Overview of Testing Methods Required to Maintain Electrical Power Equipment

Engineers Joint Committee of Long Island

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Megger

February 12, 2013

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LEGAL DISCLAIMER

- This presentation is offered for informational purposes only and shall not be relied upon for any work in the field
- Only fully qualified personnel shall work on electrical equipment
- Electrical equipment shall only be worked on in a de-energized state
- All tables have accompanying footnotes that have been removed for brevity

QUESTIONS

- What is an acceptable power reliability?
- What are some of the things that could interrupt the continuous flow of power?
- Is maintenance an income or an expense?
- Why do we test?
- Who should test?

WHAT IS AN ACCEPTABLE POWER RELIABILITY?

- Only one acceptable answer to the consumer – continuous power
- To the facility manager – cost of maintaining a bullet proof system vs. cost of an outage
- P.S. As I'm typing this, the power goes out at the Super Bowl – what did this cost?

WHAT COULD INTERRUPT POWER?

- GENERATION – loss of cooling, electrical shutdown, etc.
- TRANSMISSION – Lightning, protective device malfunction, overload?
- DISTRIBUTION – animal contact, car pole accident, storms, lightning, overload!
- UTILIZATION – lack of maintenance, inadvertent operation, ground fault, human error

IS MAINTENANCE INCOME OR EXPENSE?

- To the bean counters – an expense?
- To the maintenance technician – a necessity since the flow of power = the flow of business?

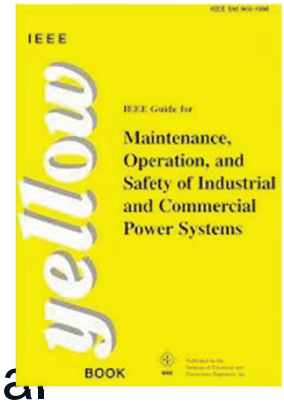
WHY DO WE TEST?

- Personnel safety – arc flash protection assumes equipment will interrupt precisely as intended
- Fire safety – NFPA National Electrical Code
- Insurance company required
- Regulatory – NERC/FERC
- Aging infrastructure
- Equipment manufactured to precise specifications (i.e. no fluff)
- Increase life cycle and defer the need for capital investment

WHO SHOULD TEST?

- Hospitals
- Data centers
- Utilities
- Industrials
- Commercial
- Everyone should have some form of testing to ensure safety

RESOURCES



- AVO Training Institute - Substation Maintenance
- IEEE - Color Book Series (Yellow Book - Guide for Maintenance, Operation, & Safety of Industrial & Commercial Power Systems)
- NETA – Standard for Acceptance/Maintenance Testing Specifications
- NETA Level II, III and IV test technicians
- NFPA 70B: Recommended Practice for Electrical Equipment Maintenance
- ANSI, NEMA, IEC
- Manufacturers of apparatus
- Authors such as Paul Gill - Electrical Power Equipment Maintenance and Testing

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RESOURCES (Continued)

- Manufacturers of test equipment:
  - Megger
  - Doble
  - Omicron
  - Vanguard
  - Flir
  - Fluke
  - Many more

REGULATORY

- NFPA – National Fire Protection Association
- NFPA 70: NEC – National Electrical Code
- NFPA 70E: Standard for Electrical Safety in the Workplace
- NESC – National Electrical Safety Code
- OSHA – Occupational Safety & Health Administration

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ELECTRICAL PREVENTIVE MAINTENANCE (EPM)

