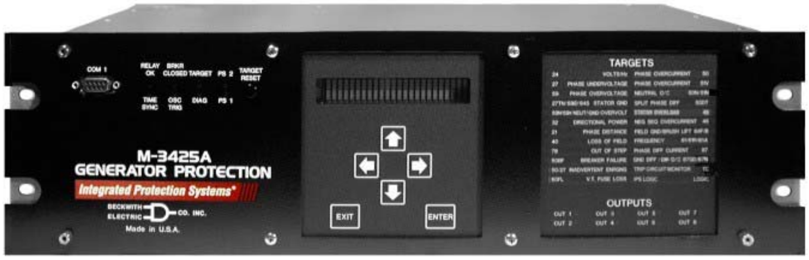
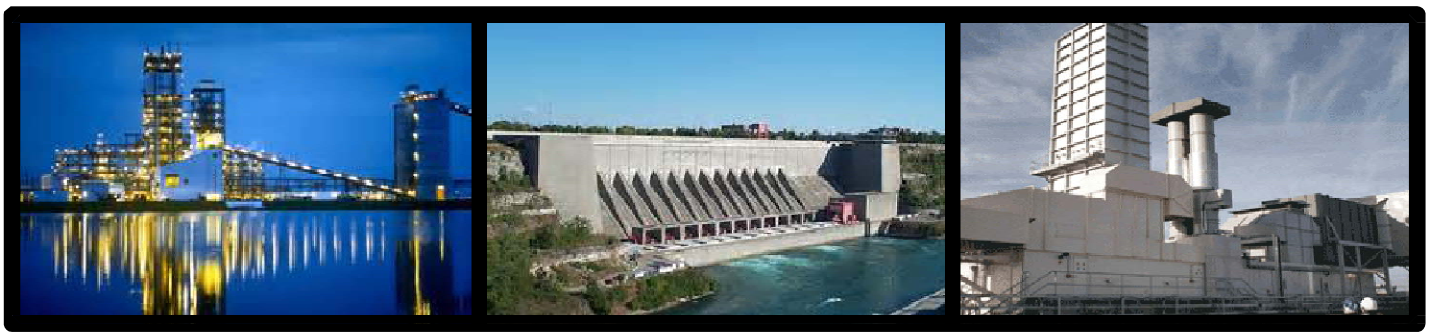


M-3425A

GENERATOR PROTECTION

TEST PLAN



Conducted at:

BECKWITH ELECTRIC CO. INC.

6190-118th Avenue · Largo, Florida 33773-3724 U.S.A.
PHONE (727) 544-2326 · FAX (727) 546-0121
www.beckwithelectric.com

BECKWITH ELECTRIC CO. INC.

Presenter Contact Info

Drew Welton

Vice President of Sales, Creative Technical Solutions

Beckwith Electric Company

dwelton@beckwithelectric.com

727-317-8899

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.

1

BECKWITH ELECTRIC CO. INC.

Presenter Contact Info

Wayne Hartmann

Senior VP, Customer Excellence

Beckwith Electric Company

whartmann@beckwithelectric.com

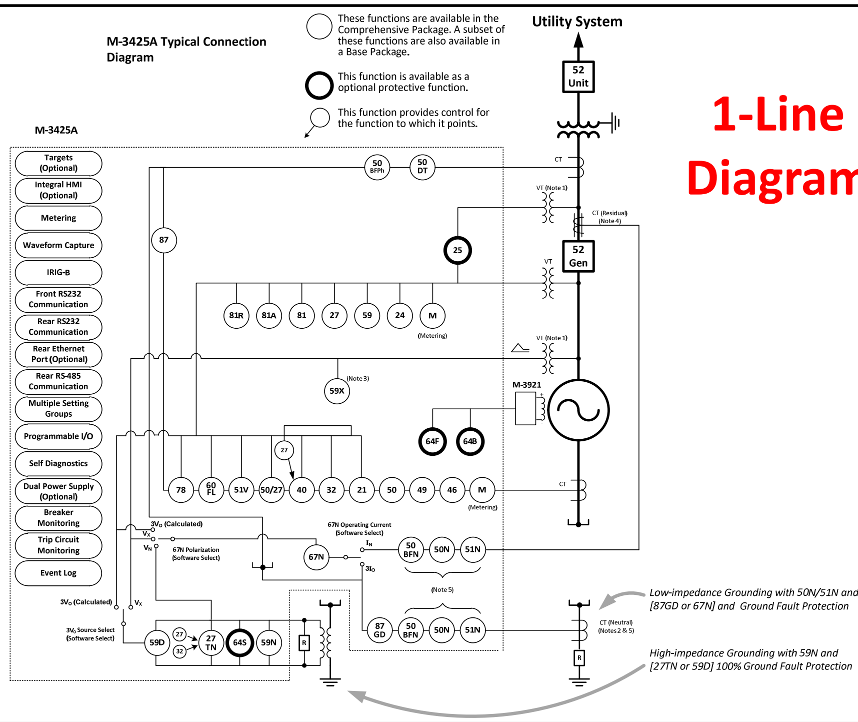
904-238-3844

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 PSRCC 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.
- Contributed to McGraw-Hill's "Standard Handbook of Power Plant Engineering."

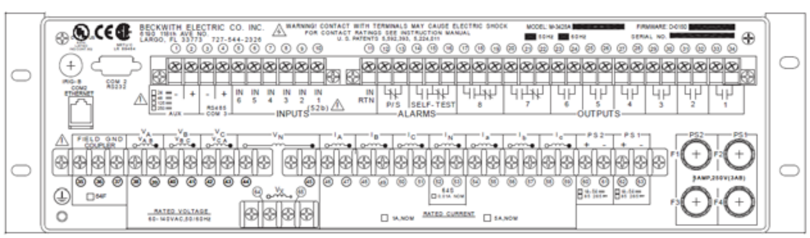
2

1-Line Diagram

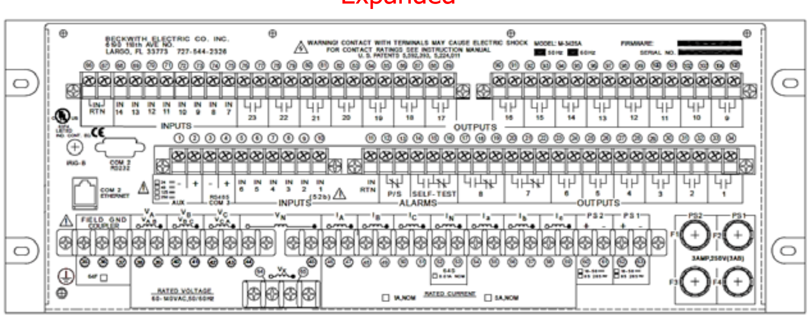


BECKWITH ELECTRIC CO. INC.

Standard

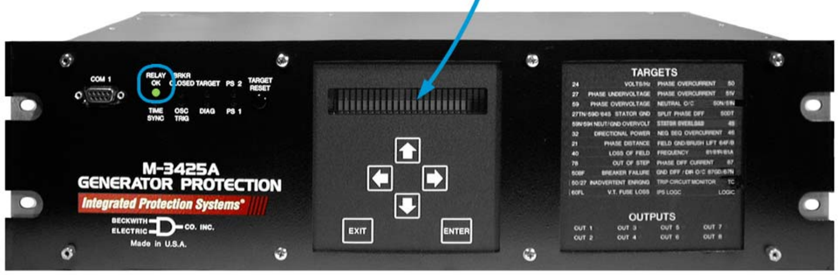


Expanded

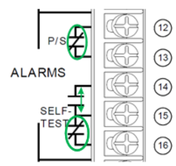


Normal Operation - No Targets

Display dark if there are no active targets

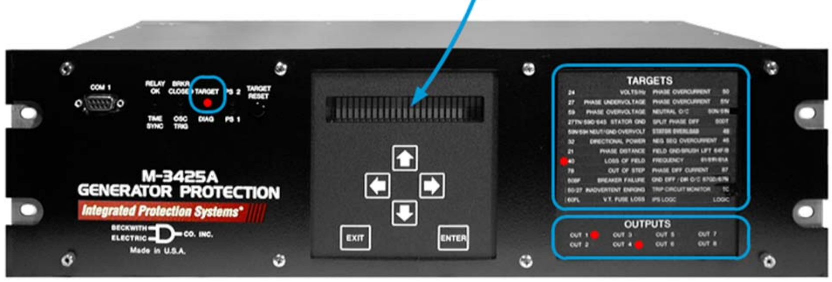


- Power supply fail contact = energized
  - Note: On relays with 2 power supplies installed, both must be powered up to energize this contact.
- Diagnostic Contact = coils energized, "OK" state



Tripped

Target, Time, Outputs, Function, Phase



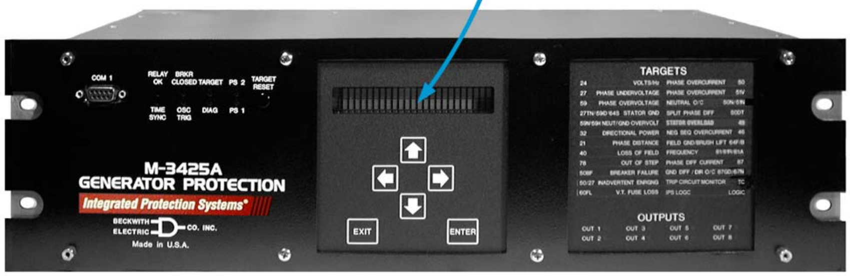
•One or more "OUTPUT" LEDs illuminated

BECKWITH ELECTRIC CO. INC.

M-3425A Operation

Trip Cleared and Target Present

Target, Time, Outputs, Function, Phase



•All “OUTPUT” LEDs Extinguished

7

BECKWITH ELECTRIC CO. INC.

M-3425A Operation

Relay failed internal self diagnostics

Relay “OK” LED Extinguished

Relay “Diagnostic” LED Blinks

“System Halt!” Error Code X

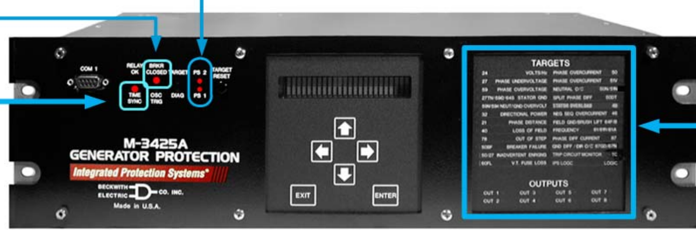
Self-Diagnostic Contact Operates (on relay rear)

- 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.

8

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

BECKWITH ELECTRIC CO. INC. M-3425A Operation

Front panel controls

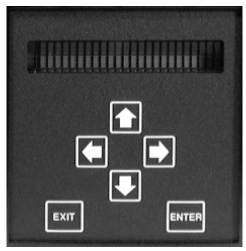
Target Reset Button:

- **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.



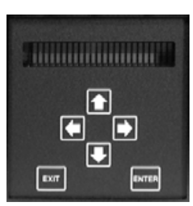
HMI Operation

VOLTAGE RELAY
VOLT curr freq v/hz →

- 27 Phase Undervoltage
- 59 Phase Overvoltage
- 27TN Neutrl Undervolt
- 59X Overvoltage
- 59N Neutral Overvoltage
- 59D Volt. Diff. 3rd Har.

CURRENT RELAY
volt CURR freq v/hz →

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



HMI Operation

FREQUENCY RELAY
volt curr FREQ v/hz →

- 81 Frequency
- 81R Rate of Change Freq
- 81A Frequency Accum.

VOLTS PER HERTZ RELAY
volt curr 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

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

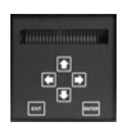
TRIP CIRCUIT MONITOR
← brkr TRPCKT ipslog →

- 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



BECKWITH ELECTRIC CO. INC.

M-3425A Operation

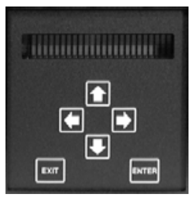
HMI Operation

SETUP SYSTEM
← config SYS stat →

- Input Activated Profiles
- Active Setpoint Profile
- Copy Active Profile
- Nominal Voltage
- Nominal Current
- V. T. Configuration
- Delta-Y Transform
- Phase Rotation
- 59/27 Magnitude Select
- 50DT Split-phase Diff.
- Pulse Relay
- Latched Outputs
- Relay Seal-in Time
- Active Input State
- V.T. Phase Ratio
- V.T. Neutral Ratio
- V.T. VX Ratio
- C.T. Phase Ratio
- C.T. Neutral Ratio

STATUS
← config sys STAT →

- Voltage Status
- Current Status
- Frequency Status
- V/Hz Status
- Power Status
- Impedance Status
- Sync Check Status
- Breaker Mon Acc Status
- 81A Accumulators Status
- In/Out Status
- Timer Status
- Relay Temperature
- Counters
- Time of Last Power Up
- Error Codes
- Checksums



VIEW TARGET HISTORY
← TARGETS osc_rec comm →

- View Target History
- Clear Target History

15

BECKWITH ELECTRIC CO. INC.

M-3425A Operation

HMI Operation

OSCILLOGRAPH RECORDER
← targets OSC_REC comm →

- View Record Status
- Clear Records
- Recorder Setup

COMMUNICATION
← targets osc_rec COMM →

- COM1 Setup
- COM2 Setup
- COM3 Setup
- Communication Address
- Response Time Delay
- Communication Access Code
- Ethernet Setup
- Ethernet IP Address

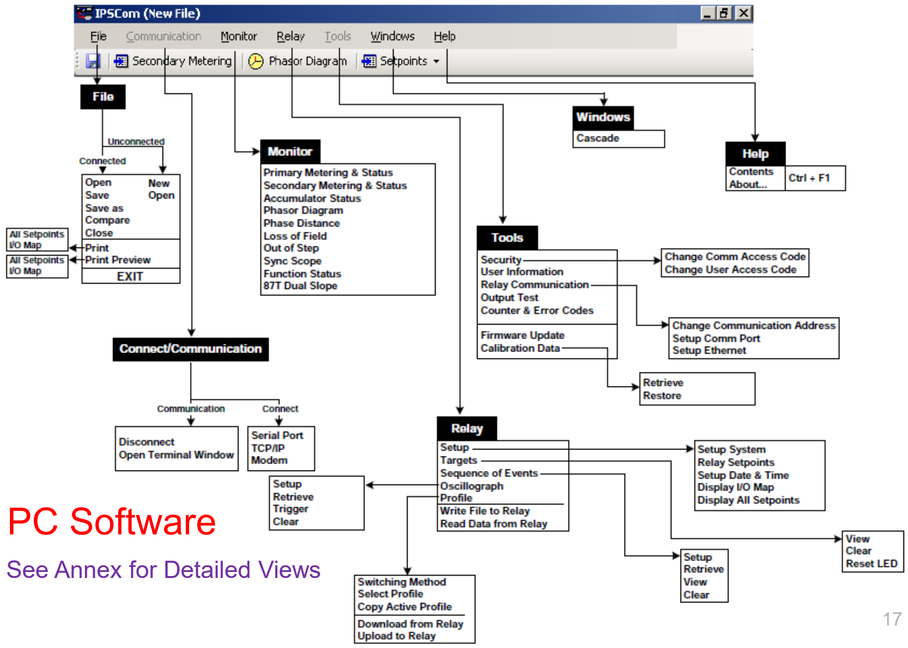
SETUP UNIT
← SETUP exit

- Software Version
- Serial Number
- Alter Access Codes
- User Control Number
- User Logo Line 1
- User Logo Line 2
- Clear Output Counters
- Clear Alarm Counter
- Date & Time
- Clear Error Codes
- Ethernet Firmware Ver.
- Diagnostic Mode

EXIT LOCAL MODE
← setup EXIT

16

BECKWITH ELECTRIC CO. INC.



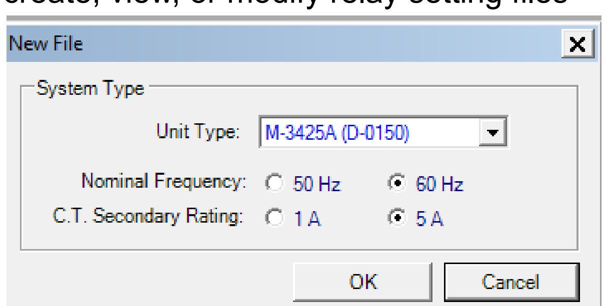
PC Software

See Annex for Detailed Views

BECKWITH ELECTRIC CO. INC.

