3425A GENERATOR PROTECTIVE RELAY TEST PLAN

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Consultant – Beckwith Electric
Chuck Mozina -- is a Consultant, Protection and Protection Systems for Beckwith Electric and resides in Palm Harbor (near Tampa), Florida. He is a Life Fellow of the IEEE. His consulting practice involves projects relating to protective relay applications, protection system design and coordination. He specializes in generator and power plant protection.

Chuck is an active 20-year member of the IEEE Power System Relay Committee (PSRC) and is the past chairman of the Rotating Machinery Subcommittee. He is active in the IEEE IAS I&CPS, PCIC and PPIC committees, which address industrial system protection. He is a former U.S. representative to the CIGRE Study Committee 34 on System Protection and has chaired a CIGRE working group on generator protection. He also chaired the IEEE task force that produced the tutorial “The Protection of Synchronous Generators,” which won the PSRC’s 1997 Outstanding Working Group Award. Chuck is the 1993 recipient of the Power System Relay Committee’s Career Service Award and he recently received the 2002 IAS I&CPS Ralph Lee Prize Paper Award. His papers have been republished in the IAS Industrial Applications Magazine.

Chuck has a Bachelor of Science in Electrical Engineering from Purdue University and is a graduate of the eight month GE Power System Engineering Course. He has authored a number of papers and magazine articles on protective relaying. He has over 25 years of experience as a protection engineer at Centerior Energy, a major investor-owned utility in Cleveland, Ohio where he was the Manager of the System Protection Section. He is also a former instructor in the Graduate School of Electrical Engineering at Cleveland State University as well as a registered Professional Engineer in the state of Ohio.
A major US manufacturer of:

- Digital multifunction generator, interconnection and transformer protection
- Generator synchronizing and bus transfer equipment
- Voltage control devices for LTC transformer, regulators, and capacitor banks
- Packaged systems using Beckwith products
Multifunction Digital Relay
M-3425A
Multifunction Digital Relay

Utility System

52 Unit

52 Gen

High-impedance Grounding with Third Harmonic 100% Ground Fault Protection

Low-impedance Grounding with Overcurrent Stator Ground Fault Protection

Targets (Optional)

Integral HMI (Optional)

Metering

Waveform Capture

IRIG-B

Front 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

59R 59A 81 59 27 24

87Q

25

78 60FL 51V 50/27 46 42 21 50 49 46

64F 64B

87N

59D 59N

To Terminal CTs

S7 GO

S0N S1N

CT

CT

CT

CT

3Vn

M-3921

VT

CT

CT

CT

VT

VT
OVERALL TEST PLAN

1. Relay set-up
2. Simulate full load at unity P.F.
3. Loss of Field – 40
4. Distance relay – 21
5. Reverse Power – 32
6. Generator Differential – 87
7. Negative Sequence – 46
8. Overexcitation – 24 V/Hz
9. Oscillograph Demo
SOFTWARE DEMO
M-3425A TESTING
NOTES:
All relays are shown in the de-energized state.
Output contacts #1 through #4 are high speed operation contacts.
The power supply relay (P/S) is energized when the power supply is OK.

The self-test relay is energized when the relay has performed all self-tests successfully.

WARNING: ONLY DRY CONTACTS must be connected to inputs (terminals 5 through 10 with 11 common) because these contact inputs are internally wetted. Application of external voltage on these inputs may result in damage to the units.
Programmable Inputs

EXTERNALLY WETTED

Digital Relay

\[ + \]

\[ \text{In-1} \]

\[ 52a \]

INTERNALLY WETTED

Digital Relay

Internal Battery

\[ + \]

\[ \text{In-1} \]

\[ - \]

\[ 52a \]
Three-Line Connection Diagram
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Functions to disable when testing
NOTE: The phase angles shown here use leading angles as positive and lagging angles as negative. Some manufacturers of test equipment have used lagging angles as positive, in which case $V_B=120\degree\ V\angle120\degree$ and $V_C=120\degree\ V\angle240\degree$. Similarly other voltages and currents phase angles should be adjusted. These test configurations are for ABC phase rotation. They must be adjusted appropriately for ACB phase action.
OVERALL TEST PLAN