- Let's start with Acceptance Testing – Startup & Commissioning

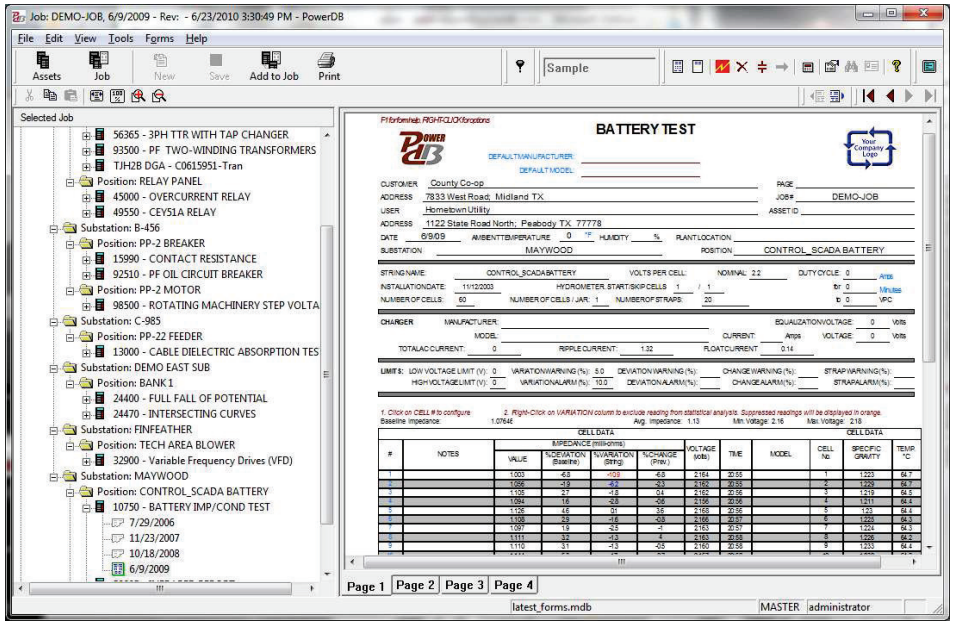
  - Establish baseline data for future trending
  - Ensure compliance of equipment to specifications
  - Check "full" range of apparatus, not just operating range
  - Confirm that equipment installed without damage

ELECTRICAL PREVENTIVE MAINTENANCE (Continued)

- Let's proceed to Maintenance Testing
  - Traditionally these programs were time based
  - Preventive vs. Predictive
  - Reliability Centered Maintenance (RCM)
  - Condition Monitoring – online
  - Historical performance of different assets
  - Whichever method works best – a Computerized Maintenance Management System should be utilized

CMMS

- Computerized Maintenance Management Systems
  - Manage work orders
  - Track PM
  - As found & as left data
  - Asset management
  - Inventory control
  - Root cause analysis
  - Trending
  - Regulatory reporting
  - Advanced analysis



- Example: PowerDB, Maximo, Cascade, Pow-R-Test

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PERSONNEL QUALIFICATIONS

- Technicians must be trained and experienced for apparatus being tested
- Only qualified persons should attempt maintenance
- NETA - Levels II, III and IV test technician
  - www.netaworld.org/certification
- Manufacturer certified
- Union specific training

MAINTENANCE & TESTING

- This presentation is going to focus on the electrical testing aspect of a maintenance program

- There are many more steps involved with:
  - Mechanical testing
  - Visual inspections
  - Verifications
  - Terminations
  - Sequencing
  - Levels
  - Etc.

MAINTENANCE & TESTING (Continued)

- Tests **should** be done on deenergized equipment
- Test equipment should be calibrated to NIST

- Short circuit and coordination studies should be provided
- Equipment should be inspected for conformance with studies and settings

- Arc flash study should be completed and equipment properly labeled

TEST EQUIPMENT TO BE COVERED

- Low Resistance Ohmmeter (Ductor)
- Insulation Resistance Tester (Megger)
- Dielectric Withstand (Hi-Pot)
- Transformer Turns Ratio (TTR)
- Power Factor (Doble)
- Transformer Ohmmeter – Winding Resistance
- Vacuum Bottle Integrity Tester
- Ground Resistance Tester
- High Current Injection
- Circuit Breaker Analyzer

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TEST EQUIPMENT TO BE COVERED (Continued)

- Battery Capacity (Load) Tester
- Battery Impedance Tester
- Relay Test Set
- Oil Dielectric Test Set

