M-3425A
Generator Protection
Test Plan

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Drew Welton is the Vice President of Sales & Creative Technical Solutions for Beckwith Electric and provides strategic leadership to the sales management team as well as creative technical solutions to our customers. Mr. Welton joined Beckwith Electric in 2016 as Director of Sales to provide strategic sales leadership and to further develop and execute sales channels.

- North American Regional Manager for OMICRON starting in 1997.
- Regional Sales Manager with Beckwith Electric. He also served as National Sales Director for Substation Automation with AREVA T&D.
- Written numerous articles on substation maintenance testing, and has conducted numerous training sessions for substation technicians and engineers at utilities and universities across North America.
- 20 year Senior Member of IEEE-PES, has been a contributor on a number of PSRC working groups, and presented at a number of industry conferences specific to power system protection and control.
- Graduate of Fort Lewis College, Durango, CO, with a Bachelor’s degree in Business Administration.

Wayne Hartmann
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Wayne is Beckwith Electric’s top strategist for delivering innovative technology messages to the Electric Power Industry through technical forums and industry standard development.

- Before joining Beckwith Electric, performed in Application, Sales and Marketing Management capacities at PowerSecure, General Electric, Siemens Power T&D and Alstom T&D.
- Provides training and mentoring to Beckwith Electric personnel in Sales, Marketing, Creative Technical Solutions and Engineering.
- Key contributor to product ideation and holds a leadership role in the development of course structure and presentation materials for annual and regional Protection & Control Seminars.
- Senior Member of IEEE, serving as a Main Committee Member of the Power System Relaying and Control Committee for over 25 years.
  - Chair Emeritus of the IEEE PSRC Rotating Machinery Subcommittee (’07-’10).
  - Contributed to numerous IEEE Standards, Guides, Reports, Tutorials and Transactions, delivered Tutorials IEEE Conferences, and authored and presented numerous technical papers at key industry conferences.
Normal Operation - No Targets

- Power supply fail contact = energized
  - Note: On relays with 2 power supplies installed, both must be powered up to energize this contact.
- Diagnostic Contact = coils energized, “OK” state

Tripped

- One or more “OUTPUT” LEDs illuminated
M-3425A Operation

Trip Cleared and Target Present

Target, Time, Outputs, Function, Phase

- All “OUTPUT” LEDs Extinguished

M-3425A Operation

Relay failed internal self diagnostics

- If the “Relay OK LED” is extinguished, the relay is not in service.
  - Contact the factory if a “System Halt” message is displayed or the “Relay OK” LED is extinguished.

- Resetting the relay may temporarily remove the error but may result in a false trip or no trip operation.

- Do not press any HMI buttons while the relay is in diagnostic mode.
Other front panel indicators

- **Breaker Closed**: Normally on when Input 1 is open.
- **PS1 and PS2**: On when the associated power supply is on.
- **Time Sync**: On when IRIG-B signal is applied. No setting is required.
- **Target**: On when most recent event is not reset.

Front panel controls

**Target Reset Button:**

- **Button Released**: Target module and HMI display the most recent event information.
- **Button Pressed and Released**: LED test then targets are reset *IF ALL TRIPPED FUNCTIONS ARE RESET.*
- **Button Pressed and Held**: Target module displays functions that are currently picked up.

*Note*: Output LED's always display real time status of output contacts.
Front Panel Controls:

HMI Operation

- Access by pressing any button after the Power On Self Test terminates.
- The selected menu item appears in capital letters.
- Press the **RIGHT** and **LEFT** arrows to move between menu items.
- Press **ENTER** to move into a submenu or item
- Press **EXIT** move out of a submenu.
- The **UP** and **DOWN** arrows are used to change values.

HMI Operation

- VOLT: 27 Phase Undervoltage
- Volt: 59 Phase Overvoltage
- Volt: 27TN Neutl Undervolt
- 59k Overvoltage
- 59N Neutral Overvoltage
- 59D Volt. Diff. 3rd Har.

- CURR: 46 Neg Seq Overcurrent
- 50 Inst Overcurrent
- 50/27 Inadvertent Energizing
- 50BF Breaker Failure
- 50DT Def. Time Overcurr
- 50N Inst Overcurrent
- 51N Inv Time Overcurrent
- 51N Stator Overload
- 51V Int Time Overcurrent
- 87 Differential Overcurr
- 87GD Gnd Diff Overcurr
- 67N Res Dir Overcurr
HMI Operation

**M-3425A Operation**

- **FREQUENCY RELAY**
  - vol cur FREQ v/hz
  - 81 Frequency
  - 81R Rate of Change Freq
  - 81A Frequency Accum.

- **VOLTS PER Hertz RELAY**
  - vol cur freq V/Hz
  - 24 Definite Time Volts/Hertz
  - 24 Inverse Time Volts/Hertz

- **POWER RELAY**
  - PWR lof fuse dist
  - 32 Directional Power

- **LOSS OF FIELD RELAY**
  - pwr LOF fuse dist
  - 40 Loss of Field

- **V. T. FUSE LOSS RELAY**
  - pwr lof FUSE dist
  - 60 FL V.T. Fuse Loss

- **PHASE DISTANCE RELAY**
  - pwr lof fuse DIST
  - 21 Phase Distance
  - 78 Out of Step

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**HMI Operation**

- **FIELD GROUND RELAY**
  - FIELD stator sync
  - 64B/F Field Ground

- **STATOR GROUND RELAY**
  - field STATOR sync
  - 64S Stator Ground

- **SYNC CHECK RELAY**
  - field stator SYNC
  - 25S Sync Check
  - 25D Dead Volt