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

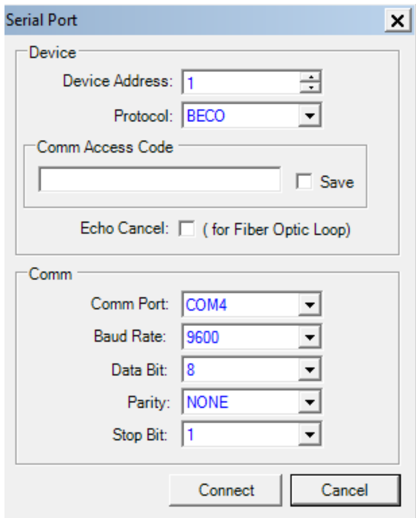
•For and Existing File:

- •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

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 Sens**ing: *Verify the breaker's position contact is working correctly.*

Digital Relay Self-Diagnostics

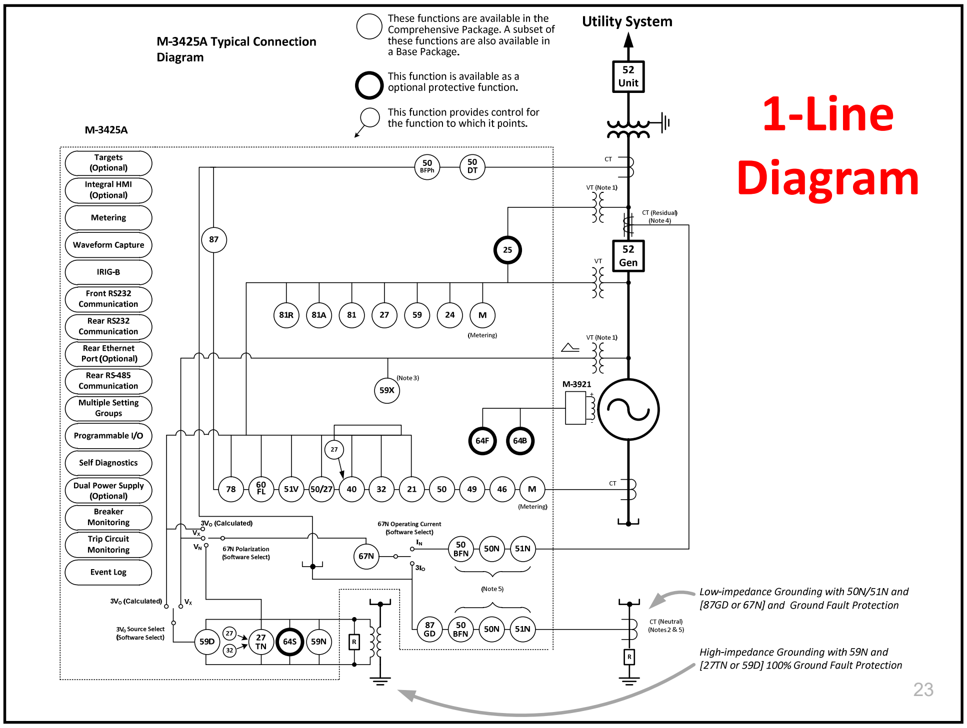
What it covers:

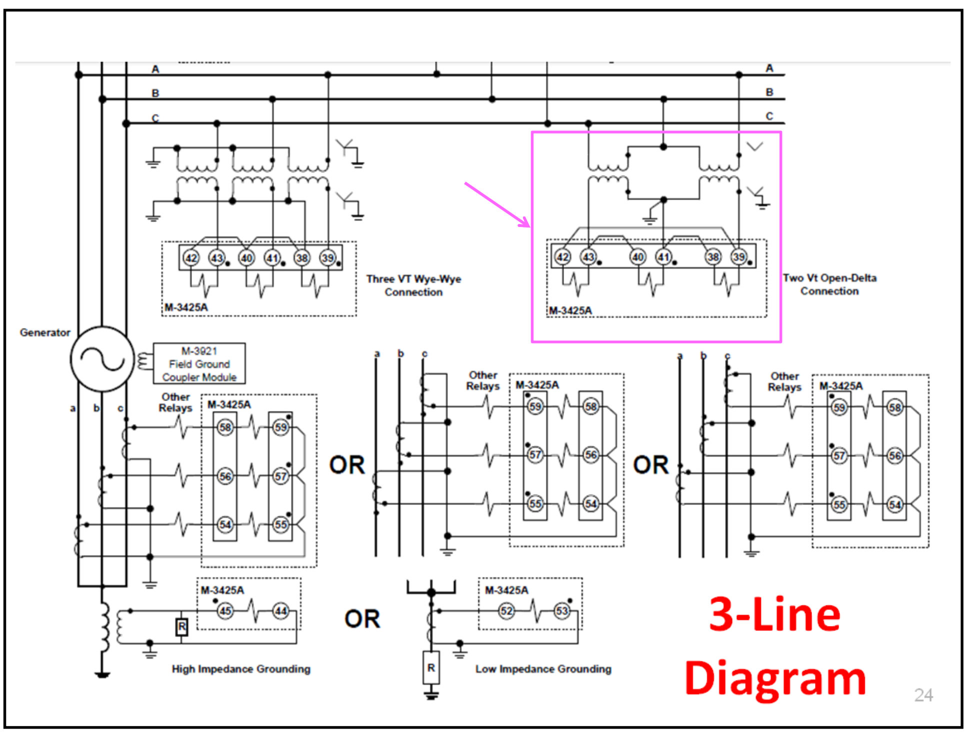
- Microprocessor hand-shaking
- ADC
- Power supply
- Communication failures
- Watchdogs
- Firmware flash failures

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.

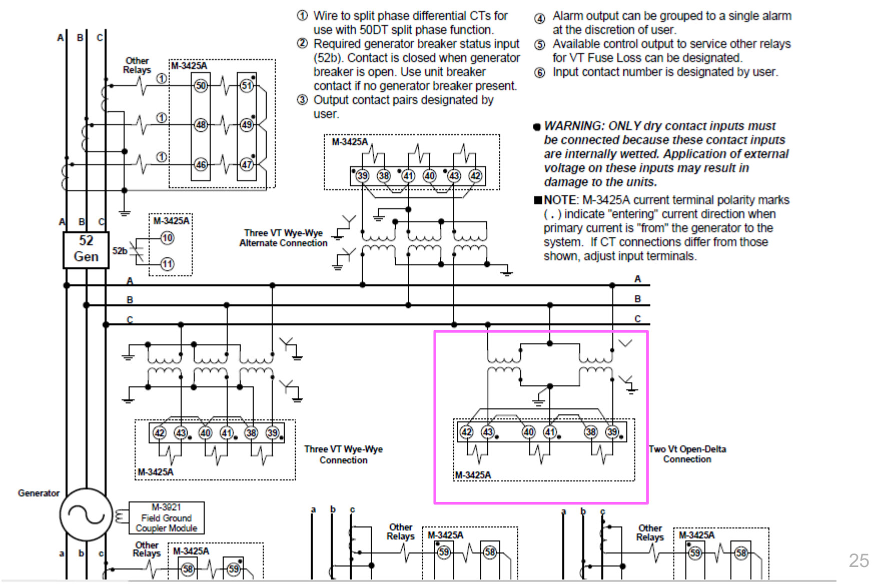

M-3425A Typical Connection Diagram
These functions are available in the Comprehensive Package. A subset of these functions are also available in a Base Package.
This function is available as a optional protective function.
This function provides control for the function to which it points.
Utility System
52 Unit
52 Gen
M-3425A
Targets (Optional)
Integral HMI (Optional)
Metering
Waveform Capture
IRIG-B
Front RS232 Communication
Rear RS232 Communication
Rear Ethernet Port (Optional)
Rear RS-485 Communication
Multiple Setting Groups
Programmable I/O
Self Diagnostics
Dual Power Supply (Optional)
Breaker Monitoring
Trip Circuit Monitoring
Event Log
M-3921
1-Line Diagram
Low-impedance Grounding with 50N/51N and [87GD or 67N] and Ground Fault Protection
High-impedance Grounding with 59N and [27TN or 59D] 100% Ground Fault Protection
23


Generator
M-3921 Field Ground Coupler Module
Three VT Wye-Wye Connection
Two Vt Open-Delta Connection
M-3425A
Other Relays
OR
High Impedance Grounding
Low Impedance Grounding
3-Line Diagram
24

BECKWITH ELECTRIC CO. INC.

M-3425A Connections

3-Line Diagram Partial: A



BECKWITH ELECTRIC CO. INC.

M-3425A Connections

3-Line Diagram Partial: B

M-3425A Pre-startup Tasks

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.

27

M-3425A Pre-startup Tasks

1. Energize the relay
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

28

BECKWITH ELECTRIC CO. INC.

M-3425A Pre-startup Tasks

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.

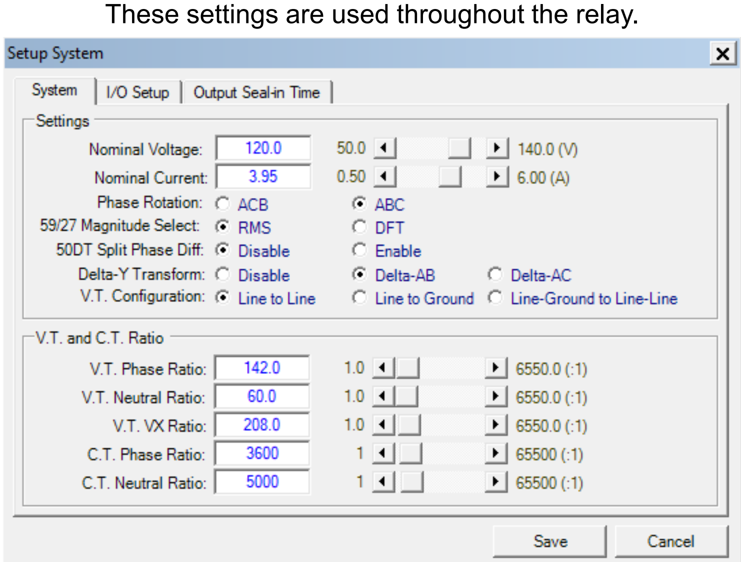
29

BECKWITH ELECTRIC CO. INC.

M-3425A Pre-startup Tasks

System Setup Settings:

These settings are used throughout the relay.



30

BECKWITH ELECTRIC CO. INC.

M-3425A Pre-startup Tasks

Basic Settings (cont.):

VT Configuration	Nominal Voltage	Used
L-G	V_{nom} = GEN V_{LL}/ (1.732*VTR)	(21, 32, 40, 46, 50/27, 51V)
L-L	V_{nom} = GEN V_{LL}/ (VTR)	
L-G to L-L	V_{nom} = GEN V_{LL}/ (VTR)	

Nominal Current

I_{nom} = GEN VA / (1.732* GEN V_{LL}*CTR) (21, 32, 40, 46, 50/27, 51V, 87)

Delta-Y Transform (21, 51V):

Determines calculation used for 21 and 51V functions

31

BECKWITH ELECTRIC CO. INC.

M-3425A Pre-startup Tasks

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.*

32

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 30cyc.
- 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.

Basic Settings (cont.):

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

M-3425A Pre-startup Tasks

Connect the relay ***voltages*** *for today's training:*

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

Test Set Connections:

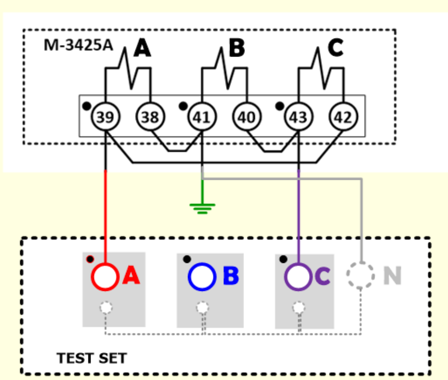
Phase A+ to terminal # 38
Phase B+ (None)
Phase C+ to terminal # 43
Return A,B,C to terminal #39

Single Phase Voltage

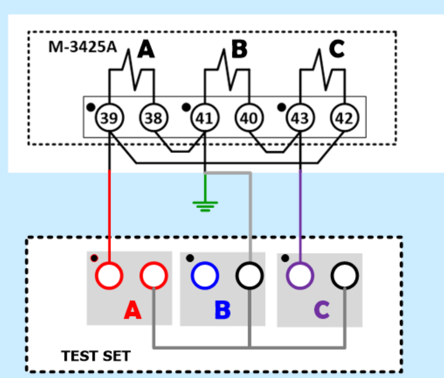
V+ to #45
V1 to #44

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.

BECKWITH ELECTRIC CO. INC.

M-3425A Pre-startup Tasks

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

M-34XX Test Connection

Test Set currents 1	M-3425A
IA	IA +
IB	IB +
IC	IC +
IN	Jumper

Neutral Terminals

Test Set currents 2	M-3425A
IA	Ia +
IB	Ib +
IC	Ic +
IN	Jumper

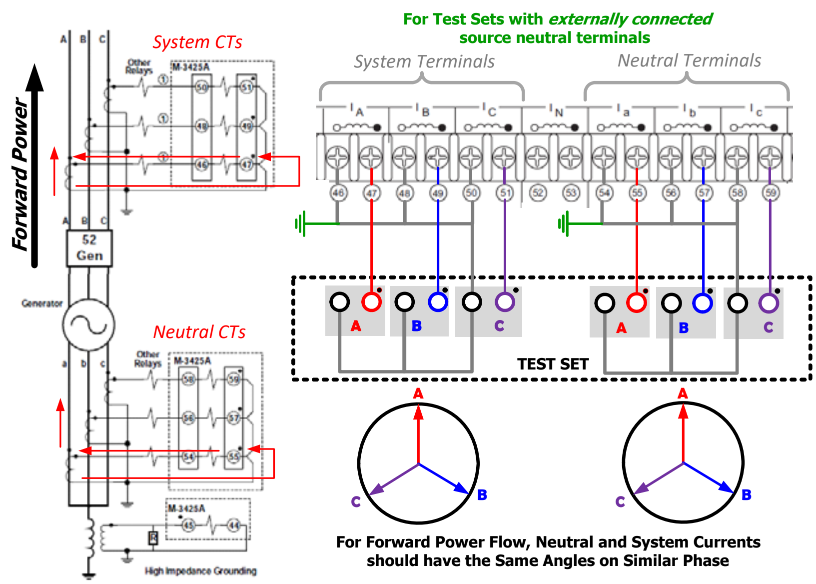
OutputTerminals

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

37

BECKWITH ELECTRIC CO. INC.

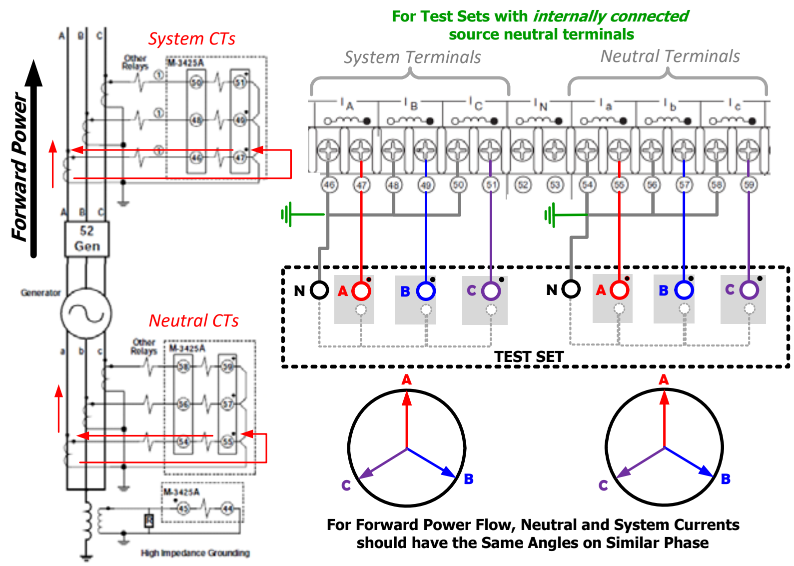
Phase Current Connections



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

38

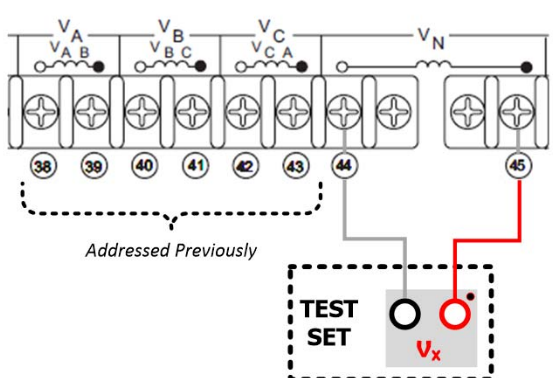
Phase Current Connections



39

BECKWITH ELECTRIC CO. INC.

Neutral Voltage Connection

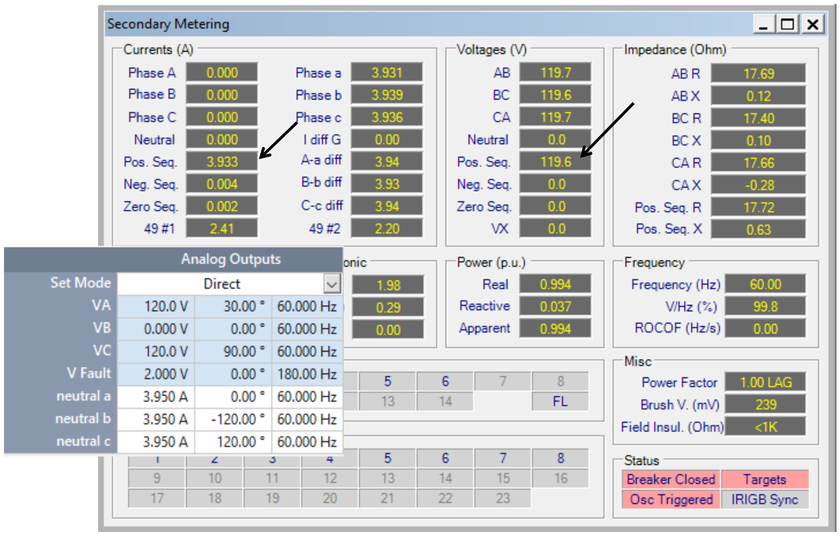


40

BECKWITH ELECTRIC CO. INC.

Apply nominal quantities and check the metering

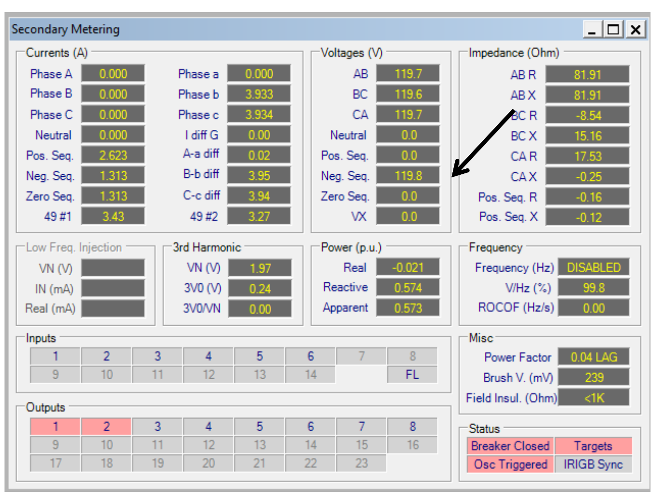
Delta-Connected PTs with Line-Line Relay Setting



41

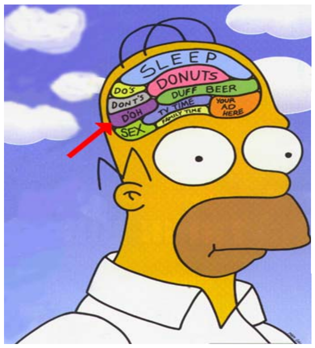
BECKWITH ELECTRIC CO. INC.

