Ground-Fault Protection, Charging Current, NGR Selection and Monitoring
Agenda

- Ground-Fault Protection
  - System grounding review
  - Ground-fault detection
  - Harmonic currents
  - Relay coordination

- Charging Current
  - Sympathetic tripping
  - Tripping Ratio

- Neutral-Grounding Resistor (NGR) Selection

- NGR Monitoring
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- NGR Monitoring
What is a ground fault?

A ground fault is an unintentional connection between an energized conductor and ground.
What is a ground fault?

15 A

Black

White

Green

Toaster
What is not a ground fault?

Toaster

15 A

Black

White

Green

I_{FAULT}
Types of System Grounding

- Ungrounded
- Directly / Solidly Grounded
- Resonance Grounded
- Resistance Grounded
Ungrounded AC System

Distributed capacitance of electrical system
Ungrounded AC System – No Ground-Fault Current

Ground Fault
Ungrounded AC System – Phase-to-Ground-to-Phase Fault

Ground Fault

LOAD
Uninterruptable Process

- Industries include
  - Petrochemical
  - Steel mills
  - Glass and ceramics
  - Older industrial plants
  - Facilities with critical processes that require continuous operation
Ungrounded AC System – Ground-Fault Detection

EL3100 Ground-Fault & Phase-Voltage Indicator
Ungrounded AC System – Ground-Fault Detection

PGR-3200
Ground-Fault Protection System

PGA-0510
Analog Ohmmeter
Phase-Voltage Indication Lights

Typical three-phase ground-fault indication scheme used on an ungrounded system
Point-of-Fault Location

Insulation Monitor’s Measuring Signal
Point-of-Fault Location
Ungrounded AC System Phase Voltages – Normal vs Faulted Operation

**NO FAULT**

- All phases are at line-to-neutral voltage above ground (e.g.: 347V)
- Neutral point established by distributed capacitance

**OPERATION WITH A GROUND FAULT**

- Phase C at ground potential
- No fault current (no return path to source)

**A & B phases are at line-line voltage above ground**

(e.g.: 600V)

**A & B phases are 6 to 8 times line-line voltage above ground**

**OPERATION WITH A RE-STRIKING GROUND FAULT**

- Phase C > ground voltage

Diagram:

- Diagram showing the neutral point established by distributed capacitance.
- Circuit diagrams for normal operation and ground fault operation.
- Notes on voltage levels and currents in normal and faulted conditions.
Causes of Arcing Ground Faults and Transient Overvoltages

Arcing Faults

- Repetitive contact between live conductor and ground, such as on a motor, vibrating machine, or the repetitive effects of rain, wind, or various contaminants

Transient Overvoltages

- Caused by arcing faults and switching surges – opening and closing a contact (or fault) across a capacitor (system capacitance to ground)
IEEE Std 242-2001 (Buff Book)
Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems

- 8.2.5 If this ground fault is intermittent or allowed to continue, the system could be subjected to possible severe over-voltages to ground, which can be as high as six to eight times phase voltage. Such over-voltages can puncture insulation and result in additional ground faults. These over-voltages are caused by repetitive charging of the system capacitance or by resonance between the system capacitance and the inductance of equipment in the system.
Ungrounded AC System

- **Advantages**
  - Ability to run with one phase faulted to ground

- **Disadvantages**
  - Difficult to detect ground-faults — no fault current
  - Ground-fault location requires significant maintenance time – INCONVENIENT!
  - Running with a ground-fault increases stress on insulation, leading to phase-to-phase faults
  - Intermittent fault may cause transient overvoltage – DANGEROUS!
Solidly Grounded AC System (3 Wire)

Wye-Connected Transformer Secondary

Distributed capacitance of electrical system
Solidly Grounded AC System (4 Wire)

Wye-Connected Transformer Secondary

Distributed capacitance of electrical system
Solidly Grounded AC System

Current limited only by system and fault impedance
Solidly Grounded AC System – Ground-Fault Detection

SE-701 Ground-Fault Monitor
Solidly Grounded AC System Hazards

- High Current Flowing Through
  - Ground wires
  - Building steel
  - Conduit
  - Water pipes

