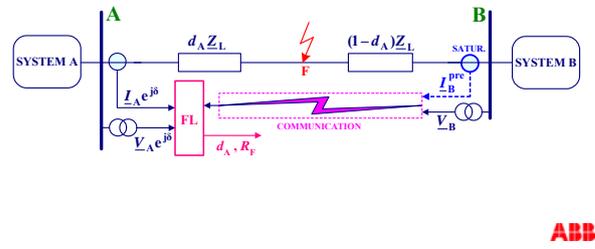
Three-end & Multi-end Fault Location
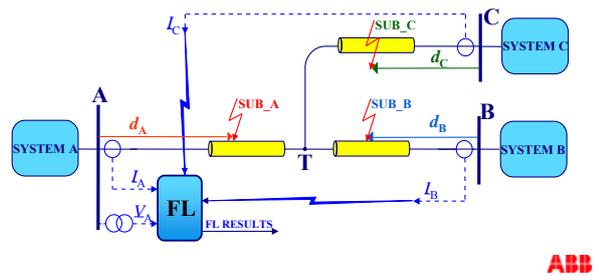
Three-end Fault Location

- Use of measurements:
    - synchronized three-phase currents from all (A, B, C) ends
    - three-phase voltage at Fault Locator bus A

Solution

- **Fault location algorithm consists of three subroutines (SUB_A, SUB_B, SUB_C) and the procedure for selecting the valid subroutine**

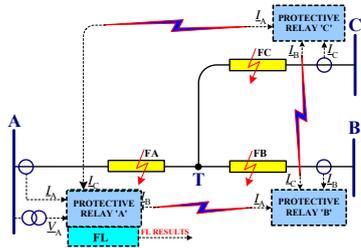## Selection of faulted line section

General algorithm:

1. **Fault distance calculation assuming the fault to be on the AT, TB or TC segment: 3 different results**
2. **Selection procedure is based on checking the rejection conditions:**
    - fault occurring outside the section range
    - calculated fault resistance has negative value
    - correctness of the estimated remote source impedances
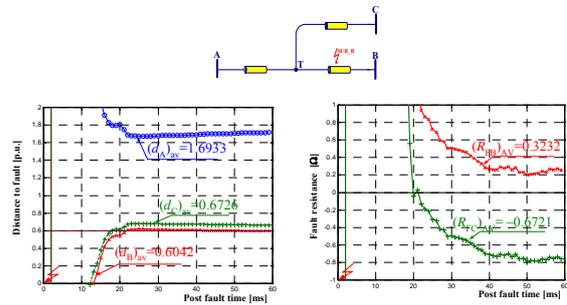
Fault Location Example

- **Network parameters:**
  - Line: $\underline{Z}'_{1L} = (0.0276 + j0.3151)$, $\underline{Z}'_{0L} = (0.275 + j1.0265)$ (Ω/km)
    $C_{1L} = 0.012\,\mu F/km$ $C_{0L} = 0.008\,\mu F/km$
  - System A: $\underline{Z}_{iSA} = (0.65125 + j3.693)\,\Omega$ $\underline{Z}_{0SA} = (1.159 + j6.5735)\,\Omega$
  - System B: $\underline{Z}_{iSB} = 2\underline{Z}_{iSA}$
  - System C: $\underline{Z}_{iSB} = 3\underline{Z}_{iSA}$

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Fault Location Example (1)

- a-g fault at the section TB, d_B=0.6 p.u., R_{FC}=0.3Ω
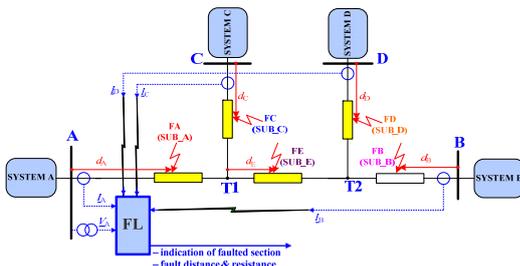

- **SUB_B** is selected as valid one

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Four-end Fault Location

- Use of measurements:
  - synchronized three-phase currents from all (A, B, C, D) ends
  - three-phase voltage at Fault Locator bus A

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Fault Location in Distribution (Medium Voltage) Networks

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Introduction

- Fault location in MV networks differs from that in HV/EHV transmission lines
- When a current of a faulty line is not directly available in the FL, certain error is introduced when assumed the current at the substation
- MV line may be multi-terminal and/or contain loops what creates problem in single ended fault location
- In the case of MV line, there are often loads located between fault point and the busbar. Since the loads change and are unknown to the FL it is difficult to compensate of them

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Issues for Distribution Networks