Incorrect Wiring: VA and VB Rolled



What shows the relay is wired wrong?

How Do We Test?



"Thinking logically as to how a relay responds in a faulted condition helps to visualize a proper test sequence"
--Drew Welton

How Do We Test?

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)

BECKWITH ELECTRIC CO. INC.

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

45

BECKWITH ELECTRIC CO. INC.

Overall Test Plan

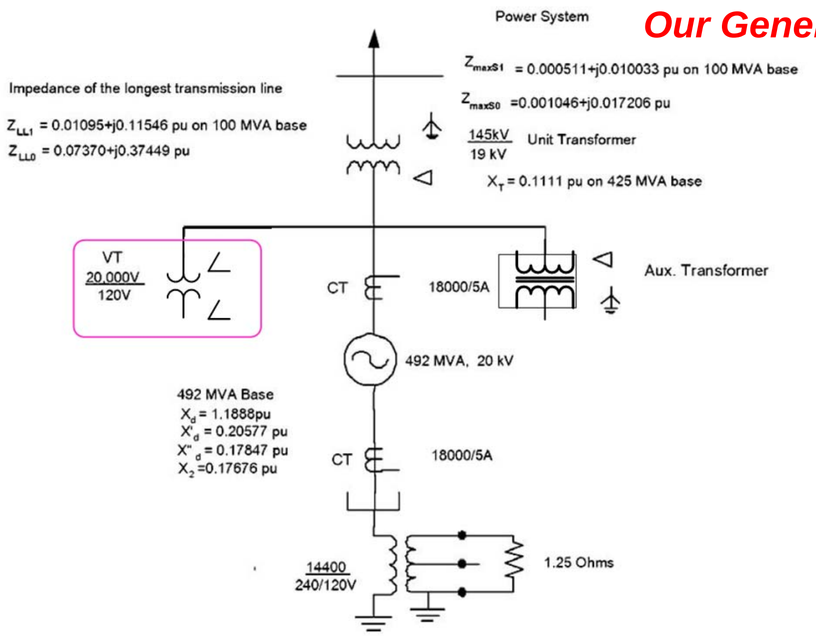
1. **Pre-Startup Tasks and Relay Setup**
2. **Negative Sequence (46)**
3. **Loss of Synchronism (78)**
4. **Stator Ground Overvoltage (59N)**
5. **Third Harmonic Neutral Undervoltage (27TH)**
6. **Oscillography and SOE Demo**

⇒W

46

BECKWITH ELECTRIC CO. INC.

Our Generator



47

BECKWITH ELECTRIC CO. INC.

Calculations for Our Generator

Z_{base} = (GEN kV^2 / GEN MVA) / (1.73*kV$_{base}$)
Z_{base} = (20 kV^2 / 492 MVA) / (1.73*20 kV$_{base}$)
Z_{base} = 0.813 Ω $_{pri}$

I_{base} = (MVA * 1000) / (1.73 * kV$_{Base}$)
I_{base} = (492 MVA * 1000) / (1.73 * 20$_{Base}$)
I_{base} = 14,219A $_{pri}$

VTR = 20,000V / 120V = 166.7
CTR = 18,000A / 5A = 3,600
CTR/VTR = 21.5996

$I_{base\ sec}$ = I $_{pri}$ / CTR
$I_{base\ sec}$ = 14,219 $_{pri}$ / 3,600
$I_{base\ sec}$ = 3.945 A $_{sec}$

$V_{LL\ sec}$ = 120V
$V_{LG\ sec}$ = $V_{LL\ sec}$ / 1.73
$V_{LL\ sec}$ = 69.28V sec

$Z_{Base\ sec}$ = $Z_{Base\ pri}$ * (CTR / VTR)
$Z_{Base\ sec}$ = 0.813 Ω $_{pri}$ * (3,600 / 166.7)
$Z_{Base\ sec}$ = 17.55 Ω $_{sec}$ (1pu)

Reactances per unit (492 MVA Base)
Xd = 1.1888 pu
X'd = 0.20577 pu

$X'_d = 0.20577 \times 17.56 = 3.613\ \Omega$

$X_{TG} = 0.11607 \times 17.56 = 2.04\ \Omega$

$X_{\max SG1} = 0.04035 \times 17.56 = 0.7086\ \Omega,\ \beta = 90°$

$Z_{Base\ sec}$ = $Z_{Base\ pri}$ * (CTR / VTR)
$Z_{Base\ sec}$ = 0.813 W $_{pri}$ * (3,600 / 166.7)
$Z_{Base\ sec}$ = 17.55 W $_{sec}$ (1pu)

48

Negative Sequence Overcurrent (46)

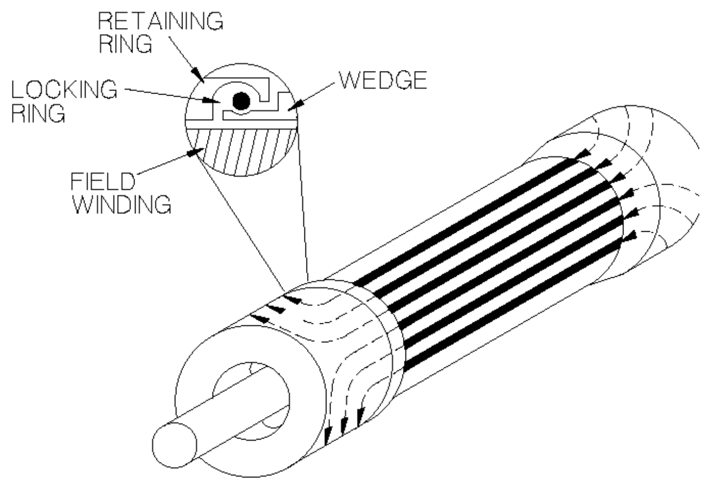
⇒W

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

BECKWITH ELECTRIC CO. INC.

Rotor End Winding Construction



Currents Flow in the Rotor Surface

51

BECKWITH ELECTRIC CO. INC.

Negative Sequence Current: Constant Withstand Generator Limits

- **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%

52

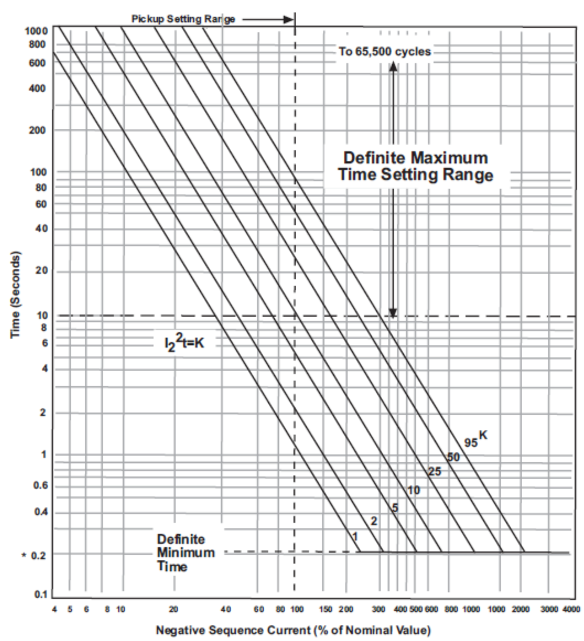
BECKWITH ELECTRIC CO. INC.

Negative Sequence Current: Constant Withstand Generator Limits

- **Nameplate**
  - Negative Sequence Current (I_2) Constant Withstand Rating
  - "K" Factor
  - Where: $I_2^2 T = K$

53

BECKWITH ELECTRIC CO. INC.



Generator Ratings

Typical
<u>K Values</u>
Salient Pole Generators
40

Cylindrical Generators
30

54

BECKWITH ELECTRIC CO. INC.

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

55

BECKWITH ELECTRIC CO. INC.

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

56

BECKWITH ELECTRIC CO. INC.

46: Setting

Type of generator	Permissible I_2 (percent)
Salient pole	10
With connected amortisseur windings	10
With non-connected amortisseur windings	5
Cylindrical rotor	
Indirectly cooled	10
Directly cooled—Up to 350 MVA	8
—351 MVA to 1250 MVA	8–(MVA–350)/300
—1251 MVA to 1600 MVA	5

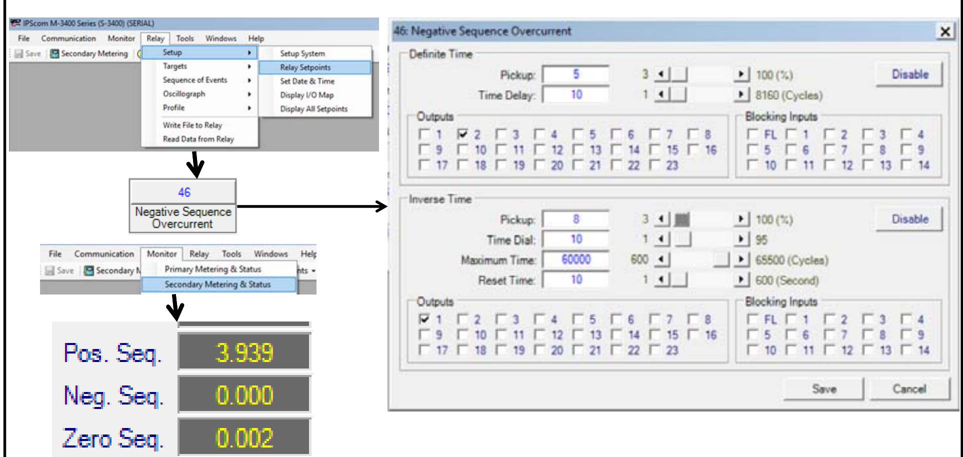
492 MVA;
Cylindrical

Type of generator	Permissible I_2^2t
Salient pole generator	40
Synchronous condenser	30
Cylindrical rotor generators	
Indirectly cooled	30
Directly cooled (0 MVA to 800 MVA)	10
Directly cooled (801 MVA–1600 MVA)	See Figure 4-39.

57

BECKWITH ELECTRIC CO. INC.

46: Setting



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

Testing the 46 Element, Def. Time

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

Alarm Contact

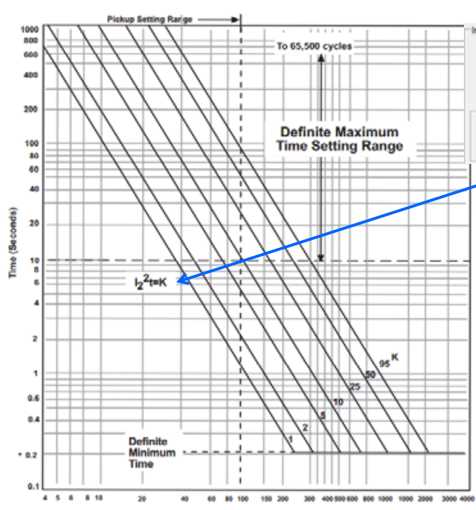
Pos. Seq.	3.939
Neg. Seq.	0.000
Zero Seq.	0.002

Pos. Seq.	3.929
Neg. Seq.	0.198
Zero Seq.	0.198

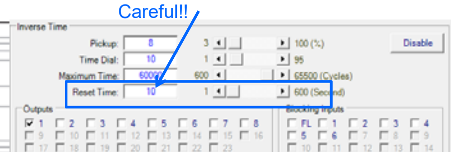
Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	0.00 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz

Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	-8.75 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz

Test Sequence for 46-Inverse Time



Careful!!



Use this formula like so:
I fault / I nom (6/3.95 = 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

Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	6.000 A	0.00 °	60.000 Hz
neutral b	6.000 A	120.00 °	60.000 Hz
neutral c	6.000 A	-120.00 °	60.000 Hz

Roll Ph b and c

Loss-of-Synchronism (78)

aka: Out-of-Step

⇒W

Generator Out-of-Step Protection (78)

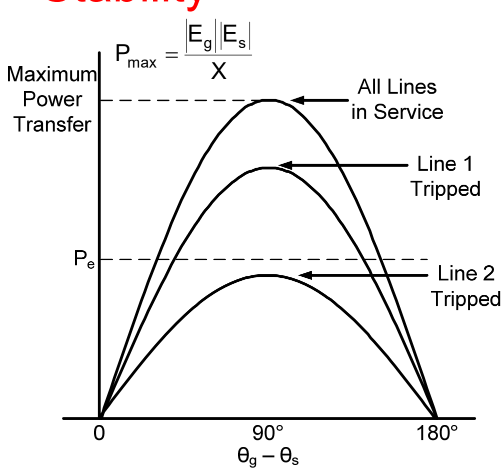
- Types of Instability
  - Steady State: Steady Voltage and Impedance (Load Flow)
  - Transient: Fault, where voltage and impedance change rapidly
  - Dynamic: Oscillations from AVR damping (usually low f)
- Occurs with unbalance of load and generation
  - Short circuits that are severe and close
  - 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 (78)

- 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

63

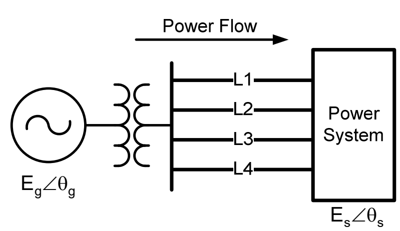
Stability



Power Transfer Equation

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

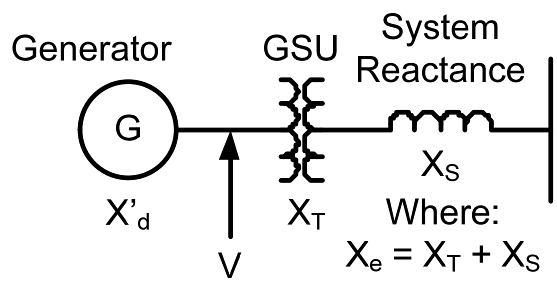
E_s - System Voltage
E_g - Generator Voltage
Θ_s - System Voltage Phase Angle
Θ_g - Generator Voltage Phase Angle
P_e - Electrical Power



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

64

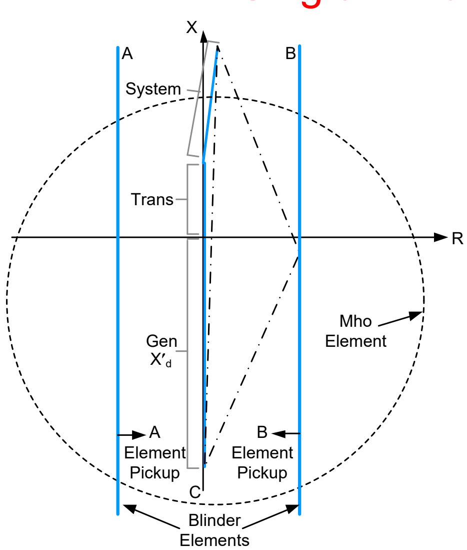
Out of Step: Generator and System Issue



Power Transfer Equation

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

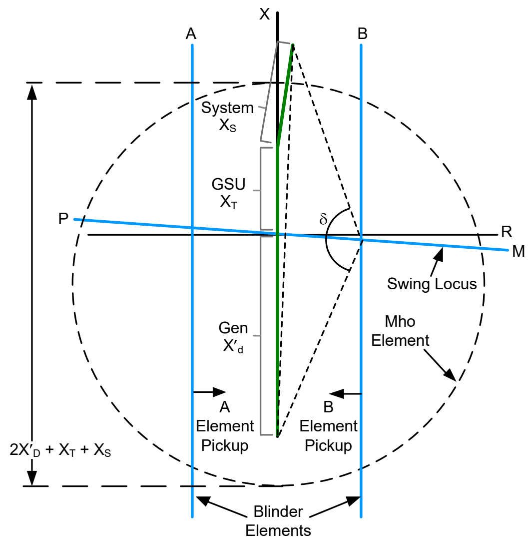
Single Blinder Scheme



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

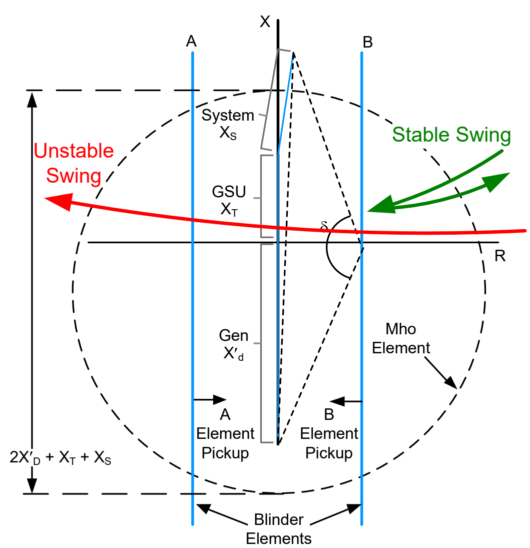
BECKWITH ELECTRIC CO. INC.

Graphical Method: 78



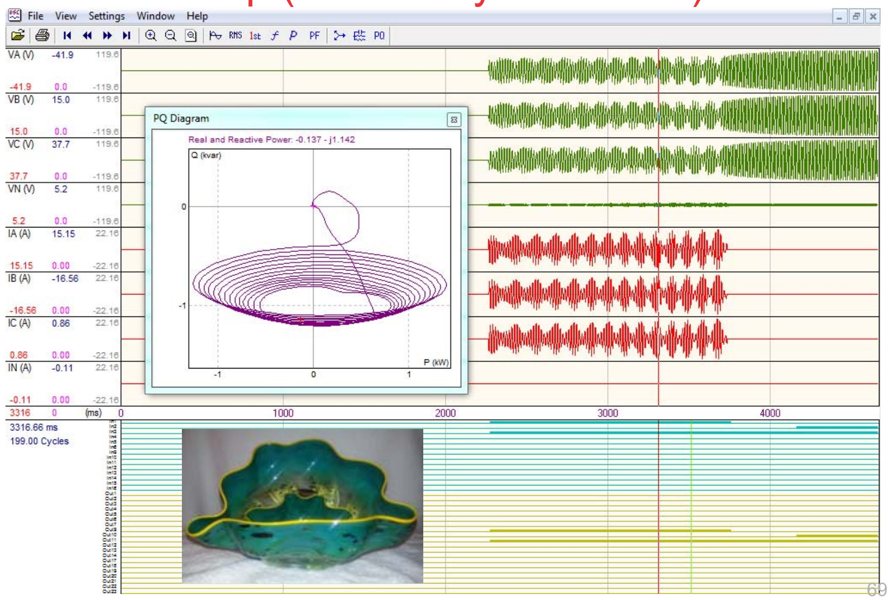
BECKWITH ELECTRIC CO. INC.

