

Substation Maintenance Instruction

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SMI 161 Condition assessment of assets using health index

SECTION 3 – POWER TRANSFORMER

Contents

3.1	Asset description.....	2
3.2	Condition assessment.....	2
3.3	Condition rating	2
3.3.1	<i>Bushing external condition</i>	<i>2</i>
3.3.2	<i>Main tank and control cubicle</i>	<i>3</i>
3.3.3	<i>Conservator, radiators and cooling system.....</i>	<i>3</i>
3.3.4	<i>Overall transformer condition</i>	<i>4</i>
3.3.5	<i>Maintenance history</i>	<i>4</i>
3.3.6	<i>DGA oil analysis.....</i>	<i>5</i>
3.3.7	<i>Furan oil analysis</i>	<i>6</i>
3.3.8	<i>Transformer winding resistance</i>	<i>6</i>
3.3.9	<i>Transformer ratio test</i>	<i>7</i>
3.3.10	<i>Transformer DDF test.....</i>	<i>7</i>
3.3.11	<i>HV bushing DDF test.....</i>	<i>7</i>
3.3.12	<i>LV bushing DDF test</i>	<i>8</i>
3.3.13	<i>Insulation resistance</i>	<i>9</i>
3.3.14	<i>Oil quality test</i>	<i>9</i>
3.3.15	<i>OLTC control cubicle and mechanism condition.....</i>	<i>10</i>
3.3.16	<i>Overall OLTC condition</i>	<i>11</i>
3.4	Health index formulation	12
3.5	Health index results and condition assessment.....	13

3.1 Asset description

Power transformers in the transmission network are static devices that transfer electrical energy between two or more circuits using magnetic induction. They consist of insulated copper windings installed on laminated iron cores and immersed in oil that insulates and cools the internal components. Other components of a power transformer assembly include the tap changer, bushings, conservator, radiator, fans, pumps, foundation, structural steel supports, protection, instrumentation and control systems.

3.2 Condition assessment

Power transformers generally represent the most costly element of power systems. Transformers can operate in extreme conditions, and both normal and abnormal operation affects their aging. As the transformers age, the winding insulation can breakdown and lead to equipment failures; this may have significant consequences to safety, operational capability and cost.

The components mentioned in Section 3.1 are assessed based on set criteria and given a condition based rating. The assessed condition of these components is the foundation on which the Health Index is calculated.

3.3 Condition rating

The condition rating process includes visual inspections and detailed review of maintenance records and test reports. Each criterion represents a factor that is critical in determining the component's condition relative to potential failure.

The following tables contain specific definitions used for each condition rating for each component or test evaluated:

3.3.1 Bushing external condition

Condition Rating	Description
A	- Bushings are not broken and no visible chips, cracks and flashover burns. - Cementing and fasteners are secure.
B	- Bushings are not broken, however minor chips and cracks are visible. - Cementing and fasteners are secure.
C	- Bushings are not broken, however major chips, cracks and some flashover burns are visible. - Cementing and fasteners are secure.
D	- Bushings are broken / damaged. - Cementing and fasteners are not secure.
E	Bushings, cementing or fasteners are broken / damaged beyond repair.

3.3.2 *Main tank and control cubicle*

Condition Rating	Description
A	- No rust or corrosion on main tank, welded seals, flanges, valve fittings, gauges, monitors and control cubicle. - No oil leakage or water ingress at any of the bushing-metal interfaces or at gaskets, welded seals, flanges, valve fittings, gauges, monitors. - Control cubicle has no evidence of condensation, moisture or insect ingress. All wiring, terminal blocks, switches, relays, monitoring and control devices are in good condition.
B	- No rust or corrosion on main tank, welded seals, flanges, valve fittings, gauges, monitors and control cubicle. - Minor oil leaks evident, no moisture ingress likely. - Some evidence of slight moisture ingress or condensation in control cubicle.
C	- Some rust and corrosion on both main tank and control cubicle. - Clear evidence of oil leaks but rate of loss is not likely to cause any operational or environmental impacts. - Requires corrective action.
D	- Significant corrosion on main tank and control cubicle. - Defective control cubicle sealing leading to water ingress and insects/rodent damage. - Major oil leakage and probable moisture ingress. - Immediate corrective action required to prevent operational and/or environmental problems.
E	Corrosion, oil leaks, water ingress or insect / rodent damage / degradation that will require immediate refurbishment / replacement.