- Network grounding
  - ungrounded networks
  - Peterson's coil
  - resistance grounded
- Lack of measured data for tapped loads
  - fault on a main or on a tap?
- Unbalanced network configuration and load
- Dynamic change in a network configuration
- Change in conductor impedance
- Multiple faults

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Algorithm Structure

Digital Fault Recorder
or
EMTP/ATP simulator

currents   voltages

Estimation of the impedance

impedance

Estimation of the distance

Which feeder short-circuited? Information from relays and/or CBs

distance

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Fault-Loop Impedance Measurement

Z_1

Z_2

Z_k

Z_m

$$\underline{I}_k = \begin{bmatrix} \underline{I}_{kA} \\ \underline{I}_{kB} \\ \underline{I}_{kC} \end{bmatrix}$$

$$\underline{V}_k = \begin{bmatrix} \underline{V}_{kA} \\ \underline{V}_{kB} \\ \underline{V}_{kC} \end{bmatrix}$$
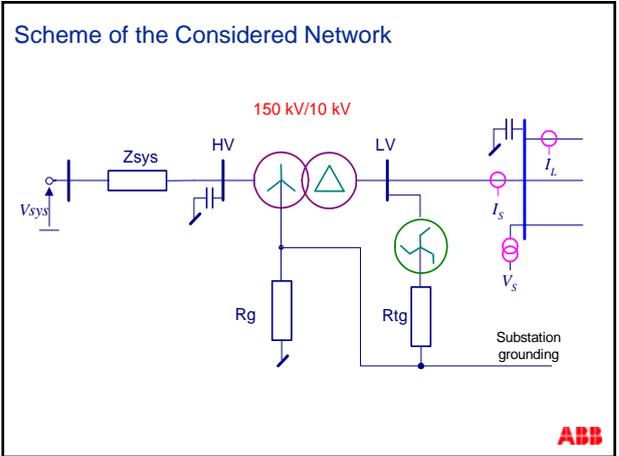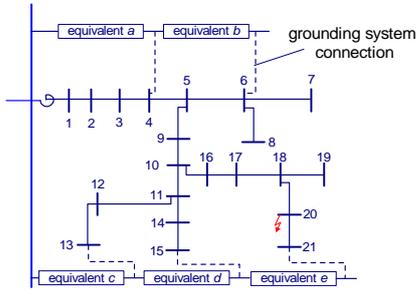
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Impedance Measured at the Faulty Feeder

Phase-phase fault loop:

$$\underline{Z}_k = \frac{\underline{V}_{pp}}{\underline{I}_{kpp}}$$

$$\underline{I}_{kpp} = \underline{I}_{kA} - \underline{I}_{kB}$$

$$\underline{V}_{pp} = \underline{V}_A - \underline{V}_B$$

Phase-ground fault loop:

$$\underline{Z}_k = \frac{\underline{V}_{ph}}{\underline{I}_{kph} + \underline{k}_{kN}\underline{I}_{kN}}$$

$$\underline{k}_{kN} = \frac{\underline{Z}_0 - \underline{Z}_1}{3\underline{Z}_1}$$

$$\underline{I}_{kN} = \underline{I}_{kA} + \underline{I}_{kB} + \underline{I}_{kC}$$

$\underline{Z}_0$, $\underline{Z}_1$ — **Fault-loop impedances for fault at the considered node**

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Distance to Fault Estimation

Equivalent diagram of the cable segment with fault:

k-1 $l_{fk-1}Z_{sk-1}$ $(1-l_{fk-1})Z_{sk-1}$ k

Z_{pk-1} R_f Z_{pk}

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EMTP/ATP simulation with an Utility Network

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Scheme of the Considered Network

150 kV/10 kV

Zsys   HV   LV I_L

Vsys

Rg   Rtg I_S

V_S

Substation grounding

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Scheme of Distribution Network

Idea of the feeder model representation:

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Distance to Fault Calculation – *from the Recorded Data*

Current measured at the faulty feeder: **Feeder 2.08**

No	File	Fault type	Estimated Distance to Fault, m	
1	97031400.MAT	A-B	GAMR-RURW	- 8867 m
			GAMR-BJCG	- 8935 m
2	97031401.MAT	A-B	BETR-GAMR	- 8491 m
3	97031402.MAT	A-B	GAMR-RURW	- 8880 m
			GAMR-BJCG	- 8918 m
4	97031403.MAT	A-G	GAMR-RURW	- 8780 m
			GAMR-BJCG	- 8776 m
5	97031404.MAT	A-G	BETR-GAMR	- 8431 m

Actual fault at 8999 m

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Distance to Fault Calculation – *from the Recorded Data*