- **BREAKER MONITOR**
  - BRKR trpckt ipslog
  - Set Breaker Monitoring
  - Preset Accumulators
  - Clear Accumulators

- **TRIP CIRCUIT MONITOR**
  - brkr TRPCKT ipslog
  - Trip Circuit Monitoring

- **IPS LOGIC**
  - brkr trpckt IPSLOG

- **CONFIGURE RELAY**
  - CONFIG sys stat
  - Voltage Relay
  - Current Relay
  - Frequency Relay
  - Volts per Hertz Relay
  - Power Relay
  - Loss of Field Relay
  - V.T. Fuse Loss Relay
  - Phase Distance Relay
  - Field Gnd Relay
  - Stator Gnd Relay
  - Sync Check Relay
  - Breaker Mon Relay
  - Trip Ckt Mon Relay
  - IPSLogic Relay
PC Software
See Annex for Detailed Views

M-3425A IPScom Operation

Working Offline
• Used to create, view, or modify relay setting files

For a new Setting file:
• Select File/New
• Set Unit type, frequency, CT, and Phase Rotation
• For and Existing File:
• Select File/Open
• Pick the file to be opened
• To Save, use the Save or Save As commands
**Working Online**

- Used to communicate directly with a relay via 232, 485, modem, or TCP/IP

- **PC Port** - Serial port on the PC

- The following must be set to match the relay settings:
  - Baud Rate: 9600 standard
  - Access Code: Defaults disabled
  - Address: 232/485 network address

- For Modem or TCP/IP communications, press the appropriate buttons and set the parameters.

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**Periodic Maintenance: General**

All our relays incorporate self diagnostic hardware and continuously run a number of self diagnostic routines.

We highly recommend the relay self test contact as well as the power supply fail contact be connected as your application dictates.

Our minimum recommended periodic maintenance focuses on those components that cannot be checked by the internal diagnostic routines:
Periodic Maintenance: Critical Checks

Each Maintenance Outage:

1) **Relay Trip Test:** Use the diagnostic feature to force a trip. Verify the breaker opens.

2) **Relay Diagnostics:** Perform relay diagnostic checks which check the operation of the status inputs and outputs.

3) **Breaker Position Sensing:** Verify the breaker's position contact is working correctly.

Digital Relay Self-Diagnostics

**What it covers:**
- Microprocessor hand-shaking
- ADC
- Power supply
- Communication failures
- Watchdogs
- Firmware flash failures

**What it does not cover:**
- Relay contacts
- Internal CT PT circuits
- Improper wiring
- Misapplied logic
- Incorrect settings

- In all cases, relay failures covered by self-diagnostics can alert operators through an alarm contact.
- The relay can then take itself out of service to avoid misoperations.
3-Line Diagram

Partial: A

M-3425A Connections

WARNING: Only dry contact inputs must be connected because there are contact inputs which may result in damage to the unit.

NOTE: M-3425A current terminal points are marked with a "+" and a "−", indicating "+" current direction when connected to the positive terminal of the generator and "−" current direction when connected to the negative terminal of the generator. If CT connections differ from those shown, adjust input terminals.
1. **Energize the relay**

- Verify which power supply installed by checking the marks on the back of the relay
- Apply the proper voltage and check the following:
  - Power supply contact drops out (if 2 power supplies are installed, both must be energized to clear power fail contact)
  - Diagnostic contact drops out after POST testing completes
  - "Relay OK" LED on/flashing

*Note: Do not press any buttons while the Power On Self Test is in process.*

2. **Set the clock**

3. **Install the relay setting using IPScom**

**From a File:**

- Connect to the relay
- Relay Menu ⇒ Write File To Relay
- Use the browsing control to select the file
  - Note: The file save must be for the same relay type and have the same phase rotation for this feature to work
- Relay Menu ⇒ Setup ⇒ Sequence of Events ⇒ Setup. Enter the settings
- Relay Menu ⇒ Setup ⇒ Oscillograph ⇒ Setup. Enter the settings
1. Energize the relay
2. Set the clock
3. **Install the relay setting using IPScom**

From a Setting Sheet:

- Connect to the relay
- Relay Menu ⇒ Setup ⇒ Setup System. *Enter the settings.*
- Relay Menu ⇒ Setup ⇒ Setpoints ⇒ Configure. *Enter the settings.*
- Relay Menu ⇒ Setup ⇒ Sequence of Events ⇒ Setup. *Enter the settings.*
- Relay Menu ⇒ Setup ⇒ Oscillograph ⇒ Setup. *Enter the settings*
- Save the file by selecting File ⇒ Save As.

System Setup Settings:
These settings are used throughout the relay.

![Image of system setup settings](image-url)
Basic Settings (cont.):

**VT Configuration**

<table>
<thead>
<tr>
<th>VT Configuration</th>
<th>Nominal Voltage</th>
<th>Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-G</td>
<td>$V_{nom} = \frac{GEN\ VLL}{1.732*VTR}$</td>
<td>(21, 32, 40, 46, 50/27, 51V)</td>
</tr>
<tr>
<td>L-L</td>
<td>$V_{nom} = \frac{GEN\ VLL}{VTR}$</td>
<td></td>
</tr>
<tr>
<td>L-G to L-L</td>
<td>$V_{nom} = \frac{GEN\ VLL}{VTR}$</td>
<td></td>
</tr>
</tbody>
</table>

**Nominal Current**

$I_{nom} = \frac{GEN\ VA}{1.732*GEN\ VLL*CTR}$  
(21, 32, 40, 46, 50/27, 51V, 87)

**Delta-Y Transform** (21, 51V):
Determines calculation used for 21 and 51V functions

Basic Settings (cont.):

**Input Active State** (all functions using blocking or external initiate):
- Sets the input logic to assert when connected contact is closed or open.
  - Note: For element blocking when GEN CB is open
    - 52/b should be set to active closed
    - 52/a to active open.