LOW RESISTANCE OHMMETER

- Ductor, Digital Low Resistance Ohmmeter (DLRO) or micro-ohmmeter
- Measure contact resistance, bus joints, etc.
- Applies DC Current
- Measures Voltage Drop
- Calculates (Low) Resistance in $\mu\Omega$
- Utilizes Kelvin connections
- $R = \frac{V}{I}$

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INSULATION RESISTANCE TESTER

- Megger or Megohmmeter
- Applied at or above rated voltage
- Affected by temperature, humidity, test voltage
- Should be normalized to 20°C
- Comparison test
- Used for Polarization Index
  - Ratio of IR @ 10 $minutes$ /IR @ 1 $minute$
- Applies DC Voltage up to 15kV
- Measures Leakage Current
- Calculates (High) Resistance in MΩ

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DIELECTRIC WITHSTAND

- High Potential, Hi-Pot
- DC test applied at 60Hz crest voltage $\sqrt{2}$ X RMS
- Overpotential – Go / No Go or Pass/Fail test
- Used for dielectric absorption
  - Good insulation should show increase in resistance
  - Because absorption current decreases
- Used for step-voltage test
- DC not recommended for cables
- AC test applied at 60Hz
- Used for testing bucket trucks

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TRANSFORMER TURNS RATIO

- TTR
- Determines ratio of transformer
- $\frac{V_p}{V_s} = \frac{N_p}{N_s} = \frac{I_s}{I_p}$
- Applies voltage to one winding and measures the other and calculates the ratio
- Used in both power and control transformers
  - 1∅ and 3∅
  - CTs and PTs

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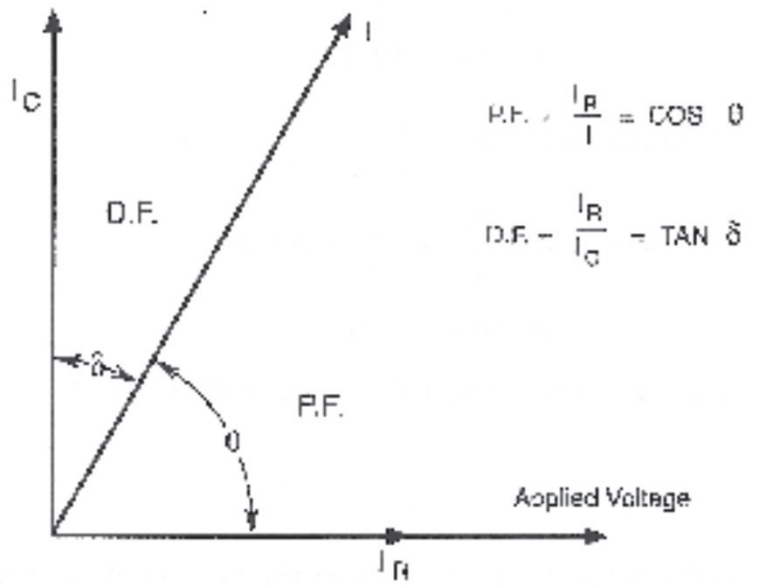
POWER FACTOR



- Doble test
- Dissipation Factor (tan δ)
- AC test
- Non destructive
- $PF = \frac{watts\ absorbed\ in\ insulation}{applied\ voltage\ X\ charging\ current}\ X\ 100$
- $DF = {}^{I_R}/_{I_C}$
- Perfect insulation would have PF of 0%
- Must be corrected to 20°C

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POWER FACTOR (Continued)

- Also used for excitation test
- Checks for:
  - Defects in manufacturing
  - Faults in windings
  - Problems with Load Tap Changers
  - Abnormal core grounds
- AC voltage applied to a transformer winding creates a magnetizing current
- This is recorded as excitation current
- Comparative test