Current measured at the substation: **Feeder 2.08**

| No	File	Fault type	Estimated Distance to Fault, m	
1	97031400.MAT	A-B	GAMR-RURW	- 8854 m
			GAMR-BJCG	- 8762 m
2	97031401.MAT	A-B	GAMR-RURW	- 8745 m
			GAMR-BJCG	- 8755 m
3	97031402.MAT	A-G	GAMR-RURW	- 8776 m
			GAMR-BJCG	- 8772 m
4	97031403.MAT	A-G	GAMR-RURW	- 8897 m
			GAMR-BJCG	- 8889 m

Actual fault at 8999 m

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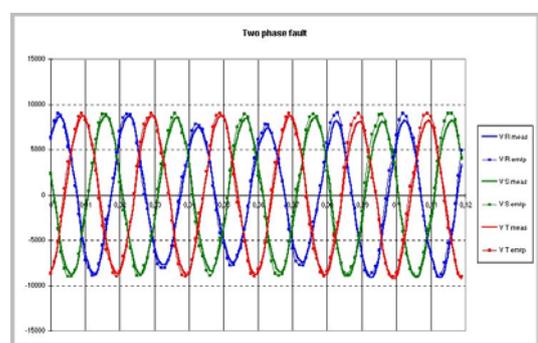## Comparison of EMTP/ATP simulation with recorded Stage Fault

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EMTP Simulation: *Comparison with Recorded Stage Fault*

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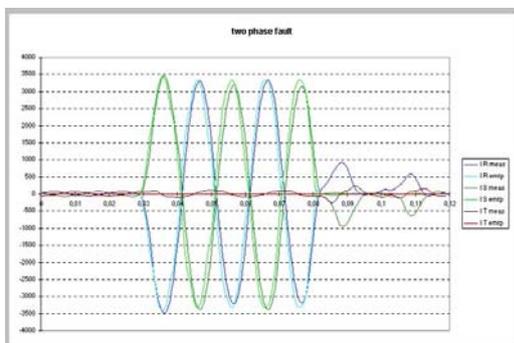
EMTP Simulation: *Comparison with Recorded Stage Fault*

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Conclusions


Conlusions – *Benefits of Fault Location*

- **Quick elimination of permanent fault to:**
  - minimize outage time
  - facilitate service and maintenance
  - minimize production losses
  - reduce cost
- **Pinpointing of weak spots due to temporary fault to:**
  - assist patrol in finding excessive tree growth
 - allow rapid arrival at the site of vandalism

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Conclusions

- Accurate fault location is key to improved operations and lower maintenance cost
- Selection of a fault location method depends on network configuration, communications, and requirements
- One-terminal methods have limited accuracy
- Two-terminal methods give higher accuracy
- Analysis at convenient site using data from existing µP devices
- The fault location algorithm can easily be expanded to cover lines with three-terminals and even more
- Fault location algorithm for Medium Voltage Network is based on voltage and current phasor estimation. The algorithm was investigated and proved on the basis of voltage and current data obtained from EMTP/ATP simulations as well as recorded at DFR experiences

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power systems

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Fault Location on Power Networks
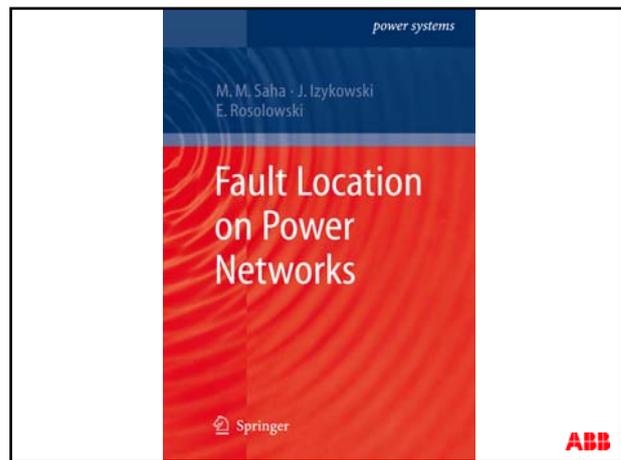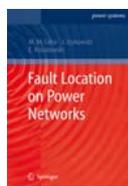
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Fault Location On Power Networks

- Fault Location on Power Lines enables readers to pinpoint the location of a fault on power lines following a disturbance.
- The nine chapters are organised according to the design of different locators. The authors have compiled detailed information to allow for in-depth comparison.
- Fault Location on Power Lines describes basic algorithms used in fault locators, focusing on fault location on overhead transmission lines, but also covering fault location in distribution networks.
- An application of artificial intelligence in this field is also presented, to help the reader to understand all aspects of fault location on overhead lines, including both the design and application standpoints.
- Professional engineers, researchers, and postgraduate and undergraduate students will find Fault Location on Power Lines a valuable resource, which enables them to reproduce complete algorithms of digital fault locators in their basic forms.

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