**VT Configuration**
- Line-to-Ground: Used with Y connected VTs
- **Line-to-Line**: Used with Delta or Open Delta VTs
- Line-to-Ground to Line-to-Line: Used with Y connected VTs
  - With this setting the relay internally calculates the equivalent phase to phase voltage and uses that voltage for trip decisions while maintaining L-G voltages for the oscillography.
  - In High-Z Grounded Generators, this setting prevents the 59 and 27 elements from tripping on stator ground faults.
Basic Settings (cont.):

59/27 Magnitude Select:
- Adjusts the calculation used for the overvoltage, undervoltage, and the inadvertent energization element.
- In generator applications, this should be set to RMS

RMS averages the most recent 8 cycles of data
- If the voltage is 0V, there are no zero crossings and the relay holds the most recent values for 30 cycles.
- After this time the relay performs the measurement on the most recent 8 cycles of data.
- This results in accurate measurements over a wide frequency but sacrifices speed.

DFT averages the most recent 16 samples (16.7mSec at 60Hz) and calculates the voltage once per cycle.
- This results in faster operation but accuracy is limited to a narrower frequency range.

Phase Rotation:
This setting adjusts nominal phase rotation.
- We do not recommend reversing the CT and PT connections to change the rotation.
- Using the software switch will result in proper phase targeting.

50DT Split phase Differential:
Used for split phase hydro applications.
- Changes IA, IB, and IC metering labels
- Disables 87G

Relay Seal In Time:
- Normal: Sets the minimum amount of time a relay output contact will be closed after tripping element deassertion.
- Pulse: Sets the relay output contact closure time duration regardless of if the tripping element maintains assertion.
- Latched: Relay output contact will remain closed until relay is reset
Connect the relay voltages for today’s training:

M-34XX Test Connection for
L-L, or Open Delta

Test Set Connections: Single Phase Voltage
Phase A+ to terminal # 38 V+ to #45
Phase B+ (None) V1 to #44
Phase C+ to terminal # 43
Return A,B,C to terminal #39

On the relay only:
Jumper #38 to #41
Jumper #39 to #42
Jumper #40 TO #43

Phase Voltage Connections

• For Test Sets with internally connected source neutrals.
• Neutral terminal on test set not connected to relay.

• For Test Sets with externally connected source neutrals.
• Neutral terminals on Test Set not connected to relay.
**M-3425A Pre-startup Tasks**

*Connect the relay currents for today’s training:*

**M-34XX Test Connection**

<table>
<thead>
<tr>
<th>Test Set currents 1</th>
<th>Test Set currents 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA</td>
<td>IA +</td>
</tr>
<tr>
<td>IB</td>
<td>IB +</td>
</tr>
<tr>
<td>IC</td>
<td>IC +</td>
</tr>
<tr>
<td>IN</td>
<td>Jumper</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutral Terminals</td>
<td>Output Terminals</td>
</tr>
</tbody>
</table>

Balance currents for all voltage-type, power and overcurrent tests, or disable 87 elements.

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**Phase Current Connections**

For Test Sets with *externally connected* source neutral terminals.

For Forward Power Flow, Neutral and System Currents should have the Same Angles on Similar Phase.
Phase Current Connections

For Forward Power Flow, Neutral and System Currents should have the Same Angles on Similar Phase

Neutral Voltage Connection

Addressed Previously
Apply nominal quantities and check the metering
Delta-Connected PTs with Line-Line Relay Setting

Incorrect Wiring: VA and VB Rolled

What shows the relay is wired wrong?
"Thinking logically as to how a relay responds in a faulted condition helps to visualize a proper test sequence"  
--Drew Welton

Utilize proper test sequences to avoid associated logic settings:

1. Apply proper pre-fault conditions
   - Nominal V, I
   - 52/a=closed, 52/b=open, contacts in non-faulted state
   - Apply long enough for reset from lockouts if needed

2. Faulted values applied

3. Post-fault State
   - V, I faulted value removed (I=0), (V=0 or Nominal, location of the VT)
   - Breaker contact status changes (52/a=open, 52/b=closed)
Rules of the Ramp!!
Always start with nominal values!
1) Times between each ramp state is > time delay for the element
2) Step size is < than the tolerance of the element

Rules of the Timing!!
1) Always start with nominal values, lock
2) Change to below or above set point
3) Unlock fault values, check timing

Overall Test Plan
1. Pre-Startup Tasks and Relay Setup
2. Negative Sequence (46)
3. Loss of Synchronism (78)
4. Stator Ground Overvoltage (59N)
5. Third Harmonic Neutral Undervoltage (27TH)
6. Oscillography and SOE Demo
Our Generator

Calculations for Our Generator

\[ Z_{\text{base}} = \frac{(\text{GEN kVA} \times \text{GEN MVA})}{(1.73 \times \text{Vbase})} \]

\[ Z_{\text{base}} = \frac{(20 \text{ kVA} \times 492 \text{ MVA})}{(1.73 \times 20\text{ kVA})} \]

\[ Z_{\text{base}} = 0.813 \Omega_{\text{pu}} \]

\[ I_{\text{base}} = \frac{\text{MVA} \times 1000}{(1.73 \times \text{Vbase})} \]

\[ I_{\text{base}} = \frac{(492 \text{ MVA} \times 1000)}{(1.73 \times 20\text{ MVA})} \]

\[ I_{\text{base}} = 14.219 \text{A}_{\text{pri}} \]

\[ \text{VTR} = 20,000 \text{V} / 120 \text{V} = 166.7 \]