3.3.3 *Conservator, radiators and cooling system*

Condition Rating	Description
A	- No rust or corrosion on conservator tank, welded seals, flanges, valve fittings, gauges, monitors. - No rust or corrosion on body of radiators, fans or pumps and all securely mounted in position. - Oil pump and fans are operating as per design. - Paintwork in good condition.
B	- No rust or corrosion on conservator tank, welded seals, flanges, valve fittings, gauges, monitors. - Minor oil leaks evident, no moisture ingress likely. - Oil pump and nearly all fans are in functional condition.
C	- Some rust and corrosion on conservator tank, welded seals, flanges, valve fittings, gauges, monitors. - Clear evidence of oil leaks but rate of loss is not likely to cause any operational or environmental impacts. - Oil pump and most fans are in functional condition. - Requires corrective action.

D	• Significant corrosion on conservator tank, welded seals, flanges, valve fittings, gauges, monitors. • Major oil leakage and probable moisture ingress. • Multiple fans not functioning and pump bearings require replacement. • Immediate corrective action required to prevent operational and/or environmental problems.
E	• Major oil leakage or water ingress has resulted in damage/degradation beyond repair. Any seal failure on a sealed tank. • Radiators, fans or pumps damaged / degraded and will require immediate refurbishment / replacement.

3.3.4 Overall transformer condition

Condition Rating	Description
A	• Power transformer is corrosion free. • All primary connections (hotspots), secondary connections, monitoring, protection, control, pressure relief, gas accumulation, silica gel devices, and auxiliary systems mounted on the power transformer are in functional condition. • No external evidence of overheating or internal overpressure. • No excess noise indicating loose internal components. • Earthing connections are secure, free from corrosion and made directly to tanks, radiators, cubicles and supports, without any intervening paint or corrosion.
B	• Power transformer shows normal signs of wear.
C	• Some corrosion and deterioration of external components. • Some signs of overheating or overpressure.
D	• Major corrosion and deterioration of external components. • Severe signs of overheating or overpressure.
E	• Power transformer is damaged / degraded beyond repair.

3.3.5 Maintenance history

Condition Rating	Description
A	• 0 defect work orders in the last 5 years
B	• ≤10 defect work orders in the last 5 years
C	• ≤15 defect work orders in the last 5 years
D	• ≤20 defect work orders in the last 5 years
E	• ≥20 defect work orders in the last 5 years

3.3.6 DGA oil analysis

DGA oil condition rating is calculated based on the average weighted score from the dissolved gas score table.

Transformer ≤ 10 years old:

Gas	Scores (S _i)						Weight (W _i)
	1	2	3	4	5	6	
Hydrogen (H ₂)	≤50	50-100	100-200	200-400	400-700	>700	4
Methane (CH ₄)	≤10	10-75	75-150	150-250	250-400	>400	3
Acetylene (C ₂ H ₂)	≤2	2-7	7-35	35-50	50-80	>80	5
Ethylene (C ₂ H ₄)	≤5	5-20	20-50	50-80	80-100	>100	3
Ethane (C ₂ H ₆)	≤20	20-35	35-50	50-70	70-100	>100	3
Carbon Monoxide (CO)	≤500	500-700	700-900	900-1100	1100-1400	>1400	1
Carbon Dioxide (CO ₂)	≤1350	≤2000	≤3000	≤4000	≤5000	>6000	1

Transformer > 10 years old:

Gas	Scores (S _i)						Weight (W _i)
	1	2	3	4	5	6	
Hydrogen (H ₂)	≤100	100-200	200-300	300-500	500-800	>800	4
Methane (CH ₄)	≤25	25-100	100-200	200-400	400-600	>600	3
Acetylene (C ₂ H ₂)	≤150	150-175	175-200	200-225	225-250	>250	5
Ethylene (C ₂ H ₄)	≤75	75-90	90-110	110-150	150-200	>200	3
Ethane (C ₂ H ₆)	≤20	20-35	35-50	50-70	70-100	>100	3
Carbon Monoxide (CO)	≤600	600-800	800-1000	1000-1200	1200-1500	>1500	1
Carbon Dioxide (CO ₂)	≤6800	≤7500	≤8200	≤8900	≤9600	>9600	1

$$\text{DGA factor calculation: } DGA \text{ factor} = \frac{\sum_{i=1}^7 (S_i \times W_i)}{\sum_{i=1}^7 W_i}$$

Condition Rating	Description
A	• DGA factor ≤ 1.0
B	• $1.0 < \text{DGA factor} \leq 1.5$
C	• $1.5 < \text{DGA factor} \leq 2.5$
D	• $2.5 < \text{DGA factor} \leq 4.0$
E	• DGA factor > 4.0

3.3.7 Furan oil analysis

If DP analysis is available:

Condition Rating	Description
A	• >430
B	• $430 - 345$
C	• $345 - 260$
D	• $260 - 200$
E	• <200

If only furan analysis available:

Condition Rating	Description
A	• <1.0 ppm of 2-furaldehyde ($\approx >430$ DP)
B	• $1.0 - 2.0$ ppm of 2-furaldehyde ($\approx 430 - 345$ DP)
C	• $2.0 - 4.0$ ppm of 2-furaldehyde ($\approx 345 - 260$ DP)
D	• $4.0 - 6.5$ ppm of 2-furaldehyde ($\approx 260 - 200$ DP)
E	• >6.5 ppm of 2-furaldehyde ($\approx <200$ DP)

Equivalent DP is estimated using:

Chendong Formula: $DP = \frac{\log(2FAL) - 1.51}{-0.0035}$

Note: DP test may be required if the Furan test results are not conducive of the expected transformer paper aging.

3.3.8 Transformer winding resistance

Condition Rating	Description
A	• Differential winding resistance less than or equal to the pre-commissioning value if available, otherwise $\leq 0.02\Omega$.
B	• Differential winding resistance less than 30% increase from the pre-commissioning value if available, otherwise between $0.02\Omega - 0.026\Omega$.
C	• Differential winding resistance between 30-70% increase from the pre-commissioning value if available, otherwise between $0.026\Omega - 0.034\Omega$.
D	• Differential winding resistance between 70-100% increase from the pre-commissioning value if available, otherwise between $0.034\Omega - 0.04\Omega$.
E	• Differential winding resistance greater than 100% increase from the pre-commissioning value if available, otherwise $>0.04\Omega$.

3.3.9 Transformer ratio test

Condition Rating	Description
A	• $\pm 0.5\%$ of nameplate value
B	• $\pm 0.6\%$ of nameplate value
C	• $\pm 0.7\%$ of nameplate value
D	• $\pm 0.8\%$ of nameplate value
E	• $\pm 0.9\%$ of nameplate value or greater

3.3.10 Transformer DDF test

Condition Rating	Description
A	• Less than or equal to the pre-commissioning value if available, otherwise ≤ 4.5 mrad @ 20°C.
B	• Less than 30% increase from the pre-commissioning value if available, otherwise between 4.5 – 6.5 mrad @ 20°C.
C	• Between 30 – 70% increase from the pre-commissioning value if available, otherwise between 6.5 – 8.5 mrad @ 20°C.
D	• Between 70 – 100% increase from the pre-commissioning value if available, otherwise between 8.5 – 10.0 mrad @ 20°C.
E	• Greater than 100% increase from the pre-commissioning value if available, otherwise ≥ 10.0 mrad @ 20°C.

3.3.11 HV bushing DDF test

Oil-impregnated paper/Resin-impregnated paper insulation:

Condition Rating	Description
A	• Less than or equal to the pre-commissioning value if available or within manufacturer's limit, otherwise ≤ 5.0 mrad @ 20°C.
B	• Less than 30% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 5.0 – 8.0 mrad @ 20°C.
C	• Between 30 – 70% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 8.0 – 11.0 mrad @ 20°C.
D	• Between 70 – 100% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 11.0 – 14.0 mrad @ 20°C.
E	• Greater than 100% increase from the pre-commissioning value if available or exceeds manufacturer's limit, otherwise ≥ 14.0 mrad @ 20°C.

Resin-bounded paper/cast or moulded resin insulation:

Condition Rating	Description
A	• Less than or equal to the pre-commissioning value if available or within manufacturer's limit, otherwise ≤ 10.0 mrad @ 20°C.
B	• Less than 30% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 10.0 – 17.0 mrad @ 20°C.
C	• Between 30 – 70% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 17.0 – 22.0 mrad @ 20°C.

D	Between 70 – 100% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 22.0 – 30.0 mrad @ 20°C.
E	Greater than 100% increase from the pre-commissioning value if available or exceeds manufacturer's limit, otherwise ≥ 30.0 mrad @ 20°C.

Gas impregnated film/gas insulation:

Condition Rating	Description
A	Less than or equal to the pre-commissioning value if available or within manufacturer's limit, otherwise ≤ 5.0 mrad @ 20°C.
B	Less than 30% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 5.0 – 6.5 mrad @ 20°C.
C	Between 30 – 70% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 6.5 – 8.5 mrad @ 20°C.
D	Between 70 – 100% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 8.5 – 10.0 mrad @ 20°C.
E	Greater than 100% increase from the pre-commissioning value if available or exceeds manufacturer's limit, otherwise ≥ 10.0 mrad @ 20°C.

