GROUND-FAULT PROTECTION ON RESISTANCE-GROUNDED POWER-DISTRIBUTION SYSTEMS WITH ADJUSTABLE-SPEED DRIVES
TWO BASIC PROBLEMS

1. Prevent nuisance or false trips because of noise on loads or feeders without an ASD.
2. Reliably detect a ground fault on an ASD-driven motor load.
SOME BACKGROUND
SENSING GROUND FAULTS
on a grounded electrical system

THE BEST WAY TO DETECT A GROUND FAULT:

• CURRENT SENSING
  - usually with a zero-sequence core-balance current transformer (CT or ZSCT)
  - permits selective coordination and ease of finding a fault
Q: What is a Core-Balance Zero-Sequence CT?

Answer: Any window-type current transformer is a core-balance zero-sequence CT when all current-carrying conductors are passed through the CT window.

Specialized CT’ s for low-level fault detection are available (EFCT-x, SE-CS30-x).
LIMITING PHYSICAL FACTORS

LOW-LEVEL GROUND-FAULT DETECTION: PHYSICAL LIMITING FACTORS

1.) System Capacitance
2.) Unbalanced 1-Phase Loads
3.) Current-Sensor Limitations
4.) Harmonic Components

1, 2, & 4 result in current flowing to earth in an unfaulted system. 3 can result in incorrect indication of a ground fault.
SYSTEM CAPACITANCE

All electrical systems have phase-to-ground capacitance
• distributed throughout the system
• modeled here as “lumped” values in a simple single-load system

Capacitor—Noun:
A device used to store an electric charge, consisting of one or more pairs of conductors separated by an insulator.
Definition of charging current:
The current that flows when one phase of an ungrounded system is shorted to ground

Note: A core-balance CT at “1” will measure charging current
A core-balance CT at “2” will measure zero
A core-balance CT on an unfaulted feeder will detect its feeder’s charging current when a ground fault occurs on another feeder.

- To avoid sympathetic tripping (alarming), protection must be set above the charging current level.
- Protection level can be set below charging current if sympathetic tripping (alarming) is acceptable.
- Charging current does not flow to the system neutral.
CAPACITANCE UNBALANCE

Balanced Phase-to-Ground Capacitance: $X_a = X_b = X_c$
- Phase capacitive currents are equal
- Core-balance CT reads zero.

Unbalanced Phase-to-Ground Capacitance: $X_a \neq X_b \neq X_c$
- Phase capacitive currents are not equal
- Core-balance CT reads a finite value
Voltage Unbalance, $V_{an} \neq V_{bn} \neq V_{cn}$: 

- May be the result of unbalanced single-phase utility loads

Voltage unbalance combined with capacitance unbalance forces capacitive current unbalance resulting in steady-state zero-sequence current.

These affects are usually small, but may affect low-level earth-fault current detection.
Do unbalanced load currents cause ground-fault trips?

No. If there is no leakage to ground, unbalanced load currents add to zero, therefore no core-balance CT output.

\[ I_a + I_b + I_c = 0 \]

Balanced or Unbalanced
Practical Current-Transformer Considerations:

• **Excitation Current**
  - minimum primary current that will give an output.
  - can require specialized ZSCT.

• **Saturation**
  - output current not proportional to large primary current (high-level fault)

• **Local Saturation**
  - output with no zero-sequence current
  - surge currents and poor conductor placement
  - correct with proper conductor location and flux conditioner
HARMONIC FREQUENCIES

• Often result from use of Adjustable-Speed Drives and Solid-State Starters
  • ASD’s build waveforms in a series of steps. Each step includes harmonic frequencies.

\[ X_C = \frac{1}{2\pi f C} \]

Where \( C \) = capacitance
\( f \) = frequency

Capacitive impedance \((X_C)\) decreases at higher frequencies
• Current per volt increases at higher frequencies
• The affect of capacitive and voltage unbalance are greater at higher frequencies...current flowing to ground, with no fault present
Building a Sine Wave

DC Voltage is switched on and off

Resulting AC current is a “noisy” sine wave.