\[ \text{CTR} = 18,000 \text{A} / 5 \text{A} = 3,600 \]

\[ \text{CTR/VTR} = 21.5996 \]

\[ I_{\text{base sec}} = 1 \text{ pu} / \text{CTR} \]

\[ I_{\text{base sec}} = 14.219 \text{ pu} / 3,600 \]

\[ I_{\text{base sec}} = 3.945 \text{ A}_{\text{sec}} \]

\[ V_{L_{\text{sec}}} = 120 \text{V} \]

\[ V_{O_{\text{sec}}} = \frac{V_{L_{\text{sec}}}}{1.73} \]

\[ V_{L_{\text{sec}}} = 69.28 \text{V sec} \]

\[ Z_{\text{sec}} = Z_{\text{base pri}} * (\text{CTR} / \text{VTR}) \]

\[ Z_{\text{sec}} = Z_{\text{base sec}} \]

\[ Z_{\text{sec}} = 0.813 \Omega_{\text{pu}} * (3,600 / 166.7) \]

\[ Z_{\text{sec}} = 17.55 \Omega_{\text{sec}} (1 \text{pu}) \]
Negative Sequence Overcurrent (46)

46: Negative Sequence Current

- Typically caused by open circuits in system
  - Downed conductors
  - Stuck poles switches and breakers

- Unbalanced phase currents create negative sequence current in generator stator and induces a double frequency current in the rotor

- Induced current (120 Hz) into rotor causes surface heating of the rotor
**Rotor End Winding Construction**

- **Salient Pole**
  - With connected amortisseur 10%
  - With non-connected amortisseur 5%

- **Cylindrical**
  - Indirectly 10%
  - Directly cooled - to 960 MVA 8%
    - 961 to 1200 MVA 6%
    - 1200 to 1500 MVA 5%
Negative Sequence Current: Constant Withstand Generator Limits

- **Nameplate**
  - Negative Sequence Current ($I_2$) Constant Withstand Rating
  - "K" Factor

- Where: $I_2^2 \cdot T = K$

### Typical K Values
- Salient Pole Generators: 40
- Cylindrical Generators: 30
46: Negative Sequence Electromechanical Relays

- Sensitivity restricted and cannot detect $I_2$ levels less than 60% of generator rating
- Fault backup provided
- Generally insensitive to load unbalances or open conductors

46: Negative Sequence Digital Relay

- Protects generator down to its continuous negative sequence current ($I_2$) rating vs. electromechanical relays that don’t detect levels less than 60%
- Fault backup provided
- Can detect load unbalances
- Can detect open conductor conditions
- Should provide thermal time reset as $I_2$ causes heating
46: Setting

- Definite Time used for Alarming; using short timer for testing
- Inverse Time used for Protection; using short reset time for testing

492 MVA; Cylindrical
Testing the 46 Element, Def. Time

Pick up = 5% of Nominal Current, 3.95 X .05 = .198
Neg. Sequence Component

Use this formula like so:

\[ \frac{I_{\text{fault}}}{I_{\text{nom}}} = 1.52 \]

1.52 squared = 2.3

TD 10 / 2.31 = 4.35 sec Pick up time

SO:

@ 6 amps trip time = 4.35 sec
@ 8 amps trip time = 2.44 sec

Test Sequence for 46-Inverse Time

Careful!!

Roll Ph b and c
Loss-of-Synchronism (78)
aka: Out-of-Step

Types of Instability
- Steady State: Steady Voltage and Impedance (Load Flow)
- Transient: Fault, where voltage and impedance change rapidly
- Dynamic: Oscillations from AVR damping (usually low f)

Occurs with unbalance of load and generation
- Short circuits that are severe and close
- Loss of lines leaving power plant (raises impedance of loadflow path)
- Large losses or gains of load after system break up

Generator accelerates or decelerates, changing the voltage angle between itself and the system

Designed to cover the situation where electrical center of power system disturbance passes through the GSU or the generator itself

More common with modern EHV systems where system impedance has decreased compared to generator and GSU impedance
Generator Out-of-Step Protection

When a generator goes out-of-step (synchronism) with the power system, high levels of transient shaft torque are developed.

If the pole slip frequency approaches natural shaft resonant frequency, torque produced can break the shaft.

High stator core end iron flux can overheat and short the generator stator core.

GSU subjected to high transient currents and mechanical stresses.

Stability

\[
P_{\text{max}} = \frac{E_g || E_s}{X}
\]

For maximum power transfer:
- Voltage of GEN and SYSTEM should be nominal – Faults lower voltage
- Impedance of lines should be low – lines out raise impedance

Power Transfer Equation

\[
P_e = \frac{E_g || E_s}{X} \sin(\theta_g - \theta_s)
\]

- \(E_g\) - Generator Voltage
- \(E_s\) - System Voltage
- \(\theta_g\) - Generator Voltage Phase Angle
- \(\theta_s\) - System Voltage Phase Angle
- \(P_e\) - Electrical Power
Out of Step: Generator and System Issue

\[ P_s = \frac{|E_g||E_s|}{X} \sin(\theta_g - \theta_s) \]

Single Blinder Scheme

- One pair of blinders (vertical lines)
- Supervisory offset mho
- Blinders limit reach to swings near the generator
Graphical Method: 78

Graphical Method: 78

Graphical Method: 78
Out-of-Step (Loss of Synchronism) Event

Generator Protection

Loss of Field Event
Loss of Field Event (1 of 6)

- Blue arrow shows where we are in the record
- On R-X and P-Q diagrams, yellow square on axis shows where “0, 0” is.
- On R-X and P-Q diagrams, blue circles show where the R-X and P-Q characteristics are respectively
- We have normal power output; lots of watts and a little VAr. All is good.