Graphical Method: 78



BECKWITH ELECTRIC CO. INC.

Out-of-Step (Loss of Synchronism) Event

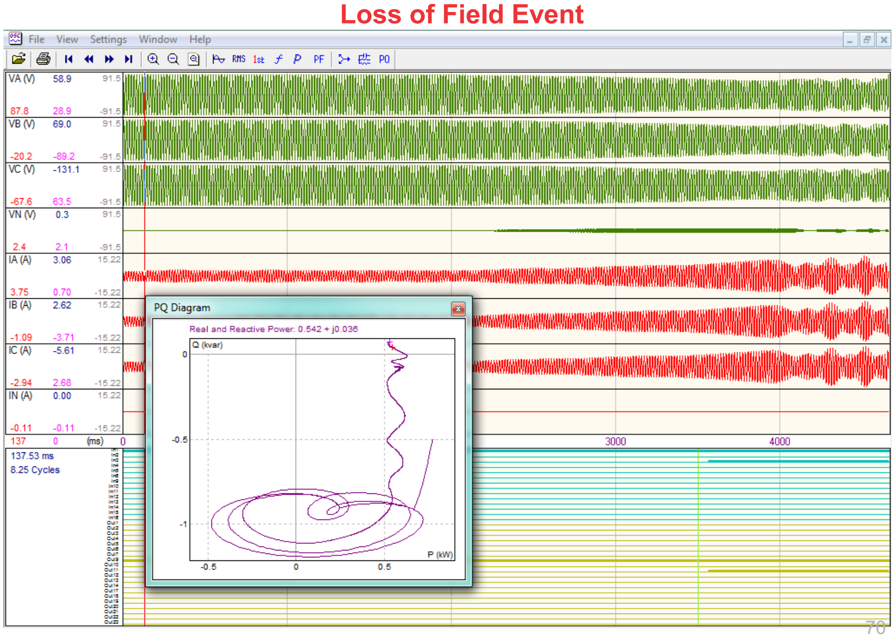


69

BECKWITH ELECTRIC CO. INC.

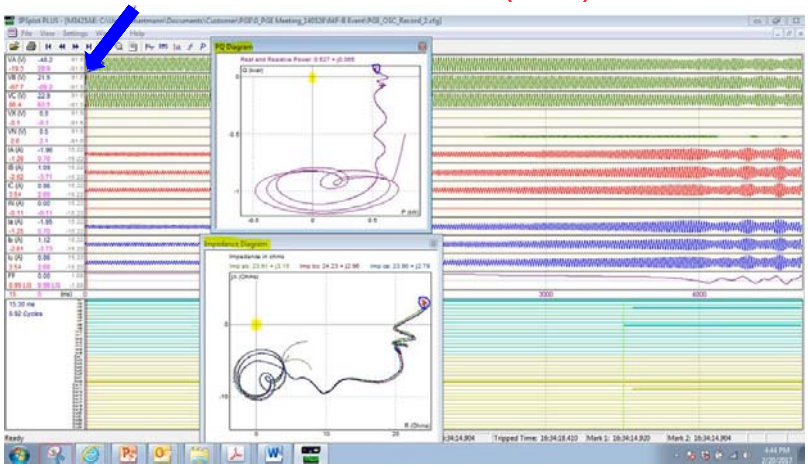
Generator Protection

Loss of Field Event



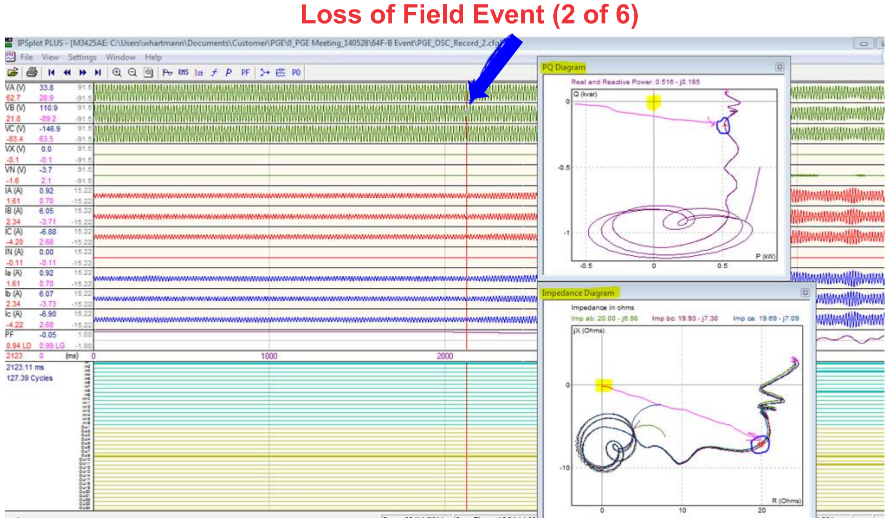
70

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)

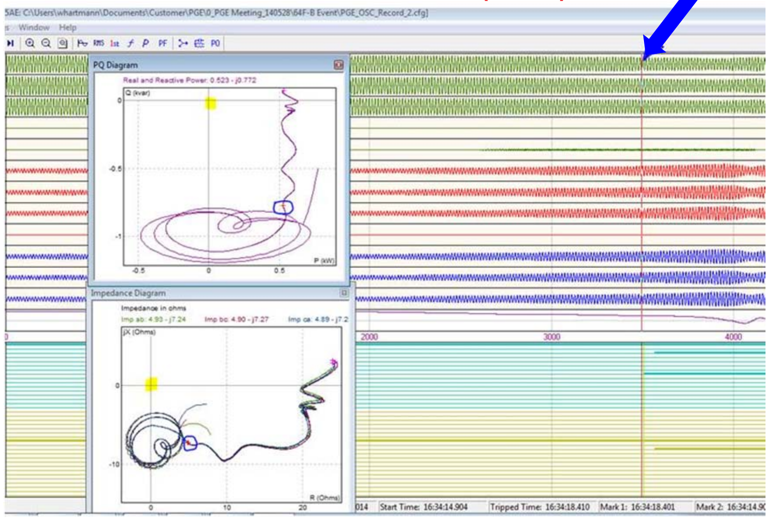


- We have lost field, and the impedance/power diagrams show we are still outputting watts but are sinking VAr
- This is before the machine goes into *asynchronous* operation with a resulting slip frequency

BECKWITH ELECTRIC CO. INC.

Generator Protection

Loss of Field Event (3 of 6)

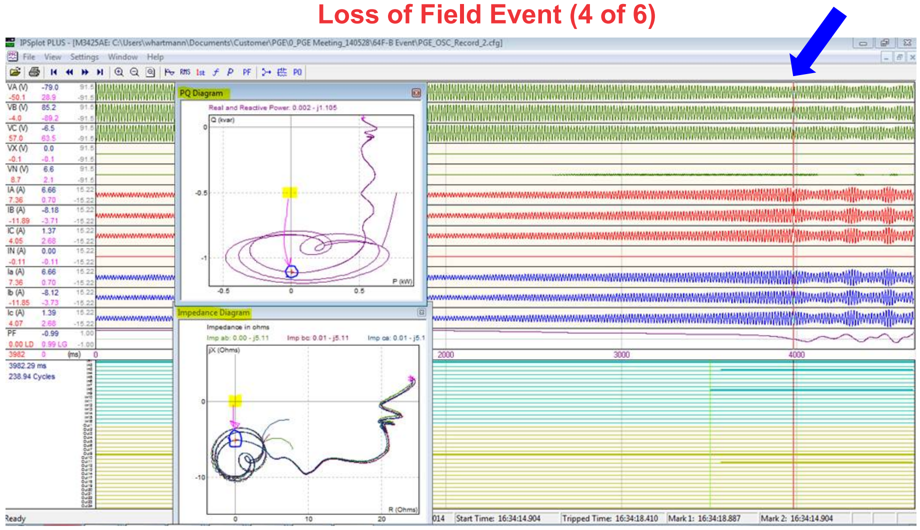


- We have lost field, and the impedance/power plan plots show we are still outputting watts but are sinking lots of VAr
- This is JUST before the machine goes into asynchronous operation with a slip

BECKWITH ELECTRIC CO. INC.

Generator Protection

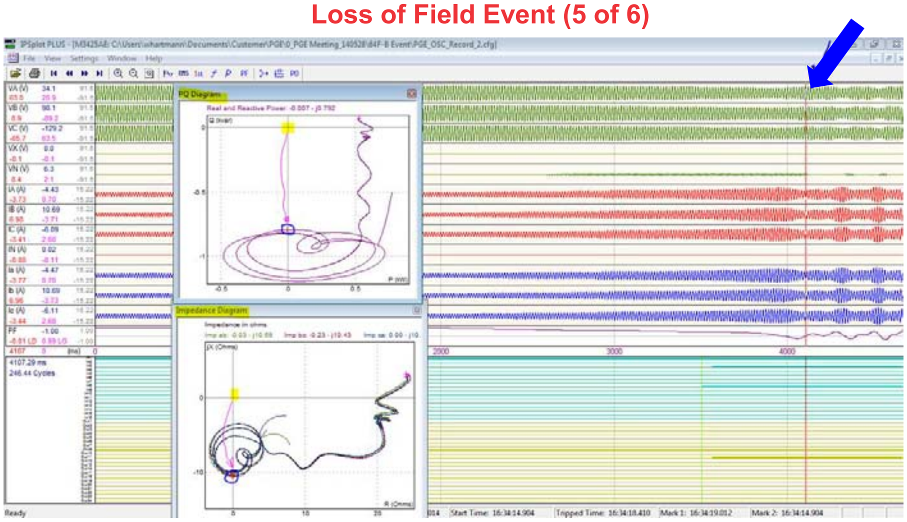
Loss of Field Event (4 of 6)



- 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).

Generator Protection

Loss of Field Event (5 of 6)

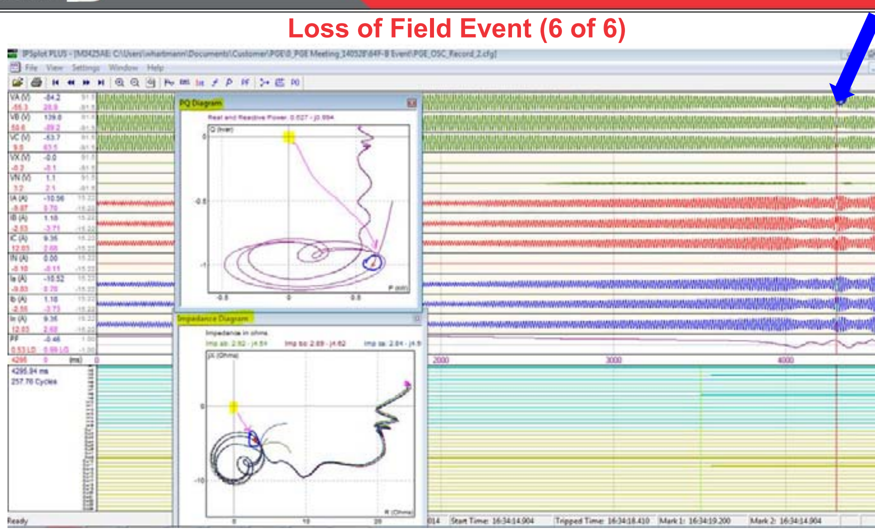


- The machine is slipping a pole. We are into the first slip cycle.

75

Generator Protection

Loss of Field Event (6 of 6)



- The machine is slipping a pole. We are into the first slip cycle.

76

BECKWITH ELECTRIC CO. INC.

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).

77

BECKWITH ELECTRIC CO. INC.

78: Setting

$$Amps = \frac{KVA \times 1000}{\sqrt{3} \times Volts}$$

$14202.8A_{pri} = \frac{492{,}000kVA * 1000}{1.73 * 20{,}000V}$

$3.945A_{sec}$ = 14,202.8 / 18,000:5 (3600 CTR)

$V_{LL\_B\_relay}$ = VT primary voltage/VT ratio = 20 000/166.67 = 120 V

$V_{LN\_B\_relay}$ = 11547/166.67 = 69.28 V [$120V_{LL}$ / 1.73 = $69V_{LN}$]

$$Z_{B\_relay} = \frac{V_{LN\_B\_relay}}{I_{B\_relay}} = 69.28/3.95 = 17.56\ \Omega$$

$X'_d = 0.20577 \times 17.56 = 3.613\ \Omega$, $X_{TG} = 0.11607 \times 17.56 = 2.04\ \Omega$

$X_{max\ SG1} = 0.04035 \times 17.56 = 0.7086\ \Omega$, $\beta = 90°$

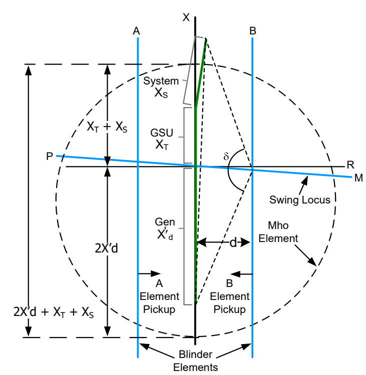
The blinder distance (d) = $((X'_d + X_{TG} + X_{max\ SG1})/2) \times \tan(90 - (\delta/2))$

For $\delta = 120°$ $d = 1.64\ \Omega$

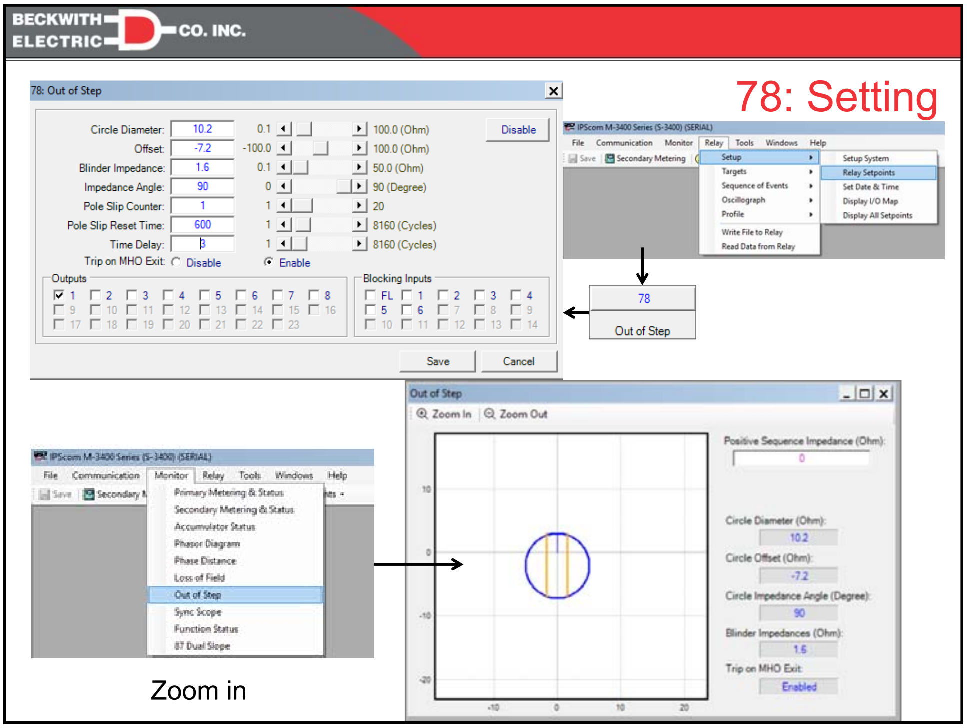
The diameter of the mho unit is $(2 \times X'_d + 1.5 \times X_{TG}) = 10.29\ \Omega$.

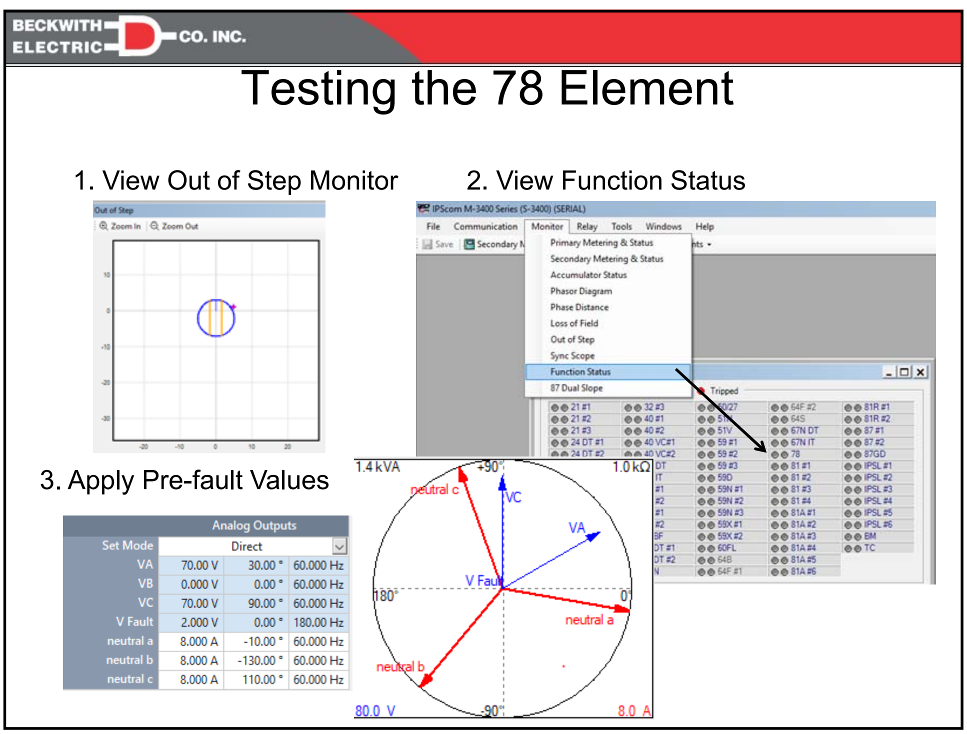
Impedance angle of the mho unit is 90°.