A real example
TRIPLEN HARMONICS: A Special Case

In 3-phase systems third-order harmonics are in-phase
• their values add; they do not cancel

Example: Fundamental & 3rd harmonic
Harmonic currents can flow to earth through system capacitance and cause nuisance earth-fault tripping

Triplen harmonics are detected by core-balance current transformers because they don’t cancel

Solution:
• set ground-fault pickup level above harmonic current “background” level, or
• filter the harmonics with a protective device that responds only to the fundamental frequency
Required Filter Characteristics

Filtering Requirements:
• Respond to the fundamental frequency to detect true zero-sequence ground-fault current
• Do not respond to dc-offset caused by starting motors
• Do not respond to harmonic-frequency components

The Discrete Fourier Transform has these characteristics

\[ I_p = \frac{2}{m} \sum_{n=0}^{m-1} I(n) \times \sin \left( \frac{2\pi n}{m} \right) \]
Example of 50-Hz Fundamental with 150-Hz Component

19
Modified_103007

2-component Signal

50 Hz

150 Hz

Sample

Sampler is set to take a known number of samples per 50 Hz cycle (here 20 samples/cycle)
DFT Measures the Desired Frequency

<table>
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<tr>
<th>Sample Number (n)</th>
<th>50 Hz Comp. ( I_r(n) )</th>
<th>150 Hz Comp.</th>
<th>Sampled Value ( I(n) )</th>
<th>( I_r(n)\sin(2\pi n/20) )</th>
<th>( I(n)\sin(2\pi n/20) )</th>
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DFT of 50 Hz component = 14.142

DFT of signal = 14.142

The result for the multiple-frequency signal is the same as the result for the 50 Hz component.

Only one cycle is required to calculate earth-fault current, and is updated every sample.
A SOLUTION FOR AVOIDING FALSE TRIPS IN HARMONIC-RICH SYSTEMS

Use a ground-fault protection device incorporating sampling technology and DFT processing for:

• DC-offset filtering
• Harmonic filtering
• Speed - one cycle maximum detection time

Examples are: SE-701, SE-704, SE-330, MPU-32, MPS, FPU-32, FPS
What about detecting a ground fault in a VFD circuit when the VFD is operating outside of 50-60 Hz?

Another filtering algorithm is necessary; Peak Detection.
THE TROUBLE WITH VFD BUILT-IN GROUND-FAULT PROTECTION

MANY LOW-VOLTAGE DRIVES HAVE A FIXED (Non-Adjustable) GROUND-FAULT PROTECTION LEVEL.

• Often presumes a solidly grounded system
• Often a large percentage (eg: 50%) of rated current
• Often not compatible with a high-resistance grounded system

THESE DRIVES REQUIRE SUPPLEMENTAL GROUND-FAULT PROTECTION
Why is Inability to Detect a GF in an ASD System a Problem?
Why is Inability to Detect a GF in an ASD System a Problem?
What Happened Here?

The System:
• Low-voltage
• Variable-speed drive
• 5-A neutral-grounding resistor (NGR)

Some type of fault occurred with

The Result:
• Melted copper and steel
• Luckily, no fire

Ground was obviously involved

But the ground fault was not detected!
What Happened Here?

The System:
- Low-voltage
- Variable-speed drive
- 5-A neutral-grounding resistor (NGR)

Could the damage be the direct result of the ground fault?

No.

\[ P = I^2R \text{ and } I_{GF} \leq 5 \text{ A.} \]

Furthermore, for 5 A to flow, the fault impedance \( R \) must = 0 \( \Omega \) (so \( P=0 \)). As fault impedance rises, current decreases and power dissipation at the fault is small.

Fault Power Dissipation
600-Vll, 5-A NGR
What Happened Here?
A Theory

A phase-to-winding connection became disconnected in the terminal box, but electrical continuity was maintained by (hi-impedance) contact with the grounded terminal-box cover.

\[ I_{\theta} = I_{\text{motor}} + 5 \text{ A, max} \]

VFD

Motor

51G > 5 A

This fault wouldn’t cause an overcurrent trip

And the ground fault was not detected
THE CHALLENGE IN VFD GROUND-FAULT PROTECTION

CHALLENGE: RELIABLY DETECT A LOW-LEVEL GROUND FAULT ACROSS VFD OPERATING-FREQUENCY RANGE WITHOUT NUISANCE TRIPS.

BIG QUESTION—WHERE TO PUT THE CT? LINE SIDE? LOAD SIDE?