Loss of Field Event (2 of 6)

- We have lost field, and the impedance/power diagrams show we are still outputting watts but are sinking VAr
- This is before the machine goes into asynchronous operation with a resulting slip frequency
We have lost field, and the impedance/power plan plots show we are still outputting watts but are sinking lots of VAr.

This is JUST before the machine goes into asynchronous operation with a slip.

We have lost field, and the impedance/power plan plots show we are NOT putting out ANY watts and sucking a lot of VAr. The machine is slipping a pole.

At the instant shown, all the current into the machine is reactive (VAr sink).
- The machine is slipping a pole. We are into the first slip cycle.
Generator Out-of-Step Protection (78)

**Dependability Concerns**

- Positive sequence quantities used to maintain security and accuracy over a wide frequency range.

- Required to operate correctly (and not misoperate) with wide frequency variations possible during power swing conditions
  - Must work properly from 50 to 70 Hz (60 Hz systems).

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### 78: Setting

\[
\text{Amps} = \frac{KV\times 1000}{\sqrt{3} \times \text{Volts}}
\]

14202.8A\(_{\text{min}}\) = 492,000kVA * 1000 / 1.73 * 20.000V

3.945A\(_{\text{min}}\) = 14,202.8 / 18,000.5 (3600 CTR)

\[
V_{\text{LL}_{\text{max}}} = \text{VT primary voltage; VT ratio = 20,000/166.67 = 120 V}
\]

\[
V_{\text{LL}_{\text{max}}^{\text{kV}}} = 11547 \times 166.67 = 69.28 \text{V} \quad \left(120\text{V}_{\text{kV}} / 1.73 = 69\text{V}_{\text{kV}}\right)
\]

\[
Z_{\text{B}_{\text{relay}}} = \frac{V_{\text{IN}_{\text{B}_{\text{relay}}}}}{I_{\text{B}_{\text{relay}}}} = 69.28 / 3.95 = 17.56 \Omega
\]

\[
X_{\text{Q}} = 0.20577 \times 17.56 = 3.613 \Omega, \quad X_{\text{TG}} = 0.11007 \times 17.56 = 2.04 \Omega
\]

\[
X_{\text{max}} = 0.04035 \times 17.56 = 0.7066 \Omega, \quad \beta = 90^\circ
\]

The blinder distance \(d\) = \((X_{\text{Q}} + X_{\text{TG}} + X_{\text{max}}.69))\times \tan (90 - (\beta/2))

For \(\beta = 120^\circ\) \(d = 1.64 \Omega\)

The diameter of the mho unit is \((2 \times X_{\text{Q}} + 1.5 \times X_{\text{TG}}) = 10.29 \Omega\).

Impedance angle of the mho unit is 90°.

MHO offset = \(-2X_{\text{Q}}d = -7.21\)
78: Setting

Testing the 78 Element

1. View Out of Step Monitor
2. View Function Status
3. Apply Pre-fault Values
Testing the 78 Element

Rotate 3 ph currents up in 10 degree increments simultaneously

78 Picks up when it hits the load blinder

Testing the 78 Element

Continue to rotate 3 ph currents up in 10 degree increments

If we stop here before the boundary of the mho and go back, the target clears, no trip.

If we cross the boundary, the relay will trip within 2 to 3 cycles.
Stator Ground Fault (59N)
95% Stator Coverage

Generator Behavior During Short Circuits

Current

Time

Generator Breaker Trips

I_{\text{Gen}} \text{ Current Decay}

I_{\text{System}}

I_{\text{Gen}}

G

Power System
Generator Short-Circuit Current Decay

- Subtransient Period
- Transient Period
- Steady-State Period

Actual Envelope
Extrapolation of Transient Envelope
Extrapolation of Steady Value

1/\(X_{d}^{''}\) = \% Impedance
1/\(X_{d}^{'}\) = \% Impedance = \(X_{d}^{''}\)
F.L.A. / \% Impedance = S.S.A

Effect of DC Offsets

- Phase A
  - DC Component

- Phase B
  - DC Component

- Phase C
  - DC Component
Grounding Techniques

Why Ground?
- Improved safety by allowing detection of faulted equipment
- Stop transient overvoltages
  - Notorious in ungrounded systems
- Ability to detect a ground fault before a multiphase to ground fault evolves
- If impedance is introduced, limit ground fault current and associated damage faults
- Provide ground source for other system protection (other zones supplied from generator)

Types of Generator Ground Fault Damage

- Following pictures show stator damage after an internal ground fault
- This generator was high impedance grounded, with the fault current less than 10A
- Some iron burning occurred, but the damage was repairable
- With low impedance grounded machines, the damage is severe
Stator Ground Fault Damage

Stator Ground Fault Damage
Stator Ground Fault Damage

Stator Ground Fault Damage
Types of Generator Grounding

**High Impedance**
- System ground source obtained from GSU
- Uses principle of reflected impedance
  - Eq: \( R_{NGR} = \frac{R_R}{[V_{pri}/V_{sec}]^2} \)
    - \( R_{NGR} \) = Neutral Grounding Resistor Resistance
    - \( R_R \) = Reflected Resistance
- Ground fault current typically \( \leq 10\text{A} \)

**Compensated**
- Most expensive using tuned reactor
- System ground source obtained from GSU
- Uses reflected impedance from grounding transformer, same as high impedance grounded system does
- Generator damage mitigated from ground fault
- Reactor tuned against generator capacitance to ground to limit ground fault current to very low value (can be less than 1A)
Stator Ground Fault-High Z Grounded Machines