1. Relay set-up
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RELAY SET-UP & SIMULATION OF GENERATOR FULL LOAD

- Relay Set-up
- Nominal voltage = 120V
- Nominal current = 5A
- VT configuration = Line-to-ground
- 27/59 Magnitude selection = RMS
- Delta-Y transformer = Disable
- Relay Seal-In = 30 cycles

- Simulate Generator at Full Load and Unity P.F.
  - I=5A
  - V = 120V
  - Current in-phase with voltage
RELAY SET-UP & SIMULATION OF GENERATOR FULL LOAD
RELAY SET-UP & SIMULATION OF GENERATOR FULL LOAD
RELAY SET-UP & SIMULATION OF GENERATOR FULL LOAD
Loss-of-Field
(40)
Loss of Field (40)

CAUSES

• Field open circuit
• Field short circuit
• Accidental tripping of field breaker
• Regulator control failure
• Loss of main exciter
Loss of Field (40)

DETRIMENTS

• Generator
  - synchronous generator becomes induction
  - slip induced eddy currents heat rotor surface
  - high reactive current drawn by generator overloads sensor

• Power system
  - loss of reactive support
  - creates a reactive drain
  - can trigger system / area voltage collapse
Loss of Field
GE and Westinghouse Methods

Two Zone Offset Mho
GE
CEH

Impedance w/Directional Unit
Westinghouse
KLF
- Desired sequence of events:
  - Turbine was tripped due to oil valve solenoid failure
  - Sequential tripping scheme failed to shut down unit
  - Operator wanted to trip generator breaker A and then field breaker
Field (40) Oscillograph
40 - Loss of Field

+X

-X

+R

- \frac{Xd'}{2}

1.0 pu

Xd

- Xd

- X

Zone 1

Zone 2

Steady State Stability Limit

Impedance Locus During Loss of Field

Generator Capability

Under Excitation Limiter (UEL)
LOSS OF FIELD

Setting:
- Circle diameter -- 35Ω
- Offset -- 5Ω
- Delay = 1 cycle

Check top of circle:
\[ X = \frac{V}{I} = 0 \rightarrow 25V \]
\[ X = \frac{V}{I} = 5A \]
Trip V = 25V
I = 5A
Current Lead Voltage = 90°

Check bottom of circle:
\[ X = \frac{V}{I} = 120V \]
\[ X = \frac{V}{I} = 3A \]
Trip V = 120V
I = 3A
Current Lead Voltage = 90°

Check timing – Set at 30 cycles
Loss of Field

Circle Diameter: 35.0
Offset: -5.0
Time Delay: 1

Outputs
1 2 3 4 5 6 7 8
9 10 11 12 13 14 15 16
17 18 19 20 21 22 23

Blocking Inputs
FL 1 2 3 4
5 6 7 8
10 11 12 13
14

VC
Delay: 30

Outputs
1 2 3 4 5 6 7 8
9 10 11 12 13 14 15 16
17 18 19 20 21 22 23

Blocking Inputs
FL 1 2 3 4
5 6 7 8
10 11 12 13
14

Setting
Directional Element: 0
Voltage Control: 120

Save  Cancel
System Phase Fault
Backup (21)
System Phase Fault Backup (21)

- Provide protection for failure of system primary relaying
  - pilot vs. step-time
- Provide protection for breaker failure
  - local vs. remote
- Must balance sensitivity vs. security
  - loadability
  - load swings
System Phase Fault Backup (21)

For a fault at F with Failure at an approximately apparent impedance effect

\[ Z_{G1} = X_T \left[ \frac{|I_{G1} + I_{G2}|}{|I_{G1}|} \right] + Z_L \left[ \frac{|I_T + I_2 + I_3|}{|I_T|} \right] \]
System Phase Fault Backup (21)

CONSIDER

• Pilot vs. step-time
• Local vs. remote breaker failure
• Loadability / load swings
System Phase Fault Backup (21)

LOADABILITY CONSIDERATIONS

\[ Z_{LOAD} = \frac{V_{LN}}{I_{FULL \ LOAD}} \]