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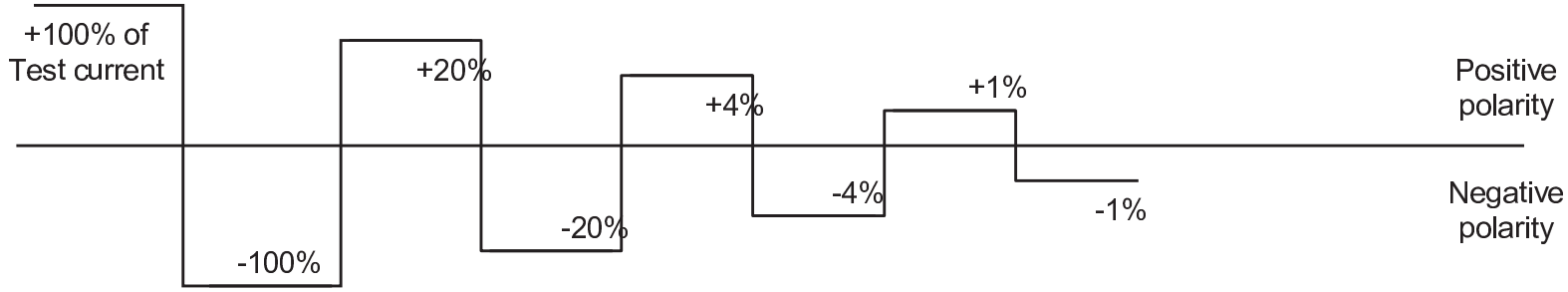
TRANSFORMER OHMMETER – WINDING RESISTANCE

- Apply a DC current and measure voltage drop
- Calculate resistance
- $V = RI + L\frac{\partial I}{\partial t}$

- Need to saturate the core so the $L\frac{\partial I}{\partial t}$ goes to zero
- DC current magnetizes the core
- Demagnetize to avoid high inrush currents



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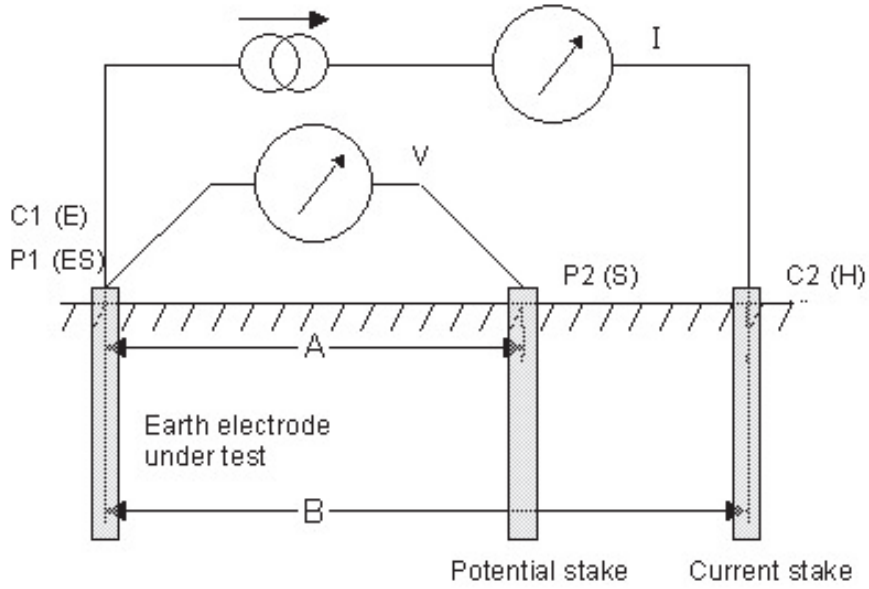
VACUUM BOTTLE INTEGRITY TESTER

- Check integrity of vacuum
- AC Hi-Pot test
- DC Hi-Pot test

GROUND RESISTANCE TESTER

- National Electrical Code 250.56
  - A single electrode > 25Ω is to be augmented by one additional electrode
- Fall-of-potential test measures R of earth electrode
- Injects AC current at fixed point
- Measures voltage at multiple points, graphed and accepted where curve is flat