MHO offset = -2X'd = -7.2Ω



78


BECKWITH ELECTRIC CO. INC.
78: Setting
78: Out of Step
Circle Diameter: 10.2 0.1 100.0 (Ohm)
Offset: -7.2 -100.0 100.0 (Ohm)
Blinder Impedance: 1.6 0.1 50.0 (Ohm)
Impedance Angle: 90 0 90 (Degree)
Pole Slip Counter: 1 1 20
Pole Slip Reset Time: 600 1 8160 (Cycles)
Time Delay: 3 1 8160 (Cycles)
Trip on MHO Exit: Disable Enable
Disable
Outputs
Blocking Inputs
Save
Cancel
78
Out of Step
Out of Step
Zoom In Zoom Out
Positive Sequence Impedance (Ohm):
Circle Diameter (Ohm): 10.2
Circle Offset (Ohm): -7.2
Circle Impedance Angle (Degree): 90
Blinder Impedances (Ohm): 1.6
Trip on MHO Exit: Enabled
Primary Metering & Status
Secondary Metering & Status
Accumulator Status
Phasor Diagram
Phase Distance
Loss of Field
Out of Step
Sync Scope
Function Status
87 Dual Slope
Zoom in

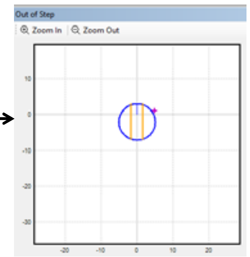

BECKWITH ELECTRIC CO. INC.
Testing the 78 Element
1. View Out of Step Monitor
2. View Function Status
3. Apply Pre-fault Values
Analog Outputs
Set Mode Direct
VA 70.00 V 30.00 ° 60.000 Hz
VB 0.000 V 0.00 ° 60.000 Hz
VC 70.00 V 90.00 ° 60.000 Hz
V Fault 2.000 V 0.00 ° 180.00 Hz
neutral a 8.000 A -10.00 ° 60.000 Hz
neutral b 8.000 A -130.00 ° 60.000 Hz
neutral c 8.000 A 110.00 ° 60.000 Hz
1.4 kVA
1.0 kΩ
neutral c
VC
VA
V Fault
neutral a
neutral b
80.0 V
8.0 A
Tripped

BECKWITH ELECTRIC CO. INC.

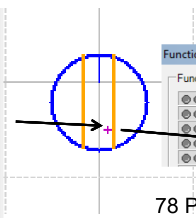
Testing the 78 Element

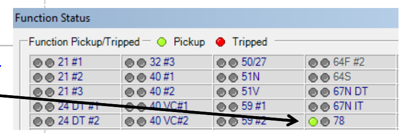
Rotate 3 ph currents up in 10 degree increments simultaneously

Analog Outputs			
Set Mode	Direct		
VA	70.00 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	70.00 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	8.000 A	-10.00 °	60.000 Hz
neutral b	8.000 A	-130.00 °	60.000 Hz
neutral c	8.000 A	110.00 °	60.000 Hz



Analog Outputs			
Set Mode	Direct		
VA	70.00 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	70.00 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	8.000 A	80.00 °	60.000 Hz
neutral b	8.000 A	-40.00 °	60.000 Hz
neutral c	8.000 A	200.00 °	60.000 Hz





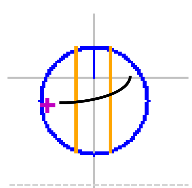
78 Picks up when it hits the load blinder

BECKWITH ELECTRIC CO. INC.

Testing the 78 Element

Continue to rotate 3 ph currents up in 10 degree increments

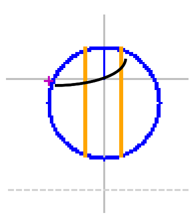
Analog Outputs			
Set Mode	Direct		
VA	70.00 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	70.00 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	8.000 A	150.00 °	60.000 Hz
neutral b	8.000 A	30.00 °	60.000 Hz
neutral c	8.000 A	270.00 °	60.000 Hz



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

Analog Outputs			
Set Mode	Direct		
VA	70.00 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	70.00 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	8.000 A	180.00 °	60.000 Hz
neutral b	8.000 A	60.00 °	60.000 Hz
neutral c	8.000 A	300.00 °	60.000 Hz

Binary Inputs / Trigger	
trip 1	2.304 cy



If we cross the boundary, the relay will trip within 2 to 3 cycles.

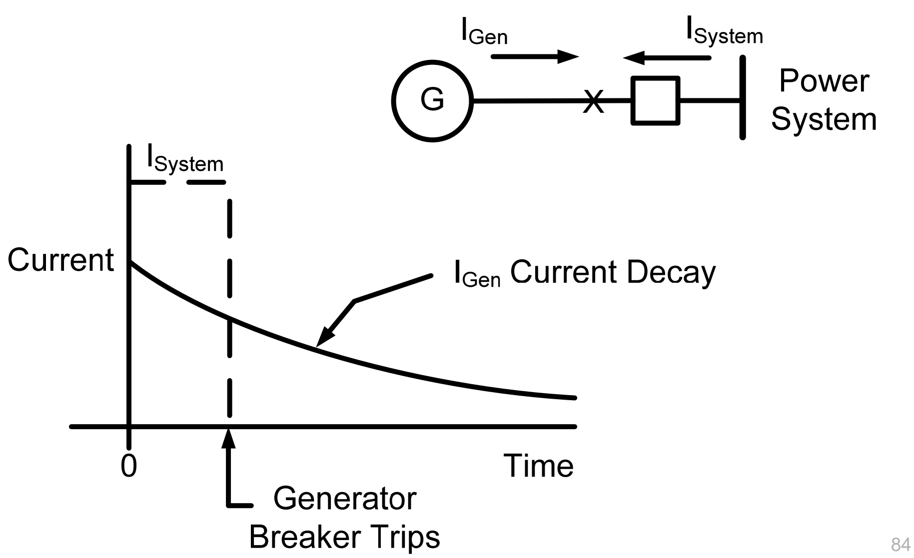
Stator Ground Fault (59N)

95% Stator Coverage

⇒W

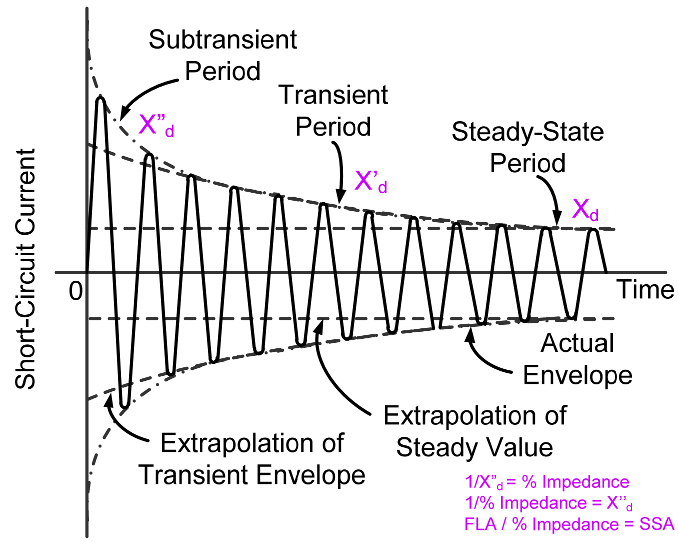
83

Generator Behavior During Short Circuits



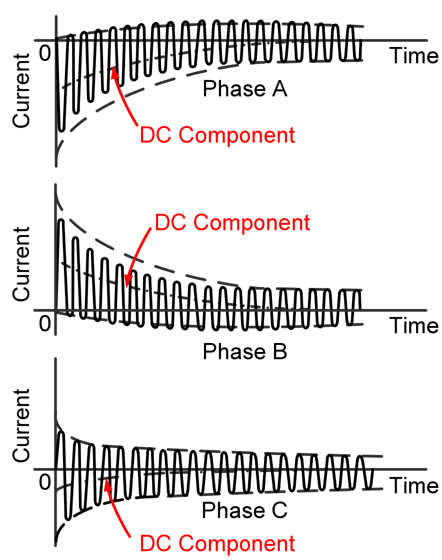
84

Generator Short-Circuit Current Decay



85

Effect of DC Offsets



86

BECKWITH ELECTRIC CO. INC.

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)

87

BECKWITH ELECTRIC CO. INC.

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

88

BECKWITH ELECTRIC CO. INC.

Stator Ground Fault Damage

89

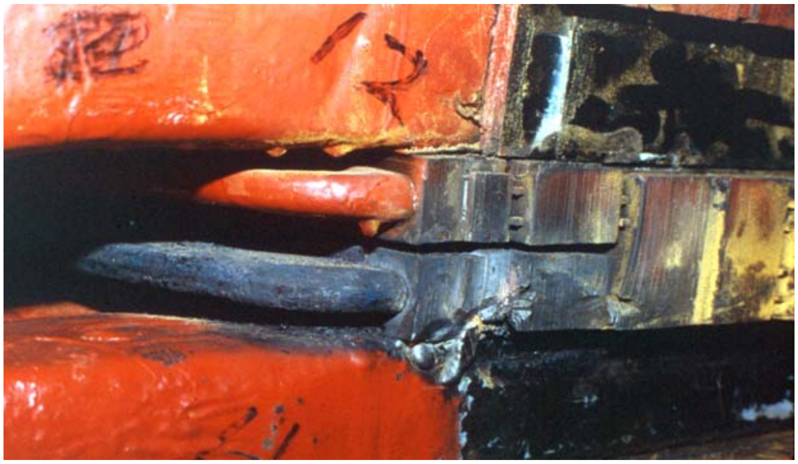
BECKWITH ELECTRIC CO. INC.

Stator Ground Fault Damage

90

BECKWITH ELECTRIC CO. INC.

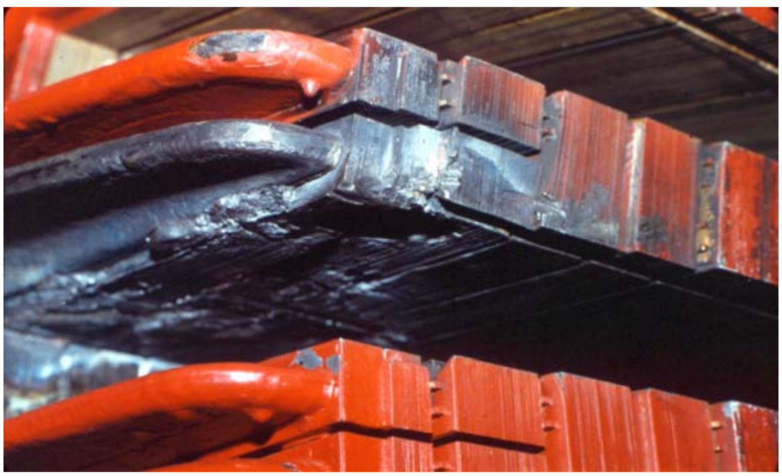
Stator Ground Fault Damage



91

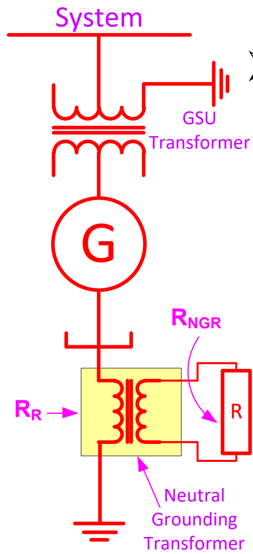
BECKWITH ELECTRIC CO. INC.

Stator Ground Fault Damage



92

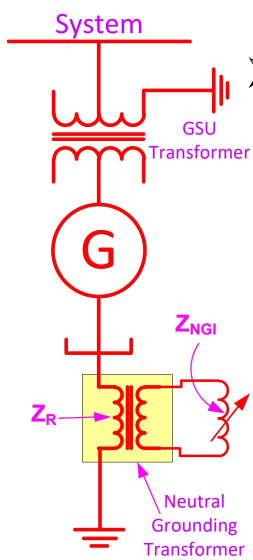
Types of Generator Grounding



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

93

Types of Generator Grounding



- 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)

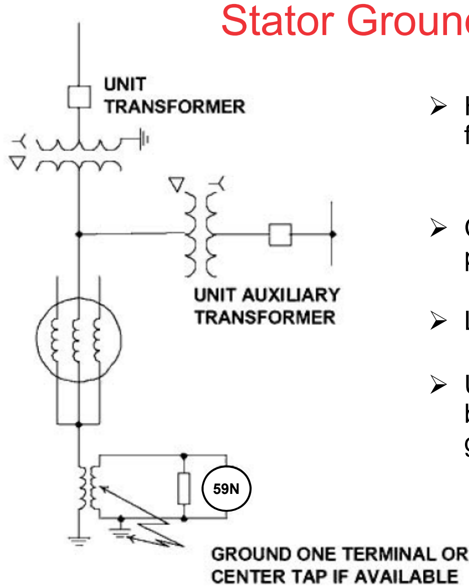
94

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)

95

Stator Ground Fault (59N)

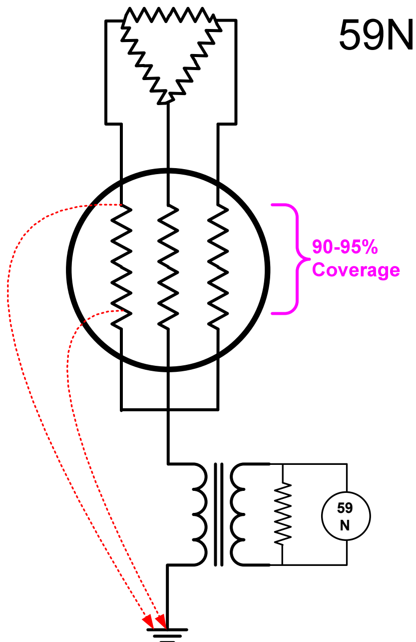


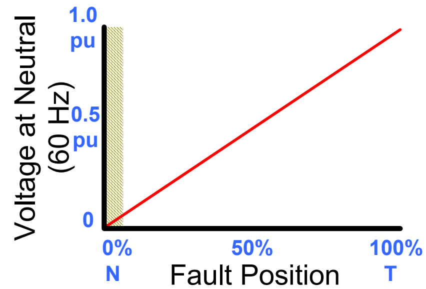
- High impedance ground limits ground fault current to about 10A
  - Limits damage on internal ground fault
- Conventional neutral overvoltage relay provides 90-95% stator coverage
- Last 5-10% near neutral not covered
- Undetected grounds in this region bypass grounding transformer, solidly grounding the machine!

96

BECKWITH ELECTRIC CO. INC.

59N Element



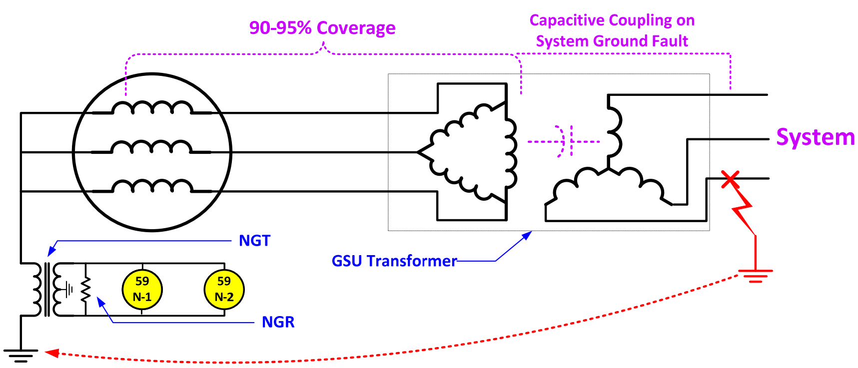


- **Neutral grounding transformer (NGT) ratio selected that provides 120 to 240V for ground fault at machine terminals**
  - **Max L-G volts =13.8kV / 1.73 = 7995V**
  - **Max NGT volts sec. = 7995V / 120V = 66.39 VTR**

97

BECKWITH ELECTRIC CO. INC.

59N System Ground Fault Issue



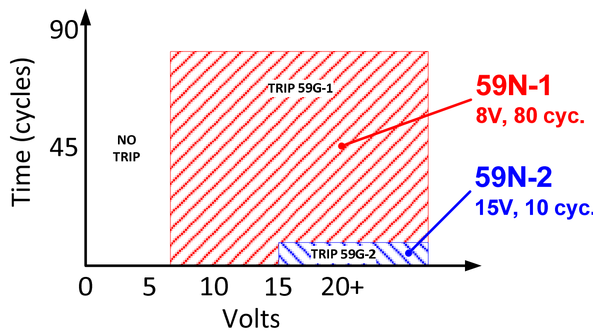
- GSU provides capacitive coupling for system ground faults into generator zone
- Use two levels of 59N with short and long time delays for selectivity
- Cannot detect ground faults at/near the neutral (very important)

98

BECKWITH ELECTRIC CO. INC.

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

99

BECKWITH ELECTRIC CO. INC.

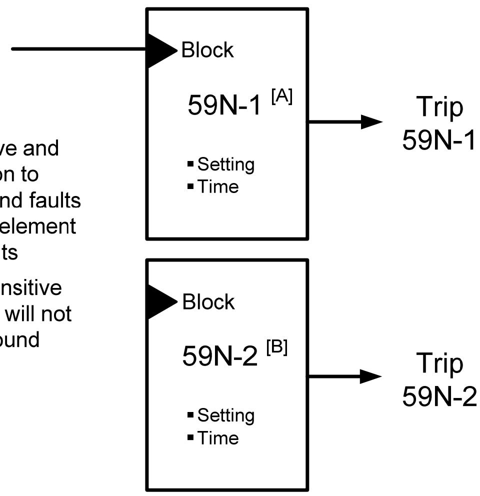
Use of Symmetrical Component Quantities to Control 59N Tripping Speed

- 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

100

Use of I_2 to Control Fast 59N Element

I_2 > 0.05 pu



NOTES:

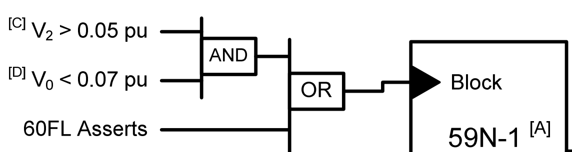
[A] 59N-1 is set sensitive and fast, using I_2 supervision to check for external ground faults and control (block) the element for external ground faults

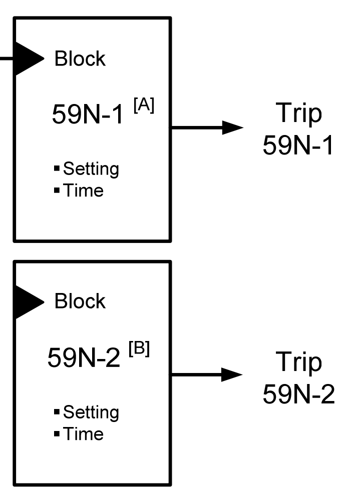
[B] 59N-2 is set less sensitive and slower, therefore it will not operate for external ground faults.