.9 Power Factor = 26° Point on R-X Diameter
PHASE BACKUP (21) SETTING COORDINATION

- Can’t Provide Remote BU due to Loadability Constraints

- May Have to Upgrade Transmission System Protection – Delineated Pri & BU and Local BF.
PHASE BACKUP (51VR) SETTING CRITERIA:
OPTIONS # 1 – PRC -025-1

1.0pu Mw + j [1.5 Mw pu] Mvars = 1.8 pu Mva

V = 0.95 X GSU Turns Ratio
115% Margin Over Stress Point

V = 0.95
PHASE BACKUP (21) SETTING CRITERIA: OPTIONS # 2 – PRC -025-1

1.0pu Mw + j [ 1.5 pu Mw] Mvars

V = Calculate Gen Terminal Voltage Corresponding to Highside GSU Voltage = 0.85pu

115% Margin Over Stress Point

V = 0.85
NERC vs IEEE PHASE BACKUP (21) SETTING COORDINATION

Proposed NERC Test Points

- **NERC Test**
  1.0pu Mw + j [1.5 Mw pu] Mvars

Converted to an Impedance at Close to .95 pu voltage (Option 1)
PHASE DISTANCE - 21

SETTINGS:
- CIRCLE DIA. = 30 Ω
- OFFSET = 0
- IMPEDANCE ANGLE = 85°
- DELAY = 1 CYCLE (MIN.)

CHECK TOP OF CIRCLE
\[ X = \frac{V}{I} = \frac{120V}{4A} = 30 \Omega \]

TRIP V = 120V
I = 4A
CURRENT LAG VOLTAGE = 85°

CHECK RELAY TIMING
SET AT 60 CYCLES
System Phase Fault Backup (21)
Reverse Power
(32)
Reverse Power (32)

- Prevents generator from motoring on loss of prime move

<table>
<thead>
<tr>
<th>TYPE OF PRIME MOVER</th>
<th>MOTORIZING POWER IN PERCENT OF UNIT RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Turbine:</td>
<td></td>
</tr>
<tr>
<td>Single Shaft</td>
<td>100</td>
</tr>
<tr>
<td>Double Shaft</td>
<td>10-15</td>
</tr>
<tr>
<td>Four Cycle Diesel</td>
<td>15</td>
</tr>
<tr>
<td>Two Cycle Diesel</td>
<td>25</td>
</tr>
<tr>
<td>Hydraulic Turbine</td>
<td>2-100*</td>
</tr>
<tr>
<td>Steam Turbine (Conventional)</td>
<td>1-4</td>
</tr>
<tr>
<td>Steam Turbine (Cond. Cooled)</td>
<td>0.5 – 1.0</td>
</tr>
</tbody>
</table>

*The larger powers are taken by turbines having submerged impellers.

- Generator unaffected by reverse power:
  Functions as synchronous motor

- Turbine has problems; exhaust hood temperature on steam turbines
Sequential Tripping

• Used on steam turbine generators to prevent overspeed

• Recommended by manufacturers of steam turbine generators as a result of field experience

• This trip mode used only for boiler/reactor or turbine mechanical problems

  - electrical protection should not trip through this mode
Sequential Tripping

STEP 1
• Abnormal turbine/boiler/reactor condition is detected

STEP 2
• Turbine valves are closed; generator allowed to briefly “motor” (i.e., take in power)

STEP 3
• A reverse power (32) relay in series with turbine valves position switches confirms all valves have closed

STEP 4
• Generator is separated from power system
Sequential Tripping Logic

Mechanical Devices "Turbine Tripped"

AND

Lockout or Aux Relay

Trip Generator Breakers

Trip Field Breaker

Transfer Unit Auxiliaries

Reverse Power Relay

Time Delay

Typically 2 sec.
REVERSE POWER

32

Setting:
Pickup = 0.10 p.u. = 10%
Delay = 1~

Check Pickup at 0.10 p.u.
\[ I_{\text{pickup}} = [\text{par unit}] [\text{nominal current}] = [0.1] [5A] = 0.5A \]