- 95% stator ground fault provided by 59N
  Tuned to the fundamental frequency
  - Must work properly from 10 to 80 Hz to provide protection during startup

- Additional coverage near neutral (last 5%) provided by:
  - 27TN: 3rd harmonic undervoltage
  - 59D: Ratio of 3rd harmonic at terminal and neutral ends of winding

- Full 100% stator coverage by 64S
  - Use of sub-harmonic injection
  - May be used when generator is off-line
  - Immune to changes in loading (MW, MVAR)

Stator Ground Fault (59N)

- High impedance ground limits ground fault current to about 10A
  - Limits damage on internal ground fault

- Conventional neutral overvoltage relay provides 90-95% stator coverage

- Last 5-10% near neutral not covered

- Undetected grounds in this region bypass grounding transformer, solidly grounding the machine!
59N Element

- Neutral grounding transformer (NGT) ratio selected that provides 120 to 240V for ground fault at machine terminals
  - Max L-G volts = 13.8kV / 1.73 = 7995V
  - Max NGT volts sec. = 7995V / 120V = 66.39 VTR

59N System Ground Fault Issue

- GSU provides capacitive coupling for system ground faults into generator zone
- Use two levels of 59N with short and long time delays for selectivity
- Cannot detect ground faults at/near the neutral (very important)
Multiple 59N Element Application

- **59N-1**, set in this example to 5%, may sense capacitance coupled out-of-zone ground fault
  - **Long** time delay

- **59N-2**, set in this example to 15%, is set above capacitance coupled out-of-zone ground fault
  - **Short** time delay

Use of Symmetrical Component Quantities to Control 59N Tripping Speed

- A ground fault in the generator zone produces primarily zero sequence voltage
  - Negligible $V_2$, $I_2$ or $I_0$

- A fault in the VT secondary or system (GSU coupled) generates negative sequence quantities in addition to zero sequence voltage

- The $I_2$ method may be employed to control the 59N for system ground faults

- The $V_2/V_0$ method may be employed to control the 59N for system and VT secondary ground faults
Use of $I_2$ to Control Fast 59N Element

- $I_2 > 0.05 \text{ pu}$

**NOTES:**

[A] 59N-1 is set sensitive and fast, using $I_2$ supervision to check for external ground faults and control (block) the element for external ground faults.

[B] 59N-2 is set less sensitive and slower, therefore it will not operate for external ground faults.

Use of $V_2 / V_0$ to Control Fast 59N Element

- $|V_2| > 0.05 \text{ pu}$
- $|V_0| < 0.07 \text{ pu}$
- 60FL Asserts

**NOTES:**

[A] 59N-1 is set sensitive and fast, using $V_2$ and $V_0$ supervision to check for external ground faults and control (block) the element for external ground faults.

[B] 59N-2 is set less sensitive and slower, therefore it will not operate for external ground faults.

[C] $V_2$ derived from 3Y phase VTs

[D] $V_0$ derived from 3Y phase VTs
Intermittent Arcing Ground Faults

- Can be very destructive, especially at neutral
- At neutral, even though AC current is very low, arcing fault develops a high voltage DC transient
- If enough arcs occur in a short time, destructive insulation damage can occur
- Conventional time delayed ground fault protection cannot protect for these events

Burned away copper of a fractured connection ring

Side of a bar deeply damaged by vibration sparking

Premature Failure of Modern Generators, Clyde V. Maughan

Intermittent Arcing Ground Fault
**Intermittent Arcing Fault Timer Logic**

- **Stallable Trip Timer**: Times Out to Trip
- **Integrating Reset Time**: Delays Reset for Interval

**Intermittent Arcing Ground Fault**

- **Stalling Trip Timer (cycles)**
- **Arcing Fault Detected (cycles)**: 1, 1, 3, 2, 2, 1
- **Master Reset Timer (cycles)**

Arcing and Trip
Intermittent Arcing Ground Fault

Arcing and Reset (No Trip)

Intermittent Arcing Ground Fault Turned Multiphase

Gen feeding fault into low side of GSU, no low side breaker
Example of Ph-Gnd fault evolving into 3-Ph Fault
Insulation breakdown due to high voltage
59N Element

59N – Generator Neutral Overvoltage: Three elements

- 1st set sensitive to cover down to 5% of stator
  - Long delay to coordinate with close-in system ground faults capacitively coupled across GSU, or,
  - Use \( V_2/V_0 \) or \( I_2 \) Control

- 2nd set higher than the capacitively coupled voltage so coordination from system ground faults is not necessary
  - Allows higher speed tripping
  - Only need to coordinate with PT fuses

- 3rd may be:
  - Set to initiate waveform capture and not trip
  - Used for intermittent arcing fault protection

59N: Setting

\[
V_{LL} / 1.73 = V_{LG}
\]
\[
20kV / 1.73 = 11,560V
\]
\[
V_{LG} / NGT \text{ Ratio} = 100\% \text{ Ground Fault Voltage}
\]
\[
11,560V / (14,440V / 240V) = 192
\]
\[
5V \text{ Setting} = 5/192 = 2.6%,
\]
\[
100\% - 2.6\% = 97.5\% \text{ Coverage}
\]
Setting up and viewing Oscillography

- Manual trigger
- Clear records
- Assign output 8

Testing the 59G,N Element, Setting # 1,3

Pick-up test:
- Start with pre-fault
- Ramp in .1V steps
- Look for target

Timing test:
- Start with pre-fault
- Jump to 6V
- Check timing output 1
- Check timing output 8 (osc)
Testing the 59G,N Element, Setting # 2