- Arc-flash hazard during ground fault
- Creates steam if water is present in terminal boxes
- If in a hazardous area, results can be disastrous
- Increased hazard to non-electrical staff due to mechanical damage
IEEE Std 141-1993 (Red Book)
Recommended Practice for Electric Power Distribution for Industrial Plants

- 7.2.4 The solidly grounded system has the highest probability of escalating into a phase-to-phase or three-phase arcing fault, particularly for the 480V and 600V systems. The danger of sustained arcing for phase-to-ground fault probability is also high for the 480V and 600V systems, and low for the 208V systems. For this reason ground fault protection is shall be required for system over 1000A. A safety hazard exists for solidly grounded systems from the severe flash, arc burning, and blast hazard from any phase-to-ground fault.
Solidly Grounded AC System

- **Advantages**
  - Detect ground-faults
    - Annunciate
    - Trip
  - Eliminate transient overvoltages

- **Disadvantages**
  - Potentially large ground-fault currents
  - Cannot run with a ground fault
  - Possible equipment damage
  - Possible arc exposure at the fault – DANGEROUS!
Resistance-Grounded AC System

Wye-Connected Transformer Secondary

Neutral Grounding Resistor (NGR)

Distributed capacitance of electrical system
Edge-Wound Neutral-Grounding Resistor (NGR)
Wire-Wound NGR
Wire-Wound NGR (Coated)
Neutral-Grounding Resistors
Resistance-Grounded AC System

Current limited by NGR

Ground Fault
Resistance-Grounded AC System – Ground-Fault Detection

SE-704 Earth-Leakage Monitor
Resistance-Grounded AC System – IEEE Standard

- IEEE Std 141-1993 (Red Book)
  Recommended Practice for Electric Power Distribution for Industrial Plants
  - 7.2.2 There is no arc flash hazard, as there is with solidly grounded systems, since the fault current is limited to approximately 5 A. Another benefit of high-resistance grounded systems is the limitation of ground fault current to prevent damage to equipment. High values of ground faults on solidly grounded systems can destroy the magnetic core of rotating machinery.
Most three-phase faults are man-made, typically caused by improper operating procedure or wiring

- Courtesy of Jack Woodham – Jedson Engineering Power System Grounding Course System Failures – Short Circuits (Faults) Industrial Power Systems
Initiators of Electrical Faults

- IEEE Std 493-1997 (Gold Book)
  - Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems

<table>
<thead>
<tr>
<th>LEADING INITIATORS OF FAULTS</th>
<th>% OF ALL FAULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure to moisture</td>
<td>22.5%</td>
</tr>
<tr>
<td>Shorting by tools, rodents, etc.</td>
<td>18.0%</td>
</tr>
<tr>
<td>Exposure to dust</td>
<td>14.5%</td>
</tr>
<tr>
<td>Other mechanical damage</td>
<td>12.1%</td>
</tr>
<tr>
<td>Exposure to chemicals</td>
<td>9.0%</td>
</tr>
<tr>
<td>Normal deterioration from age</td>
<td>7.0%</td>
</tr>
</tbody>
</table>
Resistance-Grounded AC System

- **Advantages**
  - Detect ground faults
    - Annunciate or Trip
  - Eliminate transient overvoltages
  - Limited fault current and minimized damage
  - Reduce exposure to arc faults caused by a phase-to-ground fault
  - May continue to run with a ground fault (alarming system)
  - Detect faulted resistors
  - Reduced energy available to arc flash
  - Provide adequate tripping levels for selective ground-fault detection and coordination

- **Disadvantages**
  - Line-to-neutral loads require additional consideration
Resistance-Grounded AC System – Tripping vs. Alarming System

- **Tripping Systems**
  - Ground faults automatically cleared
  - NGR let-through current > 10 A

- **Alarming Systems**
  - Continues to operate on first ground fault
  - NGR let-through current <= 10 A

- **Alarming System 10-A Limit**
  - Prevent burning of insulation and escalation to phase-to-phase
  - Prevent burning of core material
  - Maximum NGR let-through current for an alarming system as defined by Canadian Electrical Code
Resistance-Grounded AC System – Tripping vs. Alarming System

