Fault Indicators

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**Grounding Conditions**

- Affects the fault current

  - Directly connected
  - Through a resistor
  - Through a coil
  - Through a resistor and coil in parallel
  - Isolated from ground

**Ungrounded Network**

Three-Phase Simplified Representation of an Ungrounded Network

\[
I_{AC} + I_{BC} + I_{CL} + I_{AS} + I_{BS} + I_{CS} = 0
\]

\[
3I_{CL} = I_{AS} + I_{BS} + I_{CS} = \frac{-I_{AS} + I_{BS} + I_{CS}}{3}
\]

\[
I_{F} = I_{AC} = \frac{-I_{AS} + I_{BS} + I_{CS}}{3}
\]
Ungrounded Network – Sequence Analysis

Forward Fault
(Sf closed)

\[ V_o = I_o \cdot (-jX_{CS}) = jX_{CS} \cdot I_o \]

Therefore, for forward fault: \[ Z_o = V_o / I_o = +X_{CS} \]

Reverse Fault

Reverse Fault (Fault at the remaining system)

\[ -V_o = -I_o \cdot (Z_{OL} - jX_{CL}) = -I_o \cdot Z_{OL} + jX_{CL} \cdot I_o \]

\[ V_o = -jX_{CL} \cdot I_o \]

Considering \( X_{CL} >> Z_{OL} \)

Therefore, for reverse fault: \[ Z_o = V_o / I_o = -X_{CL} \]
Zero-Seq Impedance Plane Directional Element

Fault Detection/Direction Method for Compensated Networks

- Voltage Detection
  - Zero-Sequence Voltage ($V_0$)
  - Phase-to-Ground Voltage
  - Incremental Zero-Sequence Voltage ($\Delta V_0$)
- Wattmetric Method (Real Current)
- Zero Sequence Directional Relay Approach
- Conductance Method
Zero Sequence Directional in I₀ and V₀ Plane

- Zero-Sequence Directional Relay – classical solution

Forward Fault dependence on grounding type
Compensated System Network – Analysis

Patented Idea

- **United States Patent**
  - Roberts et al.
  - Patent No.: US 6,573,726 B1
  - Date of Patent: Jun. 3, 2003

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**ABSTRACT**

What is claimed is:

1. A system for detecting ground faults in a compensated distribution network, comprising:
   - means for determining the zero sequence voltage \( V_0 \) and zero sequence current \( I_0 \) on a power line;
   - a calculation system for calculating therefrom a conductance or resistance value from the real parts of said zero sequence voltage and zero sequence current;
   - a circuit for enabling the operation of the calculation system for only predescribed power line conditions; and
   - means for comparing the conductance or resistance value against a first threshold value to determine a forward fault and a second threshold value to determine a reverse fault.

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* cited by examiner

Primary Examiner—Sedat Mejajbic
Assistant Examiner—Lucene LeRoux
Attorney, Agent, or Firm—Jensen & Pentagam, PS.
Single-Line and Sequence Diagrams

Compensated Network (Forward Fault)

Forward Fault Case:

\[ Z_N = \frac{j \omega L_N}{R_w + j \omega L_N} \]

\[ Z_s = \frac{-j}{\omega C_s} \]

\[ V_0 = -I_o \left( \frac{Z_s}{Z_N + Z_s} \right) \]

\[ Z_N = \frac{3R_f \omega L_N}{3R_W + j \omega L_N} \]

\[ Z_s = \frac{R_s}{j \omega C_s} \]

\[ V_0 = -I_o \left( \frac{Z_s}{Z_N + Z_s} \right) \]

\[ I_o = -V_0 \left[ \left( \frac{1}{R_o + \frac{1}{3R_W}} \right) + j \left( \omega C_s - \frac{1}{3\omega L_N} \right) \right] \]
Compensated Network (Reverse Fault)

Reverse Fault Case:

\[ I_o = \frac{V_o}{R_{DL}} + j\omega C_{DL} \] (Reverse Fault)

\( R_N = \frac{1}{L_N} \) in forward fault:

\[ I_o = -V_o \left[ \frac{1}{R_{LS}} + j\omega C_{LS} \right] \]

\[ = -V_o \left[ \frac{1}{R_{LS}} + j\omega C_{LS} \right] \]

Directionality Phasor Diagram

Phasor Diagram

\[ I_o \]

\[ V_o \]

\[ I_o \] (Reverse)

\[ I_o \] (Forward)

Uncompensated
Sequence Current Phase-Change Method

- Phase voltage and current

Zero-Sequence Phase Change

- Fault Direction
Fault Direction Indicator

PTG FAULT AND ANALYZING OF THE DIRECTION

If the PTG fault occurs 'upstream' the LineTroll 3500 we may have residual figures as shown in the next figure.