**Pick-up test:**
- Start with pre-fault
- Ramp in .1V steps
- Look for target output 2

**Timing test:**
- Start with pre-fault
- Jump to 16V
- Check timing output 2

### Pre-fault settings

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>AB</th>
<th>BC</th>
<th>CA</th>
<th>Neutral</th>
<th>Phase Sec</th>
<th>Neutral Sec</th>
<th>Zero Sec</th>
<th>YN</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>113</td>
<td>113</td>
<td>113</td>
<td>14.4</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>0.0</td>
</tr>
<tr>
<td>BC</td>
<td></td>
<td>113</td>
<td>113</td>
<td>14.4</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>0.0</td>
</tr>
<tr>
<td>CA</td>
<td>113</td>
<td></td>
<td>113</td>
<td>14.4</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Neutral</td>
<td>14.4</td>
<td>14.4</td>
<td>14.4</td>
<td>113</td>
<td>113</td>
<td>113</td>
<td>113</td>
<td>113</td>
</tr>
</tbody>
</table>

### Pick-up #2

<table>
<thead>
<tr>
<th>Set Mode</th>
<th>V A-N</th>
<th>V B-N</th>
<th>V C-N</th>
<th>I A</th>
<th>I B</th>
<th>I C</th>
<th>V Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>120.0 V</td>
<td>0.000 V</td>
<td>120.0 V</td>
<td>3.000 A</td>
<td>3.000 A</td>
<td>3.000 A</td>
<td>15.00 V</td>
</tr>
</tbody>
</table>

### Timing #2

<table>
<thead>
<tr>
<th>Set Mode</th>
<th>V A-N</th>
<th>V B-N</th>
<th>V C-N</th>
<th>I A</th>
<th>I B</th>
<th>I C</th>
<th>V Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>120.0 V</td>
<td>0.000 V</td>
<td>120.0 V</td>
<td>3.000 A</td>
<td>3.000 A</td>
<td>3.000 A</td>
<td>15.00 V</td>
</tr>
</tbody>
</table>

Stator Ground Fault (27TN)

5% Stator Coverage, Near Neutral
Why Do We Care About Faults Near Neutral?

- A fault at or near the neutral shunts the high resistance that saves the stator from large currents with an internal ground fault
- A generator operating with an undetected ground fault near the neutral is an accident waiting to happen
- We can use 3rd Harmonic or Injection Techniques for complete (100%) coverage

Third-Harmonic Rotor Flux

- Develops in stator due to imperfections in winding and system connections
- Unpredictable amount requiring field observation at various operating conditions
- Also dependent on pitch of the windings, which a method to define the way stator windings placed in the stator slots
Generator Pitch

Pole spans 60 over 90 = \( \frac{2}{3} \) pitch

Stator Winding Diagram Illustrating “Pitch” In Winding Construction

---

Using Third Harmonic in Generators

- Generator winding and terminal capacitances (C) provide path for the third-harmonic stator current via grounding resistor
- This can be applied in protection schemes for enhanced ground fault protection coverage
3rd Harmonics are produced by some generators

- Amount typically small
  - Lumped capacitance on each stator end is $C_s/2$.
- $C_T$ is added at terminal end due to surge caps and isophase bus
- Effect is 3rd harmonic null point is shifted toward terminal end and not balanced

3rd Harmonic in Generators

- 3rd harmonic may be present in terminal and neutral ends
- Useful for ground fault detection near neutral
  - If 3rd harmonic goes away, conclude a ground fault near neutral
- 3rd harmonic varies with loading
3rd Harmonic Voltages and Ratio Voltage

- Provides 0-15% stator winding coverage (typ.)
- Tuned to 3rd harmonic frequency
- Provides two levels of setpoints
- Supervisions for increased security under various loading conditions: Any or All May be Applied Simultaneously
  - Phase Overvoltage Supervision
  - Underpower Block
  - Forward & Reverse
  - Under VAr Block; Lead & Lag
  - Power Factor Block; Lead & Lag
  - Definable Power Band Block
  - Undervoltage/No Voltage Block
  - Varies with load
  - May vary with power flow direction
  - May vary with level
  - May vary with lead and lag
  - May be gaps in output

27TN – 3rd Harmonic Neutral Undervoltage

- Provides 0-15% stator winding coverage (typ.)
- Tuned to 3rd harmonic frequency
- Provides two levels of setpoints
- Supervisions for increased security under various loading conditions: Any or All May be Applied Simultaneously

- Loading/operating variables may be Sync Condenser, VAr Sink, Pumped Storage, CT Starting, Power Output Reduction
3\textsuperscript{rd} Harmonic in Generators: Typical 3\textsuperscript{rd} Harmonic Values

<table>
<thead>
<tr>
<th>UNIT LOAD</th>
<th>MW</th>
<th>MVAR</th>
<th>180 HZ RMS VOLTAGE</th>
<th>VOLTAGE RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>NEUTRAL</td>
<td>TERMINAL/NEUTRAL</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.8</td>
<td>2.7</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>2.5</td>
<td>3.7</td>
</tr>
<tr>
<td>35</td>
<td>5</td>
<td>0</td>
<td>2.7</td>
<td>3.8</td>
</tr>
<tr>
<td>105</td>
<td>5</td>
<td>0</td>
<td>4.2</td>
<td>5.0</td>
</tr>
<tr>
<td>175</td>
<td>25</td>
<td>5</td>
<td>5.5</td>
<td>6.2</td>
</tr>
<tr>
<td>340</td>
<td>25</td>
<td>5</td>
<td>8.0</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Magnitudes of Third Harmonic Voltages for a Typical Generator

- 3\textsuperscript{rd} harmonic values tend to increase with power and VAR loading
- Fault near neutral causes 3\textsuperscript{rd} harmonic voltage at neutral to go to zero volts
27TN Settings and Supervision