HIGH CURRENT INJECTION

- Primary Injection through low voltage circuit breakers
- Injects full current through circuit breaker
- Allows measurement of instantaneous, long time, short time and ground fault
- Provides complete check of breaker and protective circuit
  - CTs
  - Control wiring
  - Relay
  - Trip Unit

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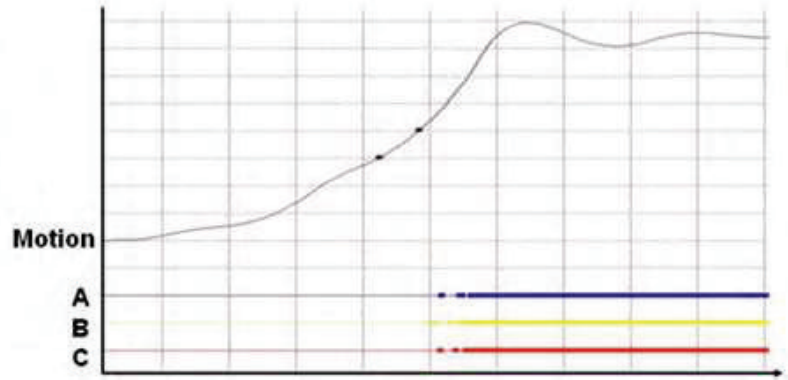
CIRCUIT BREAKER ANALYZER



- Time-Travel
- Measures
  - Closing & opening time
  - Contact bounce
  - Opening & closing synchronization
  - Closing and opening velocity
  - Trip operation
  - Trip-free operation
  - Close operation
  - Trip-close operation
- First trip

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BATTERY CAPACITY TESTER

- Load testing
- IEEE 450 for flooded lead-acid
- IEEE 1188 for sealed lead-acid
- IEEE 1106 for nickel-cadmium
- The only way to get an accurate value on the actual capacity of the battery
- Puts a resistive load on the in-service bank and measures Amp-hours the battery can deliver before the terminal voltage drops to a specified point
- Constant current

BATTERY IMPEDANCE TESTER

- Injects an AC current
- Measures AC voltage drop across each cell
- Calculates impedance
- Also calculates strap resistance
- Compare cells to one another
- Trending

- NERC PRC-005

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BATTERY GROUND FAULT FINDER

- Inject an AC signal – 20Hz
- Superimposed over DC without interruption
- Follow the path through ground
- Temporarily isolate ground fault monitors

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RELAY TEST SET

- High compliance voltage and high current test
- Test electromechanical, solid-state and microprocessor relay
- Timed outputs until relay trips
- End to end test with GPS
- IEC 61850 & GOOSE protocol
- Generic Object Oriented Substation Events

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OIL DIELECTRIC TEST SET

- Liquid dielectric breakdown testers
- Determines the dielectric strength of high voltage insulating liquids
- Measures voltage at breakdown
- Measures the insulating ability of a liquid to withstand electrical stress
- Different electrodes for different standards
- Gap is set with spacer
- Some standards call for stirring

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SWITCHGEAR/SWITCHBOARD

- Thermographic survey under full load DANGER!!!
- Test bolted electrical connections with low resistance ohmmeter
  - Investigate values which deviate >50% from lowest value
- Test insulation resistance for each section of bus – phase-to-phase and phase-to-ground
  - Run test for 1 minute
  - Compare to manufacturers requirements or NETA Table 100.1
  - Correct to 20°C per NETA Table 100.14
- Conduct dielectric withstand for each section of bus - phase-to-ground with phases not under test grounded (optional)
  - Only if insulation resistance levels are acceptable
  - Compare to manufacturers requirements or NETA Table 100.2
  - Run test for 1 minute
  - Pass / Fail or Go / No Go

SWITCHGEAR/SWITCHBOARD (Continued)