I_2 is used to control 59N for ground faults on the high voltage side of the GSU

BECKWITH ELECTRIC CO. INC.

Use of V_2 /V_0 to Control Fast 59N Element





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

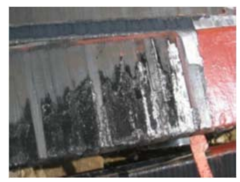
[D] V_0 derived from 3Y phase VTs

V_2 and V_0 is used to control 59N for ground faults on the high voltage side of the GSU *and* low voltage side of voltage transformers

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



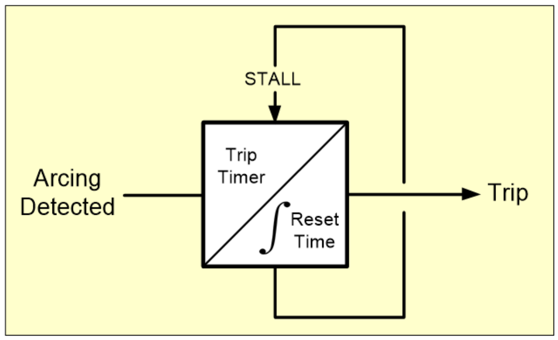
Side of a bar deeply damaged by vibration sparking

Premature Failure of Modern Generators, Clyde V. Maughan

Intermittent Arcing Ground Fault

BECKWITH ELECTRIC CO. INC.

Intermittent Arcing Fault Timer Logic

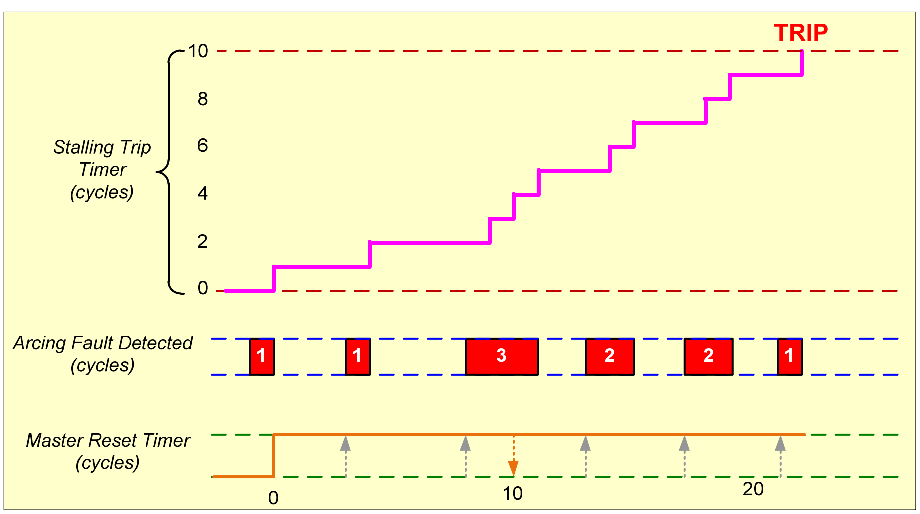


Stallable Trip Timer: Times Out to Trip
Integrating Reset Time: Delays Reset for Interval

105

BECKWITH ELECTRIC CO. INC.

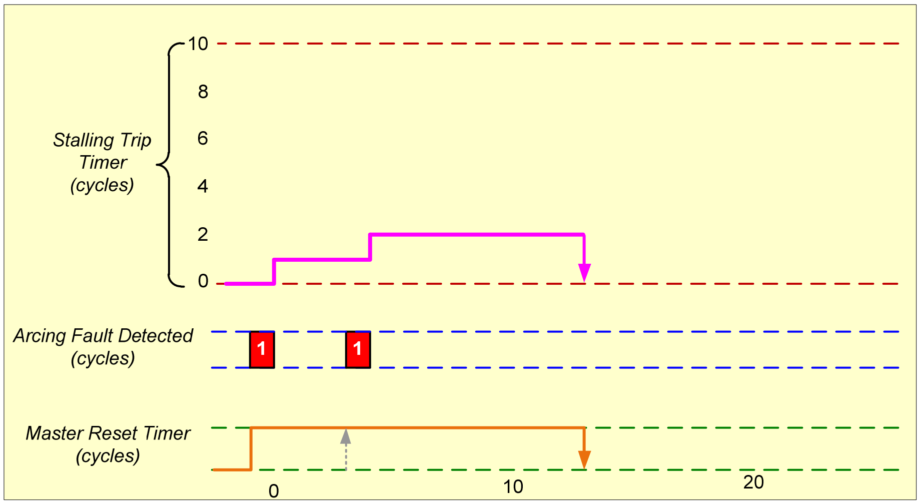
Intermittent Arcing Ground Fault



Arcing and Trip

106

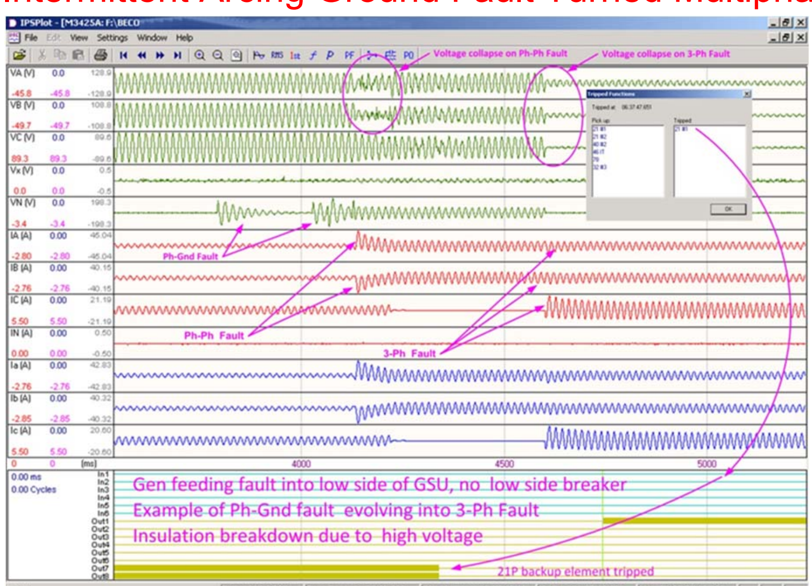
Intermittent Arcing Ground Fault



Arcing and Reset (No Trip)

107

Intermittent Arcing Ground Fault Turned Multiphase



108

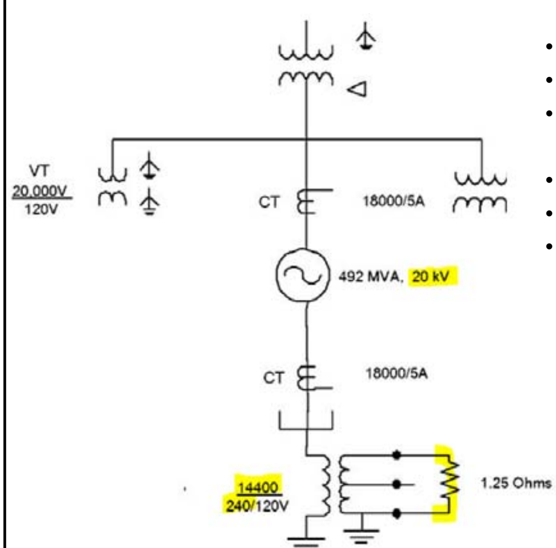
59N Element

59N – Generator Neutral Overvoltage: Three elements

- 1^{st} 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
- 2^{nd} 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
- 3^{rd} may be:
  - Set to initiate waveform capture and not trip
  - Used for intermittent arcing fault protection

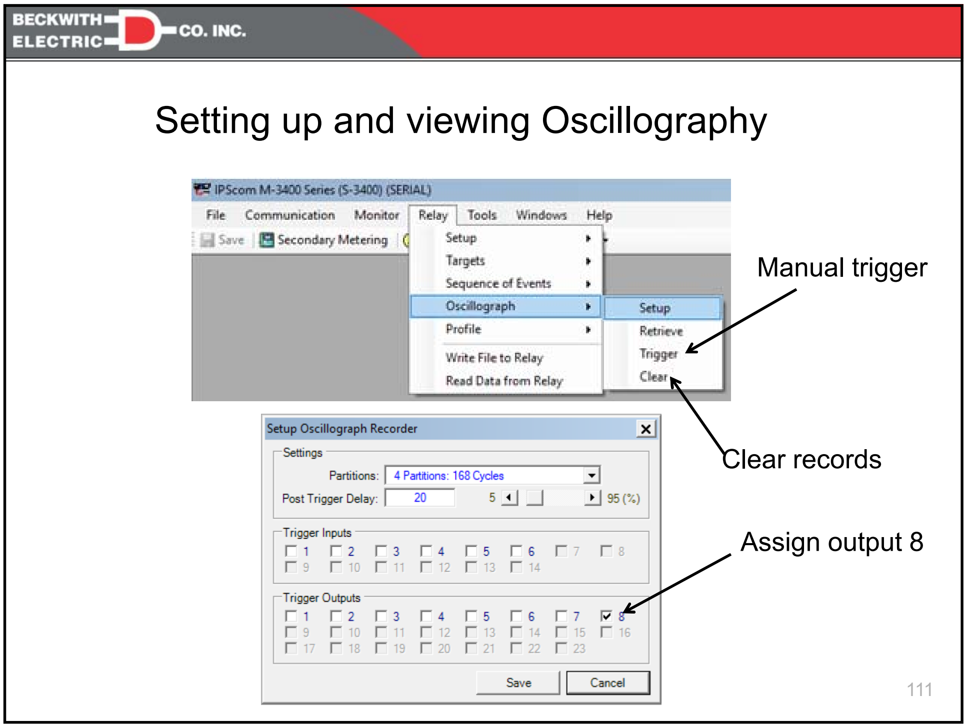
109

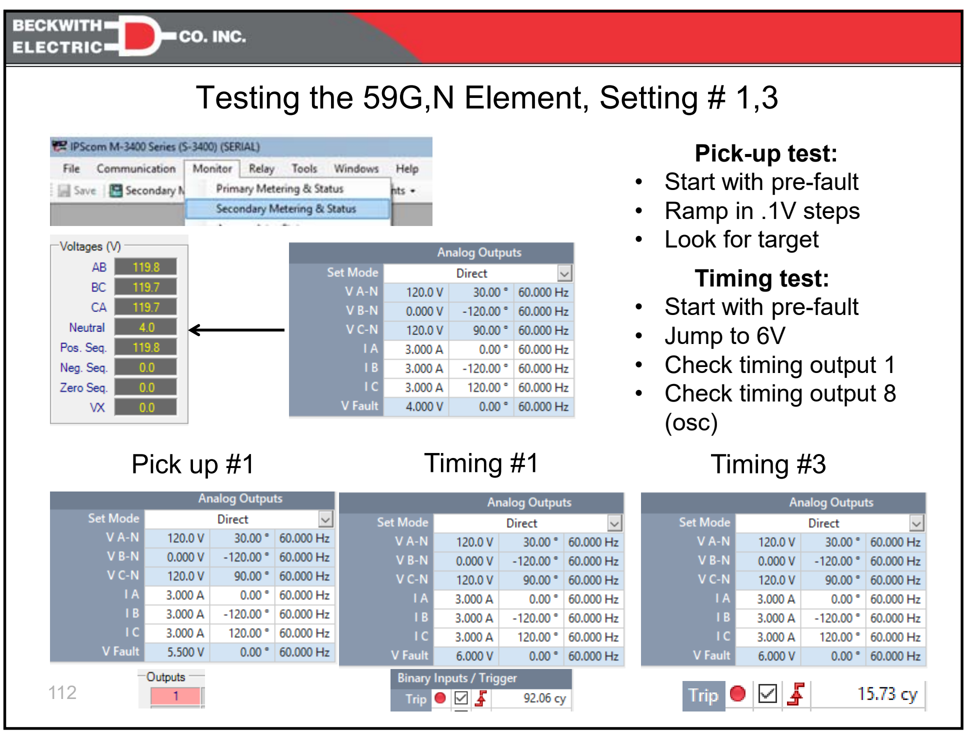
59N: Setting



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

110


BECKWITH ELECTRIC CO. INC.
Setting up and viewing Oscillography
IPScom M-3400 Series (S-3400) (SERIAL)
File Communication Monitor Relay Tools Windows Help
Save Secondary Metering
Setup
Targets
Sequence of Events
Oscillograph
Profile
Write File to Relay
Read Data from Relay
Setup
Retrieve
Trigger
Clear
Manual trigger
Clear records
Setup Oscillograph Recorder
Settings
Partitions: 4 Partitions: 168 Cycles
Post Trigger Delay: 20 5 95 (%)
Trigger Inputs
Trigger Outputs
Save
Cancel
Assign output 8
111


BECKWITH ELECTRIC CO. INC.
Testing the 59G,N Element, Setting # 1,3
IPScom M-3400 Series (S-3400) (SERIAL)
File Communication Monitor Relay Tools Windows Help
Primary Metering & Status
Secondary Metering & Status
Voltages (V)
AB 119.8
BC 119.7
CA 119.7
Neutral 4.0
Pos. Seq. 119.8
Neg. Seq. 0.0
Zero Seq. 0.0
VX 0.0
Analog Outputs
Set Mode Direct
V Fault 4.000 V 0.00 ° 60.000 Hz
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)
Pick up #1
V Fault 5.500 V 0.00 ° 60.000 Hz
Outputs
1
Timing #1
V Fault 6.000 V 0.00 ° 60.000 Hz
Binary Inputs / Trigger
Trip 92.06 cy
Timing #3
V Fault 6.000 V 0.00 ° 60.000 Hz
Trip 15.73 cy
112

BECKWITH ELECTRIC CO. INC.

Testing the 59G,N Element, Setting # 2

Pre-fault settings

Voltages (V)	
AB	119.8
BC	119.7
CA	119.7
Neutral	14.4
Pos. Seq.	119.9
Neg. Seq.	0.0
Zero Seq.	0.0
VX	0.0

Analog Outputs			
Set Mode	Direct		
V A-N	120.0 V	30.00 °	60.000 Hz
V B-N	0.000 V	-120.00 °	60.000 Hz
V C-N	120.0 V	90.00 °	60.000 Hz
I A	3.000 A	0.00 °	60.000 Hz
I B	3.000 A	-120.00 °	60.000 Hz
I C	3.000 A	120.00 °	60.000 Hz
V Fault	14.50 V	0.00 °	60.000 Hz

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

Pick up #2

Analog Outputs			
Set Mode	Direct		
V A-N	120.0 V	30.00 °	60.000 Hz
V B-N	0.000 V	-120.00 °	60.000 Hz
V C-N	120.0 V	90.00 °	60.000 Hz
I A	3.000 A	0.00 °	60.000 Hz
I B	3.000 A	-120.00 °	60.000 Hz
I C	3.000 A	120.00 °	60.000 Hz
V Fault	15.00 V	0.00 °	60.000 Hz

Outputs: 1 2

Timing #2

Analog Outputs			
Set Mode	Direct		
V A-N	120.0 V	30.00 °	60.000 Hz
V B-N	0.000 V	-120.00 °	60.000 Hz
V C-N	120.0 V	90.00 °	60.000 Hz
I A	3.000 A	0.00 °	60.000 Hz
I B	3.000 A	-120.00 °	60.000 Hz
I C	3.000 A	120.00 °	60.000 Hz
V Fault	16.00 V	0.00 °	60.000 Hz

Trip 2 21.37 cy

113

BECKWITH ELECTRIC CO. INC.

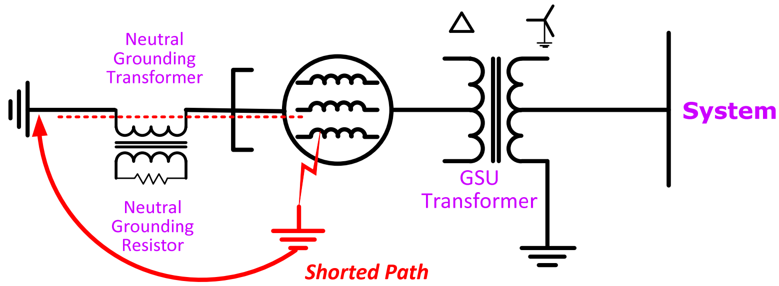
Stator Ground Fault (27TN)

5% Stator Coverage, Near Neutral

⇒W

114

Why Do We Care About Faults Near Neutral?