FI

PTG FAULT AND ANALYZING OF THE DIRECTION

If the PTG fault occurs 'downstream' the LineTroll 3500 we may have residual figures as shown in the next figure.
Wattmetric Relay Element

\[ W = \Re \{ V_o \cdot I_o^* \} = V_o I_o \cos \phi \]

- Has been used for many years for compensated networks.
- Simple, secure, dependable (for low resistance faults)
- The requirement of sensitive detection of \( V_o \) is a limit for high resistance faults.
- Dependent on CT accuracy

Real Current Component Method

- Determination of voltage sag source by the phase angle difference between current and voltage.
- Two Source System at Pre-fault condition
At Fault Condition

Equivalent Circuit (R_f=0)

\[ \vec{V} = \vec{E} - \vec{I} \cdot \vec{Z} \]
\[ \vec{I}^* M_A = \vec{E}_I \cdot \vec{I}^* - \vec{I} \cdot \vec{Z} \]

Real Part: \[ V I \cos(\theta - \alpha) = E_i I \cos(\gamma - \alpha) - I^2 R_1 \]

\( \theta \): phase angle for voltage @ M_A
\( \alpha \): phase angle of current @ M_A

Downstream: \( I \cos(\theta - \alpha) > 0 \), Power flow →
Upstream: \( I \cos(\theta - \alpha) < 0 \), Power flow ←
Phase Current Phasor Change Approach - Principle

- A directional relay algorithm for radial systems using current signals only – phasor change in current between normal and fault
- The direction of a fault can be determined by finding the difference in angle of positive-sequence current phasors from fault and pre-fault data.
- Voltage information (at the relay point) is required.

Phase Current Phase Change Approach - Example

Single-phase radial distribution system.

$\vec{I}_2 = \frac{V_A - V_C}{Z} + \frac{V_A}{Z^2}$

Different current waveforms at the secondary of CT.
How about this patented method?

United States Patent [19] [38] Patent Number: 5,796,259

Dickmander

Primary Examiners—Glenn W. Brown
Attorneys, Agent, or Firm—Woodcock Washburn Kirtz Mackiewicz & Norris LLP

ABSTRACT

Generally, the invention determines fault direction based on observations of the voltage and current conditions at the fault incepion instant. More particularly, the invention determines that fault direction is downstream if at the fault instant the polarity of the current deviation between the present cycle and the prior cycle is in the same direction as the measured voltage. For example, if the voltage has a positive polarity, a downstream fault will cause the present cycle current to deviate from the prior cycle current in the positive direction. If the voltage has a negative polarity, a downstream fault will cause the present cycle current to deviate from the prior cycle current in the negative direction.

TABLE I

CURRENT PHASOR DATA FOR SINGLE-PHASE SYSTEM, FAULT AT 0.1 s

<table>
<thead>
<tr>
<th>Fault</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mag</td>
<td>11.6</td>
<td>11.9</td>
<td>11.9</td>
</tr>
<tr>
<td>Angle (rad)</td>
<td>0.25</td>
<td>-2.11</td>
<td>0.43</td>
</tr>
<tr>
<td>Mag</td>
<td>10</td>
<td>10.1</td>
<td>10.1</td>
</tr>
<tr>
<td>Angle (rad)</td>
<td>1.34</td>
<td>1.34</td>
<td>1.34</td>
</tr>
</tbody>
</table>

TABLE II

CURRENT PHASOR DATA FOR THE SINGLE-PHASE SYSTEM, FAULT AT 0.11 s

<table>
<thead>
<tr>
<th>Fault</th>
<th>F1</th>
<th>F2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mag</td>
<td>11.6</td>
<td>11.9</td>
</tr>
<tr>
<td>Angle (rad)</td>
<td>-2.09</td>
<td>0.43</td>
</tr>
<tr>
<td>Mag</td>
<td>10</td>
<td>10.1</td>
</tr>
<tr>
<td>Angle (rad)</td>
<td>1.80</td>
<td>1.80</td>
</tr>
</tbody>
</table>
**Electric/Magnetic Field of Transient Wave from Earth Fault**

- Discharging/Recharging transients during the initiation of the fault are used to detect the direction to the fault in compensated and isolated networks.
- Peterson coil acts as high impedance to the transients, making the transients intact, not affected.
- E (~voltage)
- B (~Current)

**Transient Measurement**

- Earth fault traveling wave has long been recognized for fault detection.
- Utilized by so-called "Wischer relay" (Transient Measurement) when all other detection methods have failed in compensated networks.
- Indicator: transients due to phase-to-ground fault. Redistribution of the phase-to-ground voltage is forced throughout the whole system.
- Make use of slower subsequent transient oscillations.
- Two types of transients
  - Discharge Transient (of the faulty conductor)
  - Recharging Transient (of the healthy conductor)