WE DID SOME TESTING; …and invented a new product
We set up a system with an NGR-grounded three-phase supply to a VFD feeding a motor, with a controlled ground fault, protection relays, and instrumentation.
Analog outputs from three SE-701’s were recorded. EFCT-1 Current Transformers were input devices.
Littelfuse Startco R&D Lab
VFD Ground-Fault Test Setup

An adjustable “decade box” was used to simulate a ground fault at various system locations. Digital RMS meters and a power analyzer were used to confirm SE-701 Ground Fault Monitor readings.
Sample 1: No Ground Fault
VFD Phase-Voltage Spectrum: 30 Hz
No Filter

\[ V_{L-G} \]

\[ X_C = \frac{1}{2\pi fC} \]
Sample 1: No Ground Fault
VFD Phase-Voltage Spectrum: 30 Hz
500-Hz Low-Pass Filter

\[ V_{L-G} \]
Sample 2: System with a Ground Fault
VFD Ground-Fault Spectrum: 60 Hz, 0.3 A
No Filter

\[ V_{L-G} \]
\[ I_{L-G} \]
\[ V_{N-G} \]
\[ I_{N-G} \]
Sample 2: System with a Ground Fault
VFD Ground-Fault Spectrum: 60 Hz, 0.3 A
500-Hz Low-Pass Filter

\[ V_{L-G} \]
\[ I_{L-G} \]
\[ V_{N-G} \]
\[ I_{N-G} \]
Sample 3: System with a Ground Fault
VFD Ground-Fault Spectrum: 10 Hz, 1 A
No Filter

\[ V_{L-G} \]

\[ I_{L-G} \]

\[ V_{N-G} \]

\[ I_{N-G} \]
Sample 3: System with a Ground Fault
VFD Ground-Fault Spectrum: 10 Hz, 1 A
500-Hz Low-Pass Filter

\[ V_{L-G} \]
\[ I_{L-G} \]
\[ V_{N-G} \]
\[ I_{N-G} \]
SE-70x Monitors Have a Filter-Selector Switch

SE-701 top view

CONFIGURATION SWITCHES

RESET MODE LATCHING
FILTER SELECTION FIXED
CH SELECTION ON
CT VERIFICATION OFF
TRIP INHIBIT OFF
RELAY OPERATING MODE FAIL-SAFE

NOTE 5

CIRCUIT PROTECTION SOLUTIONS
SE-70x Filter Characteristics

SE-70X Frequency Response
Variable Frequency — Peak Detection

Peak-Detection Filter
(labeled as Variable Frequency)

SE-70X Frequency Response
Fixed Frequency — 50/60 Hz DFT

DFT Filter
(labeled as Fixed Frequency)
What about CT Location?

A Littelfuse Startco Ground-Fault Monitor can be installed upstream of the drive.

REALLY??
Yes. Really.

A VFD DOES NOT ISOLATE THE LOAD FROM THE SUPPLY

<table>
<thead>
<tr>
<th>Drive Frequency (Hz)</th>
<th>Fault Current (mA) (No Filter)</th>
<th>NGR Current (mA)</th>
<th>SE-701 Filter Selection</th>
<th>Upstream SE-701</th>
<th>Downstream SE-701</th>
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A VFD DOES NOT ISOLATE THE LOAD FROM THE SUPPLY

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A VFD Does Not Isolate the Load from the Supply
From the chart, multiply the desired pickup at a frequency by the Normalized Response Value.
What About a DC-Bus Fault?

Can an AC-sensing relay detect a DC fault?
How a VFD Makes DC from AC: Start with Full-Wave Rectification

- Single-Phase Sine Wave
  - On Average, the value is 0

- Full-Wave Rectified Single-Phase Sine Wave
  - On Average, the value is +ve
How a VFD Makes DC from AC: Start with Full-Wave Rectification, $3\theta$

Three-Phase Sine Waves  
On Average, the value is 0

Full-Wave Rectified Three-Phase Sine Waves  
On Average, the value is +ve
DC from AC

Full-Wave Rectified Three-Phase Sine Waves

AC Ripple

DC
VFD Negative DC-Bus Fault, 500 mA

All of the measurements show the 180-Hz ripple.
DC Fault Spectrum Analysis
DC Fault Spectrum Analysis

180 Hz and Harmonics
For non-ASD circuits, use a detection device with a narrow band-pass filter.

For ASD circuits, use a detection device with a low-pass filter.
SOME ASD’S ARE USED AT VERY LOW SPEEDS…<20 Hz
SOMETIMES A CONVENTIONAL GROUND-FAULT RELAY WON’T DO
SOMETIMES ACCURATE DC-to-60 Hz MEASUREMENT IS NECESSARY
SOMETIMES ACCURATE HIGH-FREQUENCY MEASUREMENT IS NECESSARY
SE-70x Filter Characteristics

SE-70X Frequency Response

Variable Frequency — Peak Detection

Fixed Frequency — 50/60 Hz DFT

Peak-Detection Filter (labeled as Variable Frequency)

DFT Filter (labeled as Fixed Frequency)

400 Hz

1000 Hz

90 Hz
Introducing the EL731

EL731
AC/DC SENSITIVE EARTH-LEAKAGE RELAY
THERE IS A NEW APPROACH TO WIDE-BAND CURRENT MEASUREMENT

THE EL731 accurately measures ground-fault current in the frequency range of 0 to 6 kHz
• using ‘conventional’ CT’s