100% Stator Ground Fault (59N/27TN)
Overlap of Third Harmonic (27TN) with 59N Relay

- Typical value of 3rd harmonic (V3rd) is around 1.7V, 27TN set to pick up at 1.1V.
- A line breaker tripped isolating plant, and they experienced a 27TN operation.
- Oscillograph shows the V3rd decreased from 1.7V to 1.0V as the frequency went from 60 Hz to 66Hz, (only 110% over speed).
- This is well below the 180-200% over speed condition that is often cited as possible with hydros upon full load rejection.
- What happens to 59N?
### 3rd Harmonic in Runaway Hydro Generator

![Graph showing 3rd harmonic in Runaway Hydro Generator](image)

### 27TN: Setting

**Table A.1—Measured primary third harmonic neutral voltages**

<table>
<thead>
<tr>
<th>MW</th>
<th>Mvar</th>
<th>X-phase</th>
<th>Y-phase</th>
<th>Z-phase</th>
<th>Average phase volts</th>
<th>Neutral Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.32</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.97</td>
</tr>
<tr>
<td>98</td>
<td>21</td>
<td>99.8</td>
<td>99.5</td>
<td>99.2</td>
<td>99.5</td>
<td>0.95</td>
</tr>
<tr>
<td>126</td>
<td>19</td>
<td>134.5</td>
<td>119.2</td>
<td>117.3</td>
<td>113.7</td>
<td>1.35</td>
</tr>
<tr>
<td>147</td>
<td>15</td>
<td>128.3</td>
<td>139.2</td>
<td>122.8</td>
<td>127.4</td>
<td>1.57</td>
</tr>
<tr>
<td>174</td>
<td>20</td>
<td>135.7</td>
<td>141.9</td>
<td>141.2</td>
<td>139.9</td>
<td>1.80</td>
</tr>
<tr>
<td>201</td>
<td>19</td>
<td>168.0</td>
<td>161.3</td>
<td>158.8</td>
<td>160.7</td>
<td>1.97</td>
</tr>
<tr>
<td>227</td>
<td>15</td>
<td>176.7</td>
<td>176.7</td>
<td>181.4</td>
<td>180.3</td>
<td>2.44</td>
</tr>
<tr>
<td>254</td>
<td>30</td>
<td>242.6</td>
<td>238.3</td>
<td>236.5</td>
<td>239.0</td>
<td>3.18</td>
</tr>
<tr>
<td>405</td>
<td>23</td>
<td>242.0</td>
<td>249.3</td>
<td>240.2</td>
<td>243.5</td>
<td>3.37</td>
</tr>
<tr>
<td>447</td>
<td>27</td>
<td>267.5</td>
<td>247.5</td>
<td>271.2</td>
<td>254.6</td>
<td>3.46</td>
</tr>
<tr>
<td>482</td>
<td>29</td>
<td>270.8</td>
<td>276.8</td>
<td>276.5</td>
<td>270.7</td>
<td>3.67</td>
</tr>
</tbody>
</table>

**Notes:**

- 20% @ 246 MVA
- 50% @ 246 MVA

---

**Ready**

Date: 11/14/201
Stopped Time: 16:25:23.1
Mark 1: 16:25:21.561
Mark 2:
27TN: Setting

27TN Blocking

Full Power Run

Enabled on Forward Power

Blocked on Low Forward Power

Field Flashed

Power Ramp Up

Power Ramp Down

Field Tripped

MW

V1

100%

50%

0%

100%

0%

70%

Power Ramp Down

70%

Power Ramp Up

50%

100%

Field Flashed

Enabled on V1

Blocked on Low V1

Full Power Run

27TN: Setting
Testing the 27TN Element

Pre-fault Condition

Verify with Metering Screen (relay)

Ramp V Fault down in .25V steps

Find the Pick-up
Testing the 27TN Element

Pre-fault Condition | Fault Condition

Check Timing

Testing the 27TN Element, Positive Seq. Voltage

Pre-fault Condition | Fault Condition

Lower 3 ph Voltage in 1 V steps

Monitor positive Seq. Voltage | Contact drops out
Testing the 27TN Element, Forward Power Block

**Pre-fault Condition**

- **Analog Outputs**
  - **Set Mode**: Direct
  - **VA**: 120.0 V
  - **VB**: 0.00 V
  - **VC**: 0.00 V
  - **V Fault**: 0.00 V
  - **Neutral a**: 3.95 A
  - **Neutral b**: 3.95 A
  - **Neutral c**: 3.95 A

**Fault Condition**

- **Analog Outputs**
  - **Set Mode**: Direct
  - **VA**: 120.0 V
  - **VB**: 0.00 V
  - **VC**: 0.00 V
  - **V Fault**: 0.00 V
  - **Neutral a**: 3.95 A
  - **Neutral b**: 3.95 A
  - **Neutral c**: 3.95 A

Rotate 3 ph current angles 1 degree steps

Monitor real power

Contact drops out

---

**Setting up and viewing Oscillography**

- **Retrieve Record**
- **Save as *.osc or *.cfg**
- **Load and View in BecoPlot Software**
Viewing Oscillography

Other Important Diagnostic Tools
SOE Viewer

Oscillography Recorder
References


8. Behavior Analysis of the Stator Ground Fault (64G) Protection Scheme; Ramón Sandoval, Fernando Morales, Eduardo Reyes, Sergio Meléndez and Jorge Félix, presented to the Rotating Machinery Subcommittee of the IEEE Power System Relaying Committee, January 2013.


10. Advanced Generator Ground Fault Protections, Wayne Hartmann, presented at Georgia Tech Protective Relay Conference 2016