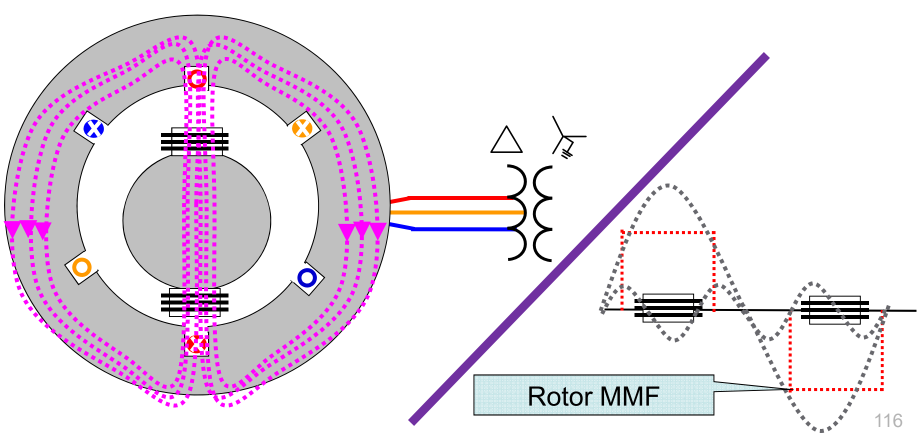


- A fault at or near the neutral shunts the high resistance that saves the stator from large currents with an internal ground fault
- A generator operating with an undetected ground fault near the neutral is an accident waiting to happen
- We can use 3rd Harmonic or Injection Techniques for complete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

115

Third-Harmonic Rotor Flux

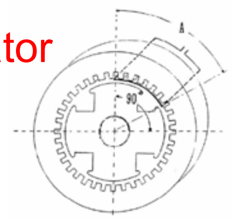
- Develops in stator due to imperfections in winding and system connections
- Unpredictable amount requiring field observation at various operating conditions
- Also dependent on pitch of the windings, which a method to define the way stator windings placed in the stator slots



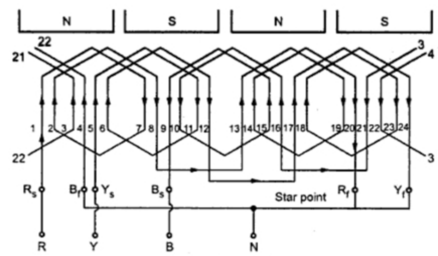
116

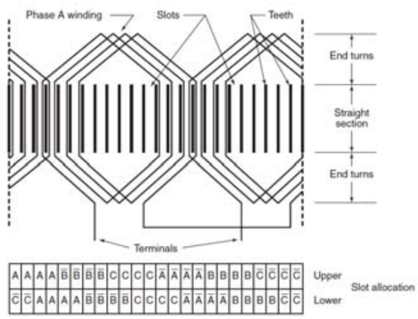
BECKWITH ELECTRIC CO. INC.

Generator Pitch



Pole spans 60 over 90 = 2/3 pitch





Pitch Factor is calculated by dividing the coil throw (–) 1 (coil span), by the number of slots per pole.

Using the examples in 1 through 3 above:

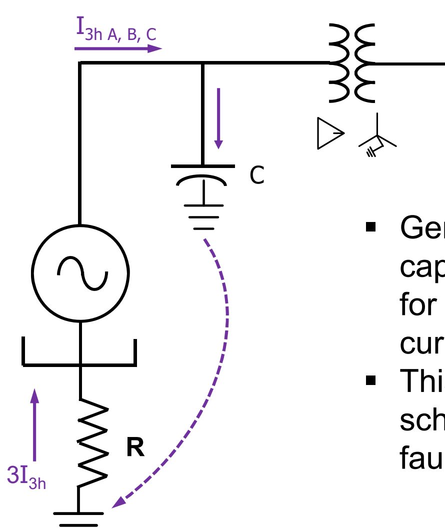
$$\text{Pitch Factor} = \frac{\text{1 to 9 throw (-) 1}}{\text{48 Slots} \div \text{4 Poles}} = \frac{8}{12}$$

Pitch Factor = 2/3

Stator Winding Diagram Illustrating "Pitch" In Winding Construction

BECKWITH ELECTRIC CO. INC.

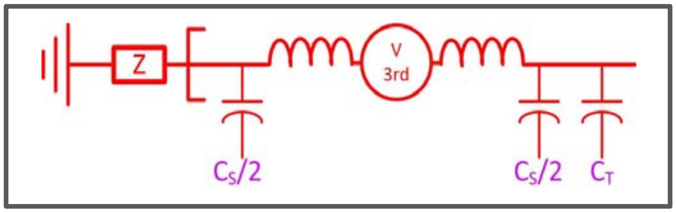
Using Third Harmonic in Generators



- 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

BECKWITH ELECTRIC CO. INC.

Generator Capacitance and 3rd Harmonics



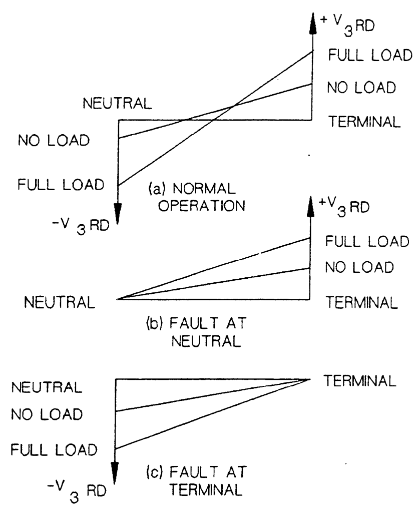
- 3rd harmonics are produced by some generators
  - Amount typically small
    - Lumped capacitance on each stator end is $C_S/2$.
  - C_T is added at terminal end due to surge caps and isophase bus
  - Effect is 3rd harmonic null point is shifted toward terminal end and not balanced

119

BECKWITH ELECTRIC CO. INC.

3rd Harmonic in Generators

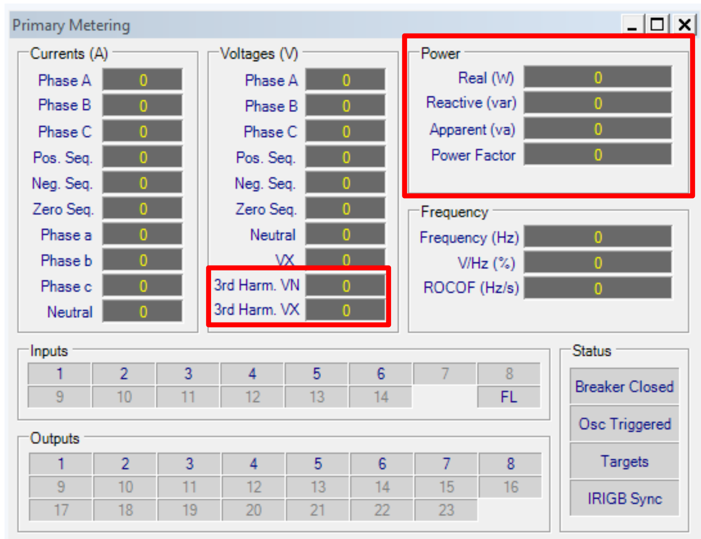
- 3rd harmonic may be present in terminal and neutral ends
- Useful for ground fault detection near neutral
  - If 3rd harmonic goes away, conclude a ground fault near neutral
- 3rd harmonic varies with loading



120

BECKWITH ELECTRIC CO. INC.

3rd Harmonic Voltages and Ratio Voltage



121

BECKWITH ELECTRIC CO. INC.

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
  - 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

Loading/operating variables may be Sync Condenser, VAr Sink, Pumped Storage, CT Starting, Power Output Reduction

122

BECKWITH ELECTRIC CO. INC.

3rd Harmonic in Generators: Typical 3rd Harmonic Values

UNIT LOAD		180 HZ RMS VOLTAGE		VOLTAGE RATIO
MW	MVAR	NEUTRAL	TERMINAL	TERMINAL/NEUTRAL
0	0	2.8	2.7	1.08
7	0	2.5	3.7	1.48
35	5	2.7	3.8	1.41
105	5	4.2	5.0	1.19
175	25	5.5	6.2	1.13
340	25	8.0	8.0	1.00

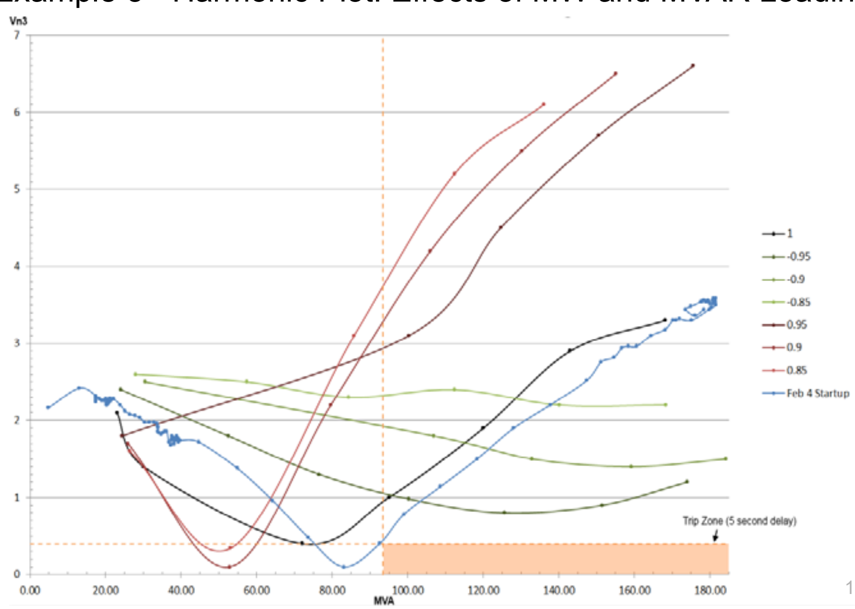
Magnitudes of Third Harmonic Voltages
for a Typical Generator

- **3rd harmonic values tend to increase with power and VAr loading**
- **Fault near neutral causes 3rd harmonic voltage at neutral to go to zero volts**

123

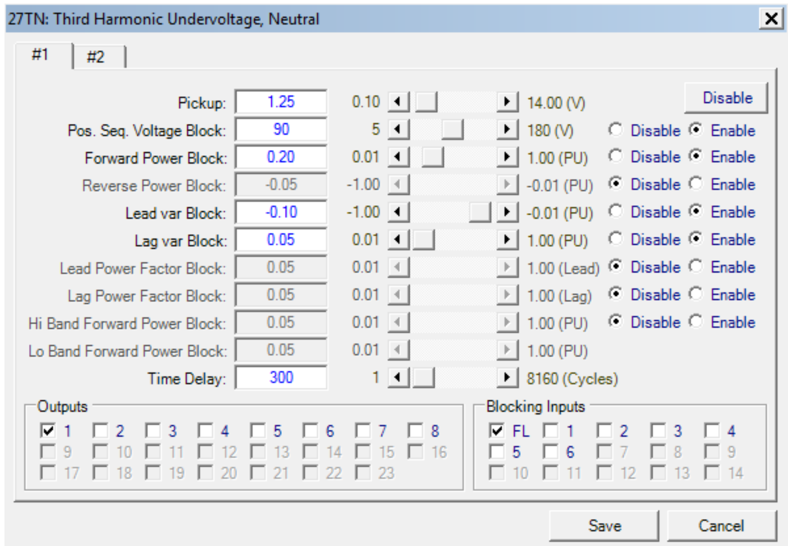
BECKWITH ELECTRIC CO. INC.

Example 3rd Harmonic Plot: Effects of MW and MVAR Loading

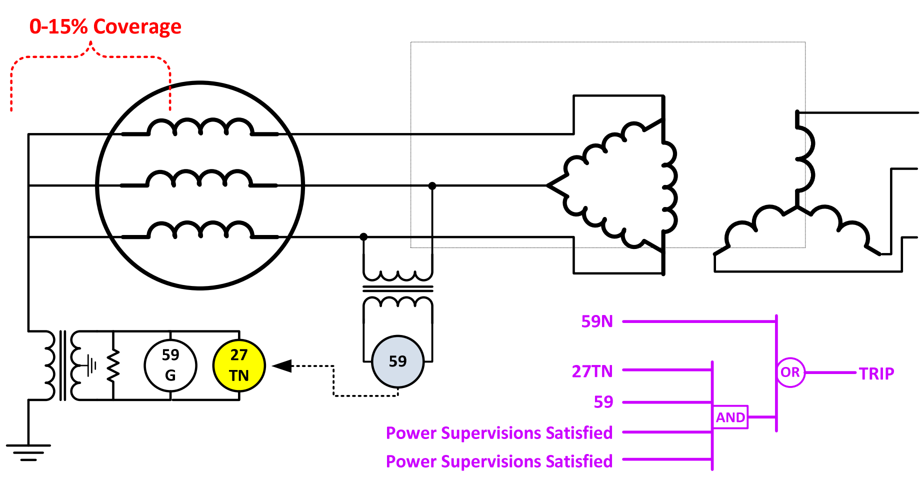


124

27TN Settings and Supervision

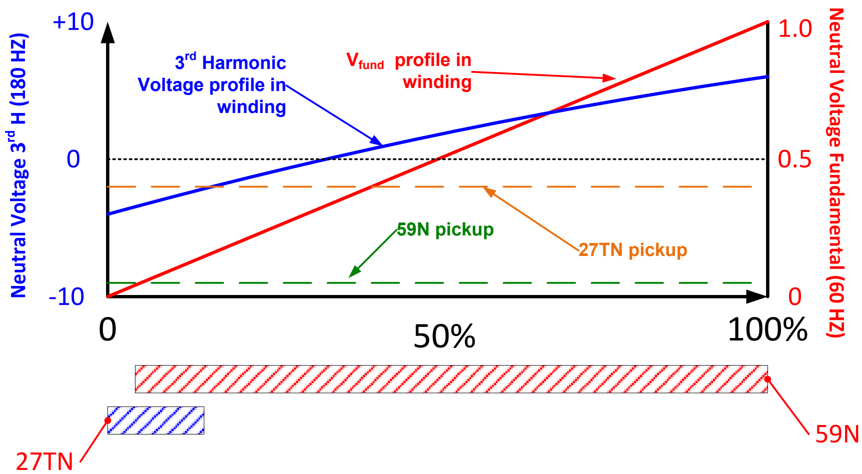


100% Stator Ground Fault (59N/27TN)



Third-Harmonic Undervoltage Ground-Fault Protection Scheme

100% Stator Ground Fault (59N/27TN)



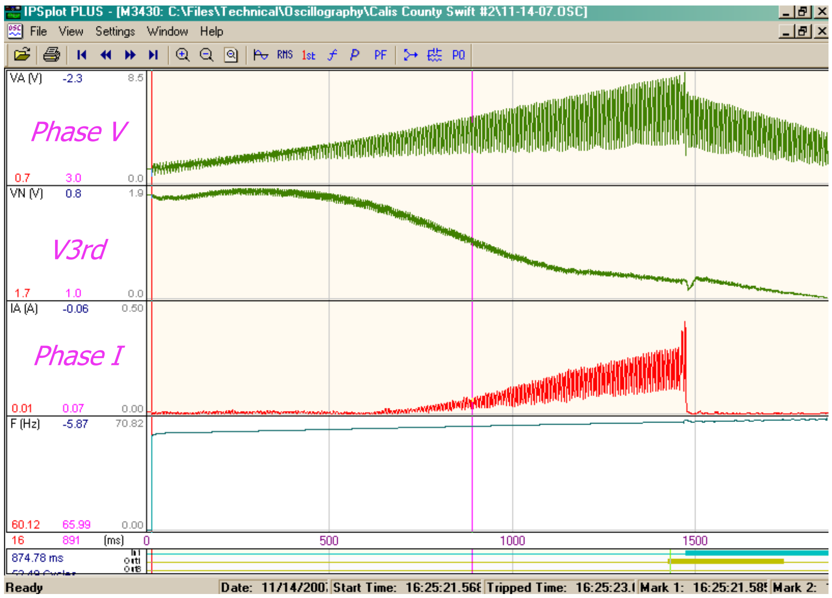
Overlap of Third Harmonic (27TN) with 59N Relay

3rd Harmonic Voltage Decrease During an Over Speed Condition in a 45MW Hydro Generator

- 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?

BECKWITH ELECTRIC CO. INC.

3rd Harmonic in Runaway Hydro Generator



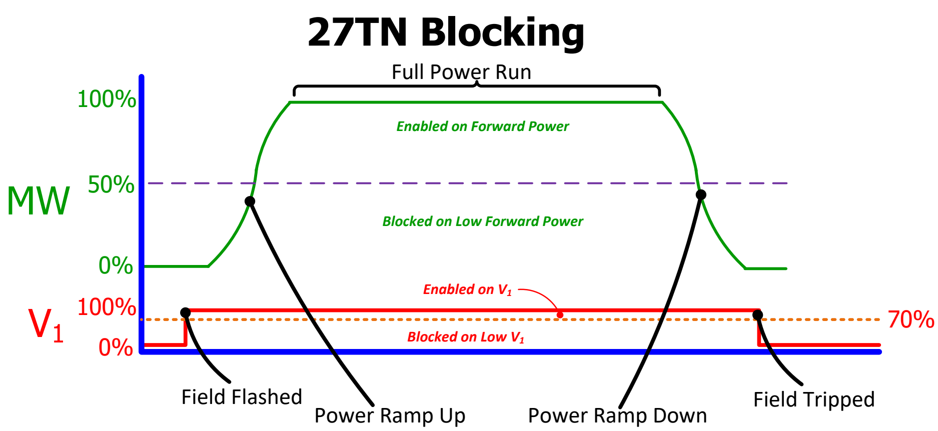
BECKWITH ELECTRIC CO. INC.