AC/DC EARTH-LEAKAGE RELAY
Benefit #1

- Provides low frequency to high frequency protection capability with one relay—0 to 6 kHz

**EL731 Frequency Response**

**SE-731 Frequency Response**

![Frequency Response Graph](image-url)
AC/DC EARTH-LEAKAGE RELAY

CURRENT TRANSFORMER #1
- CT1 MEASURES 0 TO 100 Hz
- 0 Hz = DC
- CT1 IS A STANDARD SENSITIVE EARTH-FAULT CT AND A DCCT
- USED ALONE OR WITH CT2
- 30 TO 5,000 mA SETTING RANGE
AC/DC EARTH-LEAKAGE RELAY

CURRENT TRANSFORMER #2
- CT2 MEASURES 20 TO 6,000 Hz
- A STANDARD SENSITIVE EARTH-FAULT CT
- USED ALONE OR WITH CT1
- 30 TO 5,000 mA SETTING RANGE

EFCT-SERIES
CT1 AND CT2
• USE ONE OR BOTH
• COMBINED 0 TO 6,000 HZ FREQUENCY RESPONSE
Benefit #2

- EFCT series CT used on previous applications can be re-used.
- Upgrade SE-701 applications.
Benefit #3

- Separate Alarm and Trip relay outputs
- 3 programmable Form-C relays
- Early detection of alarm conditions allows prevention of extended downtime.
DC Applications
DC Application

- Must be grounded DC supply.
Benefit # 4

- Feature: Ability to detect DC faults with a CT
- Benefit provides ability to locate the fault on a grounded-DC system.
- Improves upon previous DC ground-fault detection methods that would only tell you the system had a fault and possibly which bus was faulted. (SE-601)
But Wait There’s more

- A fan cooled motor operated at low speed draws less air over the windings. Less cooling equates to higher winding temperature.
Feature and Benefit #5

- The only ground-fault relay on the market with temperature protection.
- RTD or PTC Thermistor input for temperature measurement and protection.
  - Allows measurement of motor, load or drive temperature. Many drives operate motors at lower speed (less cooling) but most do not offer temperature protection.
Features and Benefits #6 and #7

- Communications module available to send info to data network.
- Flash upgradeable via optional communication adapter. Allows field modification of firmware if ever required.
Feature and Benefit #8

- Password Protection
- 1st of our ground-fault relays with this feature.
Features and Benefits #9 and #10

- Metering on the door. 2-Line OLED display
- Panel-mount adapter not required for door mounting.
- No PMA-55 or PMA-60 required.
- Optionally available surface-mount adapter
Accessories

**Accessories:**

- **AC700-CUA**
  Communications Adapter
  Optional network-interface and firmware-upgrade communications adapter. Field installs in EL731.

- **AC700-SMK**
  DIN- and Surface-Mount Adapter
  Provide back-plane mounting options for the EL731.

**Current Transformers:**

- **EFCT-26**
  Earth-Fault Current Transformer
  Sensitive current transformer used to detect ground-fault current. Flux conditioner not required.

- **EFCT-1FC**
  EFCT Flux Conditioner
  Helps prevent saturation when installed in the EFCT-1 window.

- **EFCT-1**
  Earth-Fault Current Transformer
  Sensitive current transformer used to detect ground-fault current. EFCT-1FC flux conditioner available.

- **EFCT-2**
  Earth-Fault Current Transformer
  Sensitive current transformer used to detect ground-fault current. Flux conditioner included.
EL731 Benefits Reviewed

1. Full Frequency Coverage
2. Re-use existing EFCT series CT
3. Detection and fault location on DC systems
4. Separate Trip and Alarm Setpoints
5. Overtemperature Protection
6. Communications Capable GF relay
7. Firmware Upgradeable
8. Password Protected
9. Panel Mount Ready; optional surface mounting
10. Metering
Ground-Fault Protection for VFD’s on High-Resistance-Grounded Systems

**SE-701**
Ground-Fault Monitor
Pickup: 50 mA to ?? A

Frequency Response:
32 to 86 Hz,
20 to 420 Hz

**SE-704**
Earth-Leakage Monitor
Pickup: 10 mA to 5 A

**EL731**
AC/DC Sensitive Earth-Leakage Relay
Pickup: 30 mA to 5 A

Frequency Response:
0 to 90 Hz,
20 to 90 Hz,
20 to 3,000 Hz,
190 to 6,000 Hz,
0 to 6,000 Hz