3.3.12 LV bushing DDF test

Oil-impregnated paper/Resin-impregnated paper insulation:

Condition Rating	Description
A	Less than or equal to the pre-commissioning value if available or within manufacturer's limit, otherwise ≤ 5.0 mrad @ 20°C.
B	Less than 30% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 5.0 – 8.0 mrad @ 20°C.
C	Between 30 – 70% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 8.0 – 11.0 mrad @ 20°C.
D	Between 70 – 100% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 11.0 – 14.0 mrad @ 20°C.
E	Greater than 100% increase from the pre-commissioning value if available or exceeds manufacturer's limit, otherwise ≥ 14.0 mrad @ 20°C.

Resin-bounded paper/cast or moulded resin insulation:

Condition Rating	Description
A	Less than or equal to the pre-commissioning value if available or within manufacturer's limit, otherwise ≤ 10.0 mrad @ 20°C.
B	Less than 30% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 10.0 – 17.0 mrad @ 20°C.
C	Between 30 – 70% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 17.0 – 22.0 mrad @ 20°C.
D	Between 70 – 100% increase from the pre-commissioning value if available or within manufacturer's limit, otherwise between 22.0 – 30.0 mrad @ 20°C.
E	Greater than 100% increase from the pre-commissioning value if available or exceeds manufacturer's limit, otherwise ≥ 30.0 mrad @ 20°C.

3.3.13 Insulation resistance

Condition Rating	Description
A	• $>IR_{min}$ and less than 10% of previous routine IR test result
B	• $>IR_{min}$ and between 10 – 20% of previous routine IR test result
C	• $>IR_{min}$ and between 20 – 30% of previous routine IR test result
D	• $>IR_{min}$ and greater than 30% of previous routine IR test result
E	• $<IR_{min}$

Minimum IR value: $IR_{min} = \frac{0.8 \times (TX \text{ primary voltage})}{\sqrt{(TX \text{ KVA})}} \text{ (M}\Omega\text{)}$

Voltage (kV)	Rating (MVA)	IR_{min} (M Ω)
132	120	305
	60	430
	45	498
66	35	282
	25	334
	15	431
33	35	141
	25	167
	15	216

3.3.14 Oil quality test

Oil quality rating is calculated based on the average weighted score from the oil tests score table.

	$\leq 66\text{kV}$	$> 66\text{kV}$	Score (S_i)	Weight (W_i)
Breakdown Voltage (kV)	≥ 40	≥ 50	1	2
	30-40	40-50	2	
	20-30	30-40	3	
	≤ 20	≤ 30	4	
Interfacial Tension (mN/m)	≥ 18		1	2
	14-18		2	
	12-14		3	
	≤ 12		4	
Acidity (mg KOH/g)	≤ 0.03		1	3
	0.03-0.07		2	
	0.07-0.10		3	
	≥ 0.10		4	
Moisture content (ppm)	≤ 10	≤ 5	1	2
	10-20	5-10	2	
	20-25	10-15	3	
	> 25	> 15	4	

Colour	≤1.5	1	2
	1.5-2.5	2	
	2.5-3.0	3	
	≥3.0	4	
Conductivity (pS/m)	≤5	1	1
	5-10	2	
	10-15	3	
	≥15	4	
DDF (mrad)	≤20	1	4
	20-30	2	
	30-40	3	
	≥40	4	

Oil quality factor calculation: $Oil\ quality\ factor = \frac{\sum_{i=1}^7 S_i \times W_i}{\sum_{i=1}^7 W_i}$

Condition Rating	Description
A	• Oil quality factor ≤ 1.2
B	• 1.2 < Oil quality factor ≤ 1.5
C	• 1.5 < Oil quality factor ≤ 2.0
D	• 2.0 < Oil quality factor ≤ 3.0
E	• Oil quality factor > 3.0

3.3.15 OLTC control cubicle and mechanism condition

Condition Rating	Description
A	• No external or internal rust or corrosion on control cubicle or peeling paint. • Weather seal in good condition, no evidence of moisture or insect ingress or condensation. • All control devices and components in good condition.
B	• No rust or corrosion, some evidence of slight moisture ingress or condensation in cubicle. • A small percentage of wiring, terminal blocks, relays and/or switches are in a degraded condition. • OLTC operating mechanism in good condition.
C	• Some rust and corrosion on cubicle. • About 20% of the wiring, terminal blocks, relays and/or switches are in a degraded state. • OLTC operation mechanism in fair condition.
D	• Significant corrosion on cubicle and defective sealing leading to water ingress and insects/rodent damage. • Significant amount of wiring, terminal blocks, relays and switches are in very