A transient-based directional function is already available in SIEMENS 7SN71 relay. The behaviour of this static non digital relay can be summarized as follows:
- startup condition: a fault is detected if 50Hz mono-sequence voltage is present for more than 70 milliseconds.
- directional checking: basically, the directional function relies on the transient behaviour of the mono-sequence voltage and current after the fault inception; indeed, the fault direction is determined by the sign of the power flow $\mathcal{P}_{\mathcal{E},\mathcal{B}}$ during the first alternating of the induced transients.
**Discharging Transient**

- Discharging transient
  - On faulty conductor
  - Charge is drained off
  - Ground is conducted to its entire length
  - Initial part of this charge is the traveling wave that passes along the faulty conductor and discharges it to ground.
  - The termination of the line ends determines the degree of reflection and damping
  - This transient is effectively damped out by skin-effect in cables and lines and by the load of the connected distribution transformer along the line.

**Recharging Transient**

- Recharging transient
  - Recharging of the healthy conductors
  - The transport of the charge from the ground to the healthy conductors is established through the inductance/windings of connected equipment (transformers).
  - This becomes much lower frequency than the discharging transient
  - This charge will initiate a damped oscillation into the steady state fault situation.

![Equivalent circuit for the recharging transient](image)
A new measurement method for a FI

- Electromagnetic field below the line (in order to distinguish faults from other switching operations.)
  - Horizontal component of magnetic field (substitute for zero sequence current)
  - Vertical component of electric field (substitute for zero sequence voltage)
- Contribution from each conductor is summed up to calculate the total electric field and magnetic field in the position of the fault indicator.

Fault Indication/Direction

- Comparison of the polarity between the measured voltage (vertical component of electrical field: Ey) and current transient (horizontal component of flux density: Bx).
- If the two transients are in phase, the fault is considered to be a forward fault (downstream if the indicator is facing the feeder), and if the two transients are in opposite phase, the fault is considered a backward fault (upstream).
Field Test

MA1: I_c = 5.6A
GR1: I_c = 3.3A
EK1: I_c = 6.8A
SK1: I_c = 16.7A

22 kV
66kV

Measurement/Simulation at Fault Site

Measured

Simulated

V_p

V_o

I_f

Forward Fault

Question mark
Surge Based Direction Discrimination

**Surge (Traveling Wave) Based Scheme**

- Use of high frequency components to determine the faulty section of an overhead power distribution feeder.
- Try to determine the faulty section of a distribution system by detecting fault-induced high frequency components on the line.
- **Principle**
  - Tuned Circuits to receive high frequency components on the line due to faults (Stack Tuners)
    - High-Z for power frequency
    - Effective Impedance that matches the line characteristic impedance at the center frequency
  - Line trap that is tuned at the center frequency so that it becomes a virtual short circuit at the frequency
    - Impedance Zt at the center frequency
Locator Arrangement

Details of the Stack Tuners

• Stack Tuners
  – At center frequency = 90kHz, the stack tuner has about 500 ohm, which is close to the typical 11kV characteristic impedance
  – The shunt path formed by each stack tuner correctly terminates the line
  – Ensures that standing wave patterns at the centre frequency are minimized.
  – The impedance of each stack tuner rises rapidly outside the narrow band of frequencies around the center frequency
  – Each stack tuner is an open circuit at power frequency.
Details of the Line Trap

- Frequency response such that, its impedance peaks at a value approaching 10 kohm at the centre frequency.
- The line trap circuit at the centre frequency, acts as an attenuator.
- Its impedance falls to a very low value at or around power frequency (of order of 0.03 ohms at 50 Hz).
- Completely transparent at power frequency but otherwise acts as a barrier between each stack tuner circuit at the center frequency.
- Frequencies outside the band immediately adjacent to the center frequency provide a voltage transfer ratio of almost unity.

Operation Principle

\[ |V_X| - |V_Y| = +ve \text{ quantity, upstream} \]
\[ |V_X| - |V_Y| = -ve \text{ quantity, downstream} \]
Decision Logic

Simulation

• Data
  – The source was represented by a simple lumped equivalent circuit with parameters set to produce a given symmetrical short circuit level at the bus-bar and a reactance to a resistance ratio of 30 at power frequency (50Hz).
  – The ratio of the source zero to positive sequence impedance is unity and the equivalent power frequency impedance of the line is
    • 0.54 + j0.64 ohms per Km (positive phase sequence)
    • 0.69 + j2.02 ohms per Km (zero phase sequence)
  – The sampling frequency was set at approximately 200 kHz thereby enabling the response of the locator to be examined for a center frequency of 90 kHz.
Simulation Results

Fault Discrimination
Operational Variables

• Type of faults
• Fault resistance
• Fault Inception Angle
• Short Circuit Capacity of Bus-Bar (kVA level)

Suggested Works
– PSpice Simulation
– Matlab/Simulink
– MathCad Practice

Reference