- Set normal current 180° to simulate reverse power
  \[ V_A = 120 \angle 0 \quad I_A = 0 \rightarrow 0.5 \angle -180° \]
  \[ V_B = 120 \angle -120 \quad I_B = 0 \rightarrow 0.5 \angle +60° \]
  \[ V_B = 120 \angle +120 \quad I_C = 0 \rightarrow 0.5 \angle -60° \]

- Set delay to 30 Sec (1800 cycles)
Check relay timer
Negative Sequence

(46)
• Unbalanced phase currents create negative sequence current in generator stator,

\[ I_2 = \frac{1}{3} (I_a + a^2 I_b + aI_c) \]

where

- \( a = 1 \angle 120 \)
- \( a^2 = 1 \angle 240 \)
- \( I_a, I_b, I_c = \text{phase currents} \)

• Negative sequence current interacts with normal positive sequence current to induce a double frequency current (120 Hz)

• Current (120 Hz) is induced into rotor causing surface heating

• Generator has established short-time rating,

\[ I_2^2 T = K \]

where

- \( K = \text{Manufacturer Factor} \)
- (the larger the generator the smaller the K value)
Currents Flow in the Rotor Surface
Negative Sequence (46)

Two Types of Relays

ELECTROMECHANICAL

- Sensitivity restricted to about .6 pu $I_2$ of generator rating
- Fault backup provided
- Generally insensitive to load unbalances or open conductors

STATIC / DIGITAL

- Protects generator down to its continuous $I_2$ rating
# Negative Sequence (46)

<table>
<thead>
<tr>
<th>TYPE OF GENERATOR</th>
<th>PERMISSIBLE $I_2$ PERCENT OF STATOR RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salient Pole</td>
<td></td>
</tr>
<tr>
<td>With connected amortisseur windings</td>
<td>10</td>
</tr>
<tr>
<td>With non-connected amortisseur windings</td>
<td>5</td>
</tr>
<tr>
<td>Cylindrical Rotor</td>
<td></td>
</tr>
<tr>
<td>Indirectly cooled</td>
<td>10</td>
</tr>
<tr>
<td>Directly cooled to 960 MVA</td>
<td>8</td>
</tr>
<tr>
<td>961 to 1200 MVA</td>
<td>6</td>
</tr>
<tr>
<td>1200 to 1500 MVA</td>
<td>5</td>
</tr>
</tbody>
</table>

†These values also express the negative-phase –sequence current capability at reduced generator KVA capabilities.

‡ The short time (unbalanced fault) negative sequence capability of a generator is also defined in ANSI C50.13.
Typical K Values
Salient Pole Generators 40
Synchronous Generators 30
NEGATIVE SEQUENCE

46

Setting Inverse Time:

- Pickup – 10% (of nominal current)
- Time dial – 30
- Max Time – 65,500 cycles (max)

- Reverse any two (a,b,c) phase currents to create negative sequence current

  Example = Ia ≤ 0
  Ib ≤ +120
  Ic ≤ -120

  Check sec status screen for negative sequence

- Increase all three phase currents from 0 → 0.5A.

- Hold down target reset. 46 target will light at pickup value of 0.5A.

- Time relay \( i^2 t = K \quad \Rightarrow \quad t = \frac{30}{1.0 \text{ p.u.}} = 30 \text{ sec, where 1.0 p.u. = 5A} \)
Negative Sequence (46)
Overexcitation – V/Hz (24)
Overexcitation/ Volts per Hertz (24)

GENERATOR
TRANSFORMER $\approx$ EXCITATION

<table>
<thead>
<tr>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
</tr>
<tr>
<td>Freq.</td>
</tr>
<tr>
<td>Hz</td>
</tr>
</tbody>
</table>

GENERATOR LIMITS (ANSI C 50.13)
- Full Load: $V/Hz = 1.05$ pu
- No Load: $V/Hz = 1.05$ pu

TRANSFORMER LIMITS
- Full Load: $V/Hz = 1.05$ pu (HV Terminals)
- No Load: $V/Hz = 1.10$ pu (HV Terminals)
Overexcitation/
Volts per Hertz (24)

CAUSES OF V/HZ PROBLEMS

• Generator voltage regulator problems
  - operating error during off-line manual regulator operation
  - control failure
  - loss of VT regulator supply voltage
  - overexcitation when regulator is on-line