27TN: Setting

Table A.1—Measured primary third harmonic neutral voltages

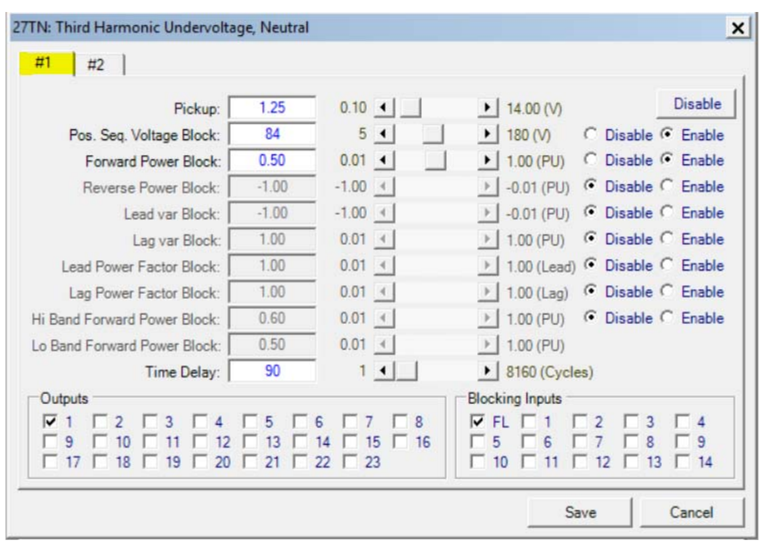
	MW	Mvar	X-phase	Y-phase	Z-phase	Average phase volts	Neutral voltage	Secondary Neutral Voltage	Secondary Neutral Voltage
			Measured primary third harmonic voltages						
	0	0	66.0	69.7	64.2	66.6	−18.9	0.32	
	80	30	80.7	84.3	88.0	84.3	−52.4	0.87	
20% @ 246 MVA	98	23	89.8	93.5	97.2	93.5	−56.8	0.95	1.25
	126	19	104.5	119.2	117.3	113.7	−81.1	1.35	
	147	15	128.3	130.2	122.8	127.1	−94.0	1.57	
	174	20	135.7	143.0	141.2	139.9	−108.2	1.80	
	201	19	165.0	161.3	155.8	160.7	−117.9	1.97	
50% @ 246 MVA	227	15	179.7	179.7	181.5	180.3	−146.4	2.44	2.5
	384	30	242.0	238.3	236.5	239.0	−191.3	3.18	
	408	25	242.0	249.3	240.2	243.8	−198.9	3.37	
	447	27	265.8	247.5	251.2	254.8	−207.5	3.46	
	482	20	276.8	276.8	258.5	270.7	−217.0	3.67	

27TN: Setting



131

27TN: Setting

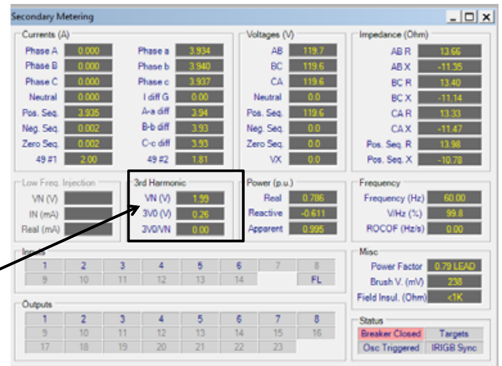


132

BECKWITH ELECTRIC CO. INC.

Testing the 27TN Element

Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	0.00 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz



Pre-fault Condition

133

BECKWITH ELECTRIC CO. INC.

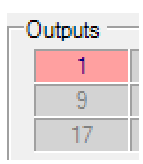
Testing the 27TN Element

Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	0.00 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz

Pre-fault Condition

Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	1.250 V	0.00 °	180.00 Hz
neutral a	3.950 A	0.00 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz

Ramp V Fault down in .25V steps



Find the Pick-up

Verify with Metering Screen (relay)

134

BECKWITH ELECTRIC CO. INC.

Testing the 27TN Element

Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	0.00 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz

Pre-fault Condition

Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	1.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	0.00 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz

Fault Condition

trip 1 91.87 cy

Check Timing

135

BECKWITH ELECTRIC CO. INC.

Testing the 27TN Element, Positive Seq. Voltage

Pre-fault Condition

Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	0.00 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz

Fault Condition

Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	1.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	0.00 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz

Lower 3 ph Voltage in1V steps

Analog Outputs			
Set Mode	Direct		
VA	84.00 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	84.00 V	90.00 °	60.000 Hz
V Fault	1.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	0.00 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz

Voltages (V)	
AB	83.8
BC	83.7
CA	83.7
Neutral	0.0
Pos. Seq.	83.8
Neg. Seq.	0.0
Zero Seq.	0.0
VX	0.0

Monitor positive Seq. Voltage

Outputs	
1	2

Contact drops out

136

Testing the 27TN Element, Forward Power Block

Pre-fault Condition

Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	2.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	0.00 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz

Fault Condition

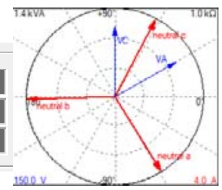
Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	1.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	0.00 °	60.000 Hz
neutral b	3.950 A	-120.00 °	60.000 Hz
neutral c	3.950 A	120.00 °	60.000 Hz

Rotate 3 ph current angles
1degree steps

Analog Outputs			
Set Mode	Direct		
VA	120.0 V	30.00 °	60.000 Hz
VB	0.000 V	0.00 °	60.000 Hz
VC	120.0 V	90.00 °	60.000 Hz
V Fault	1.000 V	0.00 °	180.00 Hz
neutral a	3.950 A	-58.00 °	60.000 Hz
neutral b	3.950 A	-178.00 °	60.000 Hz
neutral c	3.950 A	62.00 °	60.000 Hz

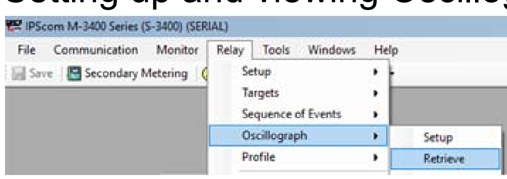
Power (p.u.)	
Real	0.497
Reactive	0.864
Apparent	0.994

Monitor real power



Contact drops out

Setting up and viewing Oscillography



Retrieve Record

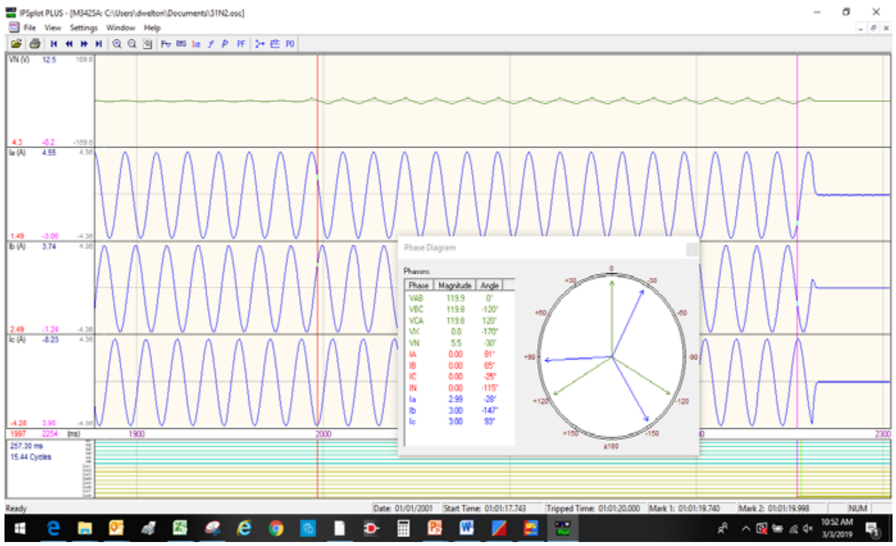
Save as *.osc or *.cfg

Load and View in BecoPlot Software

BECKWITH ELECTRIC CO. INC.

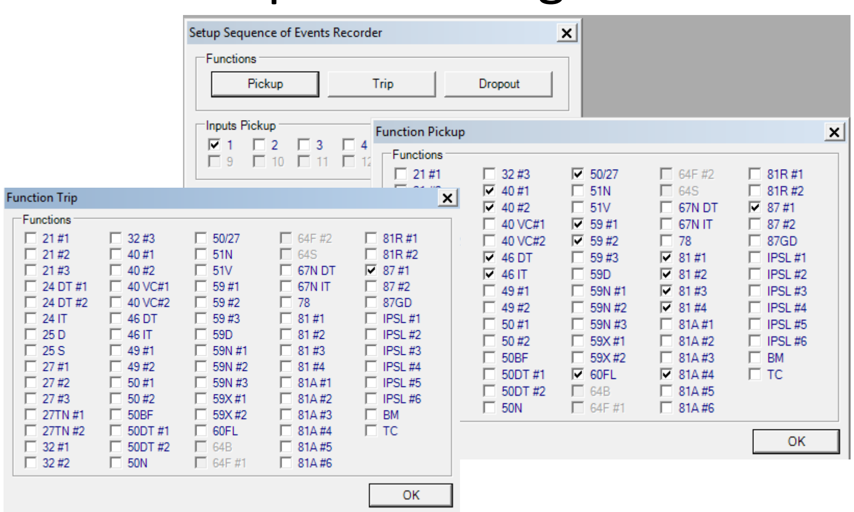
Viewing Oscillography

139

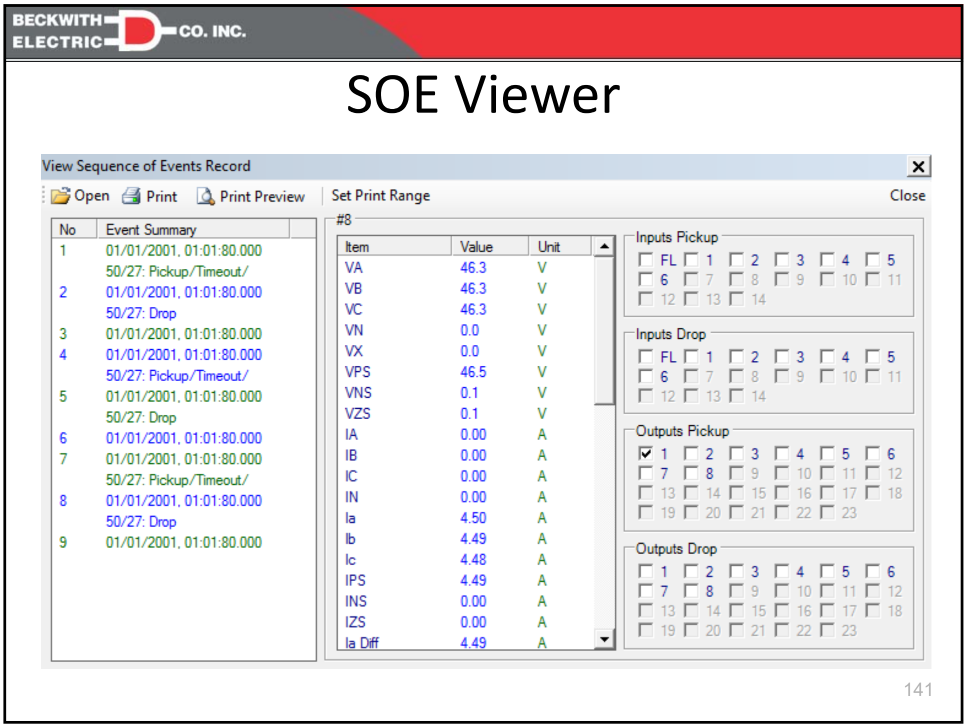


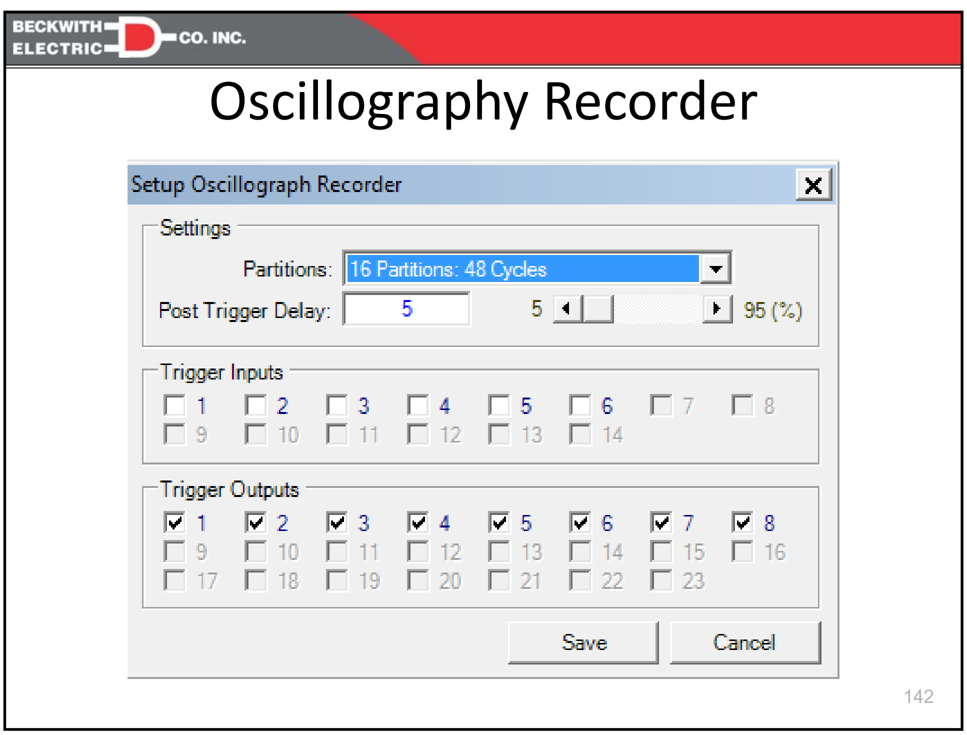
BECKWITH ELECTRIC CO. INC.

Other Important Diagnostic Tools

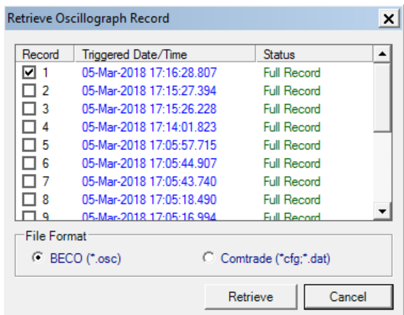


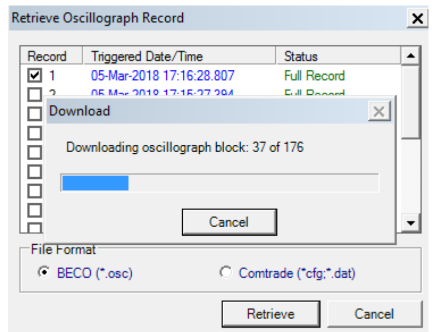
140


BECKWITH ELECTRIC CO. INC.
SOE Viewer
View Sequence of Events Record
Open
Print
Print Preview
Set Print Range
Close
No
Event Summary
1 01/01/2001, 01:01:80.000 50/27: Pickup/Timeout/
2 01/01/2001, 01:01:80.000 50/27: Drop
3 01/01/2001, 01:01:80.000
4 01/01/2001, 01:01:80.000 50/27: Pickup/Timeout/
5 01/01/2001, 01:01:80.000 50/27: Drop
6 01/01/2001, 01:01:80.000
7 01/01/2001, 01:01:80.000 50/27: Pickup/Timeout/
8 01/01/2001, 01:01:80.000 50/27: Drop
9 01/01/2001, 01:01:80.000
#8
Item Value Unit
VA 46.3 V
VB 46.3 V
VC 46.3 V
VN 0.0 V
VX 0.0 V
VPS 46.5 V
VNS 0.1 V
VZS 0.1 V
IA 0.00 A
IB 0.00 A
IC 0.00 A
IN 0.00 A
Ia 4.50 A
Ib 4.49 A
Ic 4.48 A
IPS 4.49 A
INS 0.00 A
IZS 0.00 A
Ia Diff 4.49 A
Inputs Pickup
FL 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Inputs Drop
FL 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Outputs Pickup
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Outputs Drop
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
141

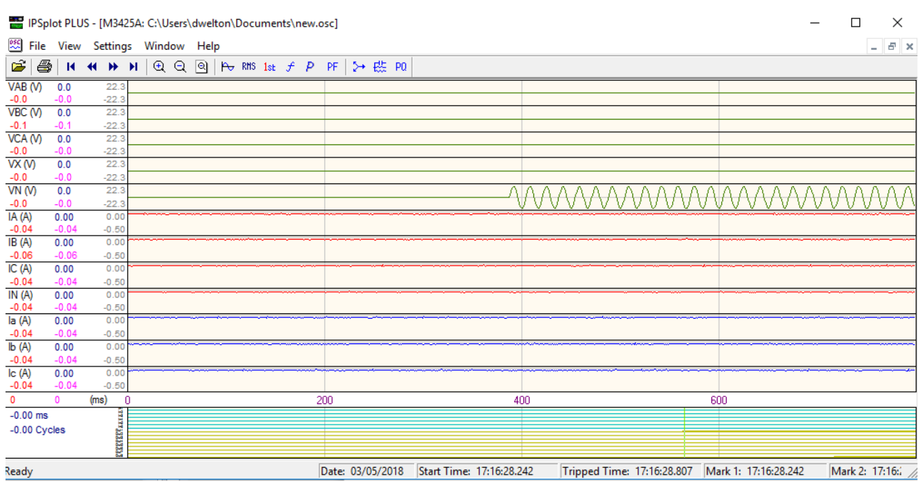

BECKWITH ELECTRIC CO. INC.
Oscillography Recorder
Setup Oscillograph Recorder
Settings
Partitions: 16 Partitions: 48 Cycles
Post Trigger Delay: 5
5
95 (%)
Trigger Inputs
1 2 3 4 5 6 7 8
9 10 11 12 13 14
Trigger Outputs
1 2 3 4 5 6 7 8
9 10 11 12 13 14 15 16
17 18 19 20 21 22 23
Save
Cancel
142

Retrieve Record





Oscillography-IPSplot Plus



BECKWITH ELECTRIC CO. INC.

References

1. *IEEE Guide for Generator Ground Protection*, ANSI/IEEE C37.101-2006.
2. *IEEE Guide for AC Generator Protection*, ANSI/IEEE C37.102-2006.
3. *IEEE Tutorial on the Protection of Synchronous Generators*, Second Edition, 2010; Special Publication of the IEEE Power System Relaying Committee.
4. *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems*, IEEE Std. 142-1991.
5. *Protection Considerations for Combustion Gas Turbine Static Starting*; Working Group J-2 of the Rotating Machinery Subcommittee, Power System Relay Committee.
6. *Protective Relaying for Power Generation Systems*; Donald Reimert, CRC Press 2006; ISBN#0-8247-0700-1.

BECKWITH ELECTRIC CO. INC.

References

7. *Practical Improvement to Stator Ground Fault Protection Using Negative Sequence Current*; Russell Patterson, Ahmed Eltom; IEEE Transactions Paper presented at the Power and Energy Society General Meeting (PES), 2013 IEEE.
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.
9. *Premature Failure of Modern Generators,* Clyde V. Maughan, presented at ASME 2013
10. *Advanced Generator Ground Fault Prote*ctions, Wayne Hartmann, presented at Georgia Tech Protective Relay Conference 2016