- Test insulation resistance on all control wiring (optional)
  - 1000V for 600V cable; 500V for 300V cable
  - Run test for 1 minute
  - Compare with prior results but not less than 2MΩ
- Test instrument transformers (detailed in a later section)
- Test ground resistance (detailed in a later section)
- Test control power transformers for insulation resistance – winding-to-winding and each winding-to-ground
  - Compare to manufacturers requirements or NETA Table 100.5
  - Correct to 20°C per NETA Table 100.14

NETA TABLE 100.1

Insulation Resistance Test Values
Electrical Apparatus and Systems

Nominal Rating of Equipment (Volts)	Minimum Test Voltage (DC)	Recommended Minimum Insulation Resistance (Megohms)
250	500	25
600	1,000	100
1,000	1,000	100
2,500	1,000	500
5,000	2,500	1,000
8,000	2,500	2,000
15,000	2,500	5,000
25,000	5,000	20,000
34,500 and above	15,000	100,000

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NETA TABLE 100.2

Switchgear Withstand Test Voltages

Type of Switchgear	Rated Maximum Voltage (kV) (rms)	Maximum Test Voltage (kV)	
		AC	DC
Low-Voltage Power Circuit Breaker Switchgear	.254/.508/.635	1.6	2.3
Metal-Clad Switchgear	4.76	14	20
	8.25	27	37
	15.0	27	37
	27.0	45	a
	38.0	60	a
Station-Type Cubicle Switchgear	15.5	37	a
	38.0	60	a
	72.5	120	a
Metal-Enclosed Interrupter Switchgear	4.76	14	20
	8.25	19	27
	15.0	27	37
	27	45	a
	38.0	60	a

NETA TABLE 100.5

Transformer Insulation Resistance Maintenance Testing

Transformer Coil Rating Type (Volts)	Minimum DC Test Voltage	Recommended Minimum Insulation Resistance (Megohms)	
		Liquid Filled	Dry
0 – 600	1000	100	500
601 – 5000	2500	1000	5000
Greater than 5000	5000	5000	25000

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NETA TABLE 100.14

Insulation Resistance Conversion Factors (20° C)

Temperature		Multiplier	
° C	° F	Apparatus Containing Oil Immersed Insulation	Apparatus Containing Solid Insulation
-10	14	0.125	0.25
-5	23	0.180	0.32
0	32	0.25	0.40
5	41	0.36	0.50
10	50	0.50	0.63
15	59	0.75	0.81
20	68	1.00	1.00
25	77	1.40	1.25
30	86	1.98	1.58
35	95	2.80	2.00
40	104	3.95	2.50
45	113	5.60	3.15
50	122	7.85	3.98
55	131	11.20	5.00
60	140	15.85	6.30
65	149	22.40	7.90
70	158	31.75	10.00
75	167	44.70	12.60
80	176	63.50	15.80
85	185	89.789	20.00
90	194	127.00	25.20
95	203	180.00	31.60
100	212	254.00	40.00
105	221	359.15	50.40
110	230	509.00	63.20

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DRY TYPE TRANSFORMERS - Small ≤500kVA

- Thermographic survey under full load
- Test bolted electrical connections with low resistance ohmmeter
  - Investigate values which deviate >50% from lowest value of similar connections
- Test insulation resistance winding-to-winding and each winding-to-ground
  - Compare to manufacturers requirements or NETA Table 100.5
  - Correct to 20°C per NETA Table 100.14
  - Perform Polarization Index and compare to prior values; should not be < 1
- Test turns ratio on in-service tap (all taps on first test) (optional)
  - Should not deviate more than ½% from average or from calculated ratio

DRY TYPE TRANSFORMERS - Large >500kVA

- Thermographic survey under full load
- Test bolted electrical connections with low resistance ohmmeter
  - Investigate values which deviate >50% from lowest value of similar connections
- Test insulation resistance winding-to-winding and each winding-to-ground
  - Compare to manufacturers requirements or NETA Table 100.5
  - Correct to 20°C per NETA Table 100.14
  - Perform Polarization Index and compare to prior values; should not be < 1
- Perform power factor test on all windings
  - Power transformers should expect ≤ 2%
  - Distribution transformer should expect ≤ 5%
  - Consult Doble, Megger, etc. or transformer manufacturer
- Test turns ratio on in-service tap (all taps on first test)
  - Should not deviate more than ½% from average or from calculated ratio