- Alarming systems are not common above 5 kV
  - Higher system capacitance – necessitates NGR let-through current above 10 A
  - Higher voltage – increased probability of ground-fault escalation to a phase-to-phase fault

- Tripping Systems
  - 15 and 25 A let-through current common
  - NGR’s up to a few hundred amps can be used on higher voltage
  - Designers familiar with solid grounding often specify more let-through current than necessary
Converting from Ungrounded to Resistance Grounded

- A zigzag transformer can be used to create an accessible neutral to connect an NGR
Zigzag Transformer

- The zigzag transformer size is specified by the system’s voltage, the NGR current, and the fault duration.
Converting from Solidly to Resistance Grounded

- A 3-wire solidly grounded system can easily be converted to a resistance grounded one
  - Ensure all equipment is rated for line-line voltage above ground e.g., VFDs, UPSs, etc.

- A 4-wire system with a distributed neutral is typically left with a solid connection to ground
  - If line-to-neutral loads can be converted to line-to-line loads, resistance grounding can be implemented
Resistance Grounding – Codes and Standards

- Resistance Grounding is widely used in mining around the world, including Canada, USA, Chile, Peru, Brazil, China (open-pit), Mongolia, Australia, and India.
- Resistance Grounding is a recommended practice for use in mining, as described by the IEEE Green Book, Chapter 1 section 1.10.
Normal Operation –
Low Voltage Resistance Grounding
Normal Operation –
Low Voltage Resistance Grounding

347 V_{NG}

600 V_{LG}

0 V_{LG}
Harmonic Currents

- Harmonics can be the result of the use of adjustable-speed drives and solid-state starters.
- Harmonic-frequency current components can make it necessary to set undesirably high ground-fault current-protection pickup levels to avoid false operation.
- In a 60-Hz system, Triplens (180-Hz, 360-Hz, …) add in phase and can cause false ground-fault trips.
To eliminate this problem, our ground-fault monitors are equipped with a discrete Fourier transform (DFT) filter to remove harmonics and respond only to the fundamental-frequency component of ground-fault current.
Relay Coordination – Zone-Selective Interlocking

- In a zone-selective interlocking system ground-fault relays coordinate using control signals
  - Upstream devices are prevented from operating by a control signal from a downstream device. If the downstream device is unable to clear the fault the upstream device operates.

- Zone-selective interlocking requires a great deal of control wiring
  - A solution used on solidly grounded systems where overcurrent- and ground-fault-protective devices would otherwise trip simultaneously.
  - With resistance-grounding, time-selective coordination achieves the same result without the need for control wiring.
Since ground-fault current is controlled to a level that will reduce fault damage, and an arc flash will not occur, time-selective coordination can be employed. This is achieved when all ground-fault relays on the system trip at the same level, with those installed furthest from the supply set to trip with the least delay. When a fault occurs, the nearest upstream relay is the first to trip.
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  - Sympathetic tripping
  - Tripping Ratio

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- NGR Monitoring
What is charging current?

Charging current is the current that flows to ground when one phase of an ungrounded power system is faulted to ground.
Charging Current (Ungrounded System)

Ideal System:
- All current flows from and returns to the source through the CT.
- Ammeter $A_1$ reads 0 amps.
• Includes distributed capacitance to ground (shown as lumped capacitance).
• All current flows from, and returns to the source, through the CT.
• Ammeter A₁ reads 0 amps.
Charging Current (Ungrounded System)

- Charging current: (read by Ammeter $A_2$)
- Ammeter $A_1$ will continue to read 0

$X = \text{Distributed Capacitance}$

$I_A + I_B + I_C = 0$
Charging Current (Ungrounded System)

Charging Current $I_1$

Charging Current $I_2$

Charging Current $I_3$

Reads $I_1$ → $A_1$

Reads $I_2$ → $A_2$

Reads $I_1 + I_2$ → $A_3$
Charging Current (Resistance-Grounded System)

- Ammeter A1 will read the NGR current – this is a similar principal to a ground-fault relay
- Ammeter A2 will read the sum of the charging currents and NGR current
Resistance-Grounded AC System – Sympathetic Tripping

- Sympathetic tripping is defined as a ground-fault trip on an unfaulted feeder in response to a ground fault elsewhere in the system.
- Sympathetic tripping can occur if the operating value of the feeder’s ground-fault relay is less than the feeder’s charging current.
- Sympathetic tripping cannot occur, regardless of the relative feeder sizes, if an operating value above the charging current of the largest feeder is used for all ground-fault relays in the system.
Resistance-Grounded AC System – Sympathetic Tripping
The tripping ratio is defined as the ratio of prospective ground-fault current to the trip setting of the ground-fault relay.