• System problems
  - unit load rejection: full load, partial rejection
  - power system islanding during major disturbances
Overexcitation/
Volts per Hertz (24)

PHYSICAL INSIGHTS
• As voltage rises above rating leakage flux increases

• Leakage flux induces current in transformer support structure causing rapid localized heating
Overexcitation/ Volts per Hertz (24)

TYPICAL CURVES

Fig. 1
Typical Limiting Curve for V/Hz Operation for Generator

Fig. 2
Typical Limiting Curve for V/Hz Operation for Power Transformer

Fig. 3
Combined Curves for V/Hz Operation for Generator and GSU Transformer (with GSU transformer curve put Generator Voltage Base)
Overexcitation/
Volts per Hertz (24)

Example of inverse volts/hertz setting
OVEREXCITATION
V/Hz – 24

- Setting definite time unit
  Pickup – 110%
  Time delay – 1 cycle

- Verify pickup
  ◆ Voltage verification:
    ▪ Keep frequency at 60Hz
    ▪ Increase nominal voltage (120V) by 110% i.e. 120V x 110% - 132V
    ▪ Relay should trip

  ◆ Frequency Verification:
    ▪ Keep voltage at 120V nominal
    ▪ Decrease frequency by 110% or 90% i.e. 90% x 60 = 54Hz
    ▪ Relay should trip

- Verify relay time
  ◆ Set time delay at 60 sec. (3600 cycles)
  ◆ Pickup relay and time out relay
Overexcitation  Volts per Hertz (24)
Phase Differential
(87)
Phase Differential (87)

- Fast response time (under 1 – 1/2 cycle)
- Percentage differential with adjustable slope
PHASE DIFFERENTIAL 87

- Connect currents to $I_A$ Input
- Simulate generator full load at unity power factor
  $I = 5A$
  $V = 120V$
  $V$ and $I$ In phase
- Set differential 87 function
  Pickup = 0.2A
  Percent slope = 10%
  Time delay = 1 cycle
- Check pickup
  - Set all current to zero
  - Increase $I_a = 0 \rightarrow 0.2A$
  - Trip should be at 0.2A
- Check slope
  Slope equation
  $I_A = \frac{1+K}{1-K} \cdot I_a$

  Where
  $K = \frac{S}{100} = \frac{10}{200} = 0.05$

  $I_a = 5A$

  $I_A = \frac{[1+0.05]}{[1-0.05]} \times [5A]$
  \[
  \frac{1.05}{0.95} [5A] = 5.53A \text{ (Trip)}
  \]
Phase Differential (87)
Oscillograph Demo
- Determine if relay and circuit breaker operated properly
  - Identify relay, control or breaker problem
  - Generators do experience faults / abnormal conditions
    - In the machine or the system?
- Speed generator’s return to service
  - Identify type of testing needed
  - Provide data to generator manufacturer
- Gives plant engineer data to force unit off-line for inspection
- Uncovers unexpected problems
  - Synchronizing, shutdown
- Comtrade Oscillographs (*.cfg)
IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems

Sponsor
Power Systems Relay Committee
of the
IEEE Power Engineering Society

Approved 18 March 1999
IEEE-SA Standards Board

Abstract: A common format for data files and exchange medium used for the interchange of various types of fault, test, or simulation data for electrical power systems is defined. Sources of transient data are described, and the use of diskettes as an exchange medium is recommended. Issues of sampling rates, filters, and sample rate conversions for transient data being exchanged are discussed. Files for data exchange are specified, as is the organization of the data. A sample file is given.

Keywords: configuration file, data file, header file, information file, transient data.
Waveform Capture (Phasor)

Area of current reversal

Phasor diagram with values displayed

Phasor display shown at Marker #1 location
Waveform Capture (MW-MVAR, R-X)

Marker #1

Marker #2

Impedance Trajectory Over Record

Impedance Values at Marker #1

Impedance Values at Marker #2

Power Trajectory Over Record

Power Value at Marker #1

Power Value at Marker #2
3425A GENERATOR PROTECTIVE RELAY TEST PLAN

THE END

????? QUESTION ?????