DRY TYPE TRANSFORMERS - Large >500kVA (Continued)

- Perform an excitation current test on each phase
  - Typically two similar current readings and one lower
- Measure winding resistance on in-service tap (all taps on first test) (optional)
  - Correct readings for temperature
  - Compare to prior values and should be within 1%
  - Demagnetize when done
- Verify secondary voltages (600V and less)
- Test surge arresters (detailed in a later section)

OIL FILLED TRANSFORMERS

- Thermographic survey under full load
- Test bolted electrical connections with low resistance ohmmeter
  - Investigate values which deviate >50% from lowest value of similar connections
- Test insulation resistance winding-to-winding and each winding-to-ground
  - Compare to manufacturers requirements or NETA Table 100.5
  - Correct to 20°C per NETA Table 100.14
  - Perform Polarization Index and compare to prior values; should not be < 1
- Test turns ratio on in-service tap (all taps on first test)
  - Should not deviate more than ½% from average or from calculated ratio
- Perform power factor test on all windings & bushings
  - Correct to 20°C
  - Consult Doble, Megger, etc. or transformer manufacturer
  - Representative values from NETA Table 100.3
  - Investigate bushing values differing by more than 10%

OIL FILLED TRANSFORMERS (Continued)

- Perform an excitation current test on each phase
  - Typically two similar current readings and one lower
- Measure winding resistance on in-service tap (all taps on first test)
  - Correct readings for temperature
  - Compare to prior values and should be within 1%
  - Demagnetize when done
- Remove oil sample and send for complete tests per ASTM D 923
  - Dielectric breakdown voltage: ASTM D 877 and/or ASTM D 1816
  - Acid neutralization number: ANSI/ASTM D 974
  - Specific gravity: ANSI/ASTM D 1298 (optional)
  - Interfacial tension: ANSI/ASTM D 971 or ANSI/ASTM D 2285
  - Color: ANSI/ASTM D 1500
  - Visual Condition: ASTM D 1524
  - Water in insulating liquids: ASTM D 1533. (Required on 25 kV or higher voltages and on all silicone-filled units.) (optional)
  - Measure power factor or dissipation factor in accordance w/ASTM D 924 (optional).
  - Compare values to NETA Table 100.4

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OIL FILLED TRANSFORMERS (Continued)

- Send oil sample for dissolved gas analysis (DGA)
- Test instrument transformers (detailed in a later section)
- Test surge arresters (detailed in a later section)
- Test neutral grounding resistor
  - Compare with prior results

LOAD TAP CHANGERS

- Test bolted electrical connections with low resistance ohmmeter
  - Investigate values which deviate >50% from lowest value of similar connections
- Test insulation resistance winding-to-winding and each winding-to-ground for any off-neutral positions
  - Compare to manufacturers requirements or NETA Table 100.5
  - Correct to 20°C per NETA Table 100.14
  - Perform Polarization Index and compare to prior values; should not be < 1
- Test turns ratio at all positions
  - Should not deviate more than ½% from average or from calculated ratio
- Perform power factor test in off neutral position
  - Correct to 20°C
  - Consult Doble, Megger, etc. or transformer manufacturer
  - Representative values from NETA Table 100.3
  - Investigate bushing values differing by more than 10%

LOAD TAP CHANGERS (Continued)

- Measure winding resistance (optional)
  - Correct readings for temperature
  - Compare to prior values and should be within 1%
  - Demagnetize when done
- Remove oil sample and send for complete tests per ASTM D 923
  - Dielectric breakdown voltage: ASTM D 877 and/or ASTM D 1816
  - Color: ANSI/ASTM D 1500
  - Visual Condition: ASTM D 1524
  - Compare values to NETA Table 100.4
- Send oil sample for dissolved gas analysis (DGA)
- Conduct vacuum integrity test across each bottle with contacts open
  - Pass / Fail or Go / No Go