- A tripping ratio between 5 and 10 is required so that there is enough fundamental-frequency component of fault current in cases where faults occur inside motors, solid-state starters, and variable-speed drives.
- If the trip setting of the ground-fault relay is greater than the charging current of the largest feeder, and tripping ratio of 5 is used, the NGR must be greater than 5 times the charging current of the largest feeder.
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- NGR Monitoring
NGR Selection

- Determine the system charging current
  - This can be done via estimation, calculation, or measurement

- Determine whether the system will be alarm only or tripping
  - Alarming systems should only be considered only for systems where system voltage is less than 5 kV and NGR let-through current is less than 10 A
  - If the system is tripping determine the amount of time that a fault will be allowed to remain on the system
NGR Selection

- Determine the desired trip level for ground-fault protection
  - The trip level should be above the charging current of the largest feeder
  - Ground-fault relaying with harmonic filtering should be used to eliminate false operation on harmonic current

- Select an appropriate tripping ratio, usually between 5 and 10
  - The higher the tripping ratio the better the ground-fault relays will be at detecting high-resistance ground faults
NGR Selection

- Determine the NGR let-through current based on the ground-fault protection trip level, and the tripping ratio
- Include continuous NGR monitoring as an NGR failure results in the loss of current-sensing ground-fault protection and the loss of many of the benefits of resistance grounding
Agenda

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- NGR Monitoring
Why an NGR Monitor?

- Broken Wire
- Loose Connection
- Resistor Failure
- Corrosion
- Stolen Wire(s)
Why an NGR Monitor?

Failure of the NGR results in an ungrounded system with all of the associated problems such as transient overvoltages.

NGR monitoring is mandated by CSA M421

Ground-fault protection, coordination, and annunciation depend on the integrity of the NGR
Approaches to NGR Monitoring – The Potential Transformer Method

- Does not continuously monitor the NGR
  - It is active only when a GF is present
  - Does not monitor NGR continuity, only measures neutral-point voltage

- Backup ground fault protection, not resistor monitoring

- Ferroresonance (with NGR failure)

- Does not limit dc current
New Approach to NGR Monitoring – SE-330 Neutral-Grounding-Resistor Monitor

Voltage at the neutral is monitored

CT is used to monitor ground-fault current (CT selected to match NGR current)

Continuously monitors loop resistance of ER-series sensing resistor and NGR

A voltage clamp in the sensing resistor eliminates hazardous voltage levels at the SE-330
Case Study – Anglo Coal, Australia

- **Situation**
  - In 2004 inspection of three NERs at a stationary surface substation of an Anglo Coal mine in Australia reveals all three to be open

- **Action**
  - Littelfuse Startco suggests a PGR-5330 package for monitoring the NERs
  - Anglo Coal presents the topic of NER monitoring at the 2004 Queensland Mine Electrical Conference

- **Result**
  - Anglo Coal is convinced that NER monitoring is beneficial
  - Another documented example of why we should monitor NGR’s is brought forward
Case Study – Anglo Coal, Australia
Case Study – Prairie Mines & Royalty, Canada

- Photos of the open NGR from the Marion 8750 dragline main transformer (25kV - 7.2kV). Prairie Mines and Royalty Ltd. - Genesee Mine, 2006
- This condition was discovered by a maintenance contractor (Meridian Power Systems) during a scheduled shut down
- The connection was repaired and the process to install an NGR monitor was started. The hardware was purchased in the first quarter 2007
Case Study – Prairie Mines & Royalty, Canada
Case Study – Prairie Mines & Royalty, Canada