NETA TABLE 100.3

Maintenance Test Values
Recommended Dissipation Factor/Power Factor at 20° C
Liquid-Filled Transformers, Regulators, and Reactors

	Oil Maximum	Silicone Maximum	Tetrachloroethylene Maximum	High Fire Point Hydrocarbon Maximum
Power Transformers	1.0%	0.5%	3.0%	2.0%
Distribution Transformers	2.0%	0.5%	3.0%	3.0%

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NETA TABLE 100.4.1

Suggested Limits for Class I Insulating Oil

Mineral Oil [a]				
Test	ASTM Method	Acceptable Values		
		69 kV and Below	Above 69 kV - Below 230 kV	230 kV and Above
Dielectric breakdown, kV minimum [b]	D 877	26	26	26
Dielectric breakdown, kV minimum @ 1 mm (0.04 inch) gap	D 1816	23	28	30
Dielectric breakdown, kV minimum @ 2 mm (0.08 inch) gap	D 1816	40	47	50
Interfacial tension mN/m minimum	D 971 or D 2285	25	30	32
Neutralization number, mg KOH/g maximum	D 974	0.20	0.15	0.10
Water content, ppm maximum @ 60° C [c]	D 1533	35	25	20
Power factor at 25° C, %	D 924	0.5	0.5	0.5
Power factor at 100° C, %	D 924	5.0	5.0	5.0
Color [d]	D 1500	3.5	3.5	3.5
Visual Condition	D 1524	Bright, clear and free of particles	Bright, clear and free of particles	Bright, clear and free of particles
Specific Gravity (Relative Density) @ 15° C Maximum [e]	D 1298	0.91	0.91	0.91

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NETA TABLE 100.4.2

Suggested Limits for Less-Flammable Hydrocarbon Insulating Liquid

Test	ASTM Method	Acceptable Values
Dielectric breakdown voltage, kV minimum	D 877	24
Dielectric breakdown voltage for 1 mm (0.04 inch) gap, kV minimum	D 1816	34
Dielectric breakdown voltage for 2 mm (0.08 inch) gap, kV minimum	D 1816	24
Water content, ppm maximum	D 1533 B	35
Dissipation/power factor, 60 hertz, % max. @ 25° C	D 924	1.0
Fire point, ° C, minimum	D 92	300
Interfacial tension, mN/m, 25° C	D 971	24
Neutralization number, mg KOH/g	D 664	0.20

NETA TABLE 100.4.3

Suggested Limits for Service-Aged Silicone Insulating Liquid

Test	ASTM Method	Acceptable Values
Dielectric breakdown, kV minimum	D 877	25
Visual	D 2129	Colorless, clear, free of particles
Water content, ppm maximum	D 1533	100
Dissipation/power factor, 60 hertz, maximum @ 25° C	D 924	0.2
Viscosity, cSt @ 25° C	D 445	47.5 – 52.5
Fire point, ° C, minimum	D 92	340
Neutralization number, mg KOH/g max.	D 974	0.2

NETA TABLE 100.4.4

Suggested Limits for Service-Aged Tetrachloroethylene Insulating Fluid

Test	ASTM Method	Acceptable Values
Dielectric breakdown, kV minimum	D 877	26
Visual	D 2129	Clear with purple iridescence
Water content, ppm maximum	D 1533	35
Dissipation/power factor, % maximum @ 25° C	D 924	12.0
Viscosity, cSt @ 25° C	D 445	0
Fire point, ° C, minimum	D 92	-
Neutralization number, mg KOH/g maximum	D 974	0.25
Neutralization number, mg KOH/g maximum	D 664	-
Interfacial tension, mN/m minimum @ 25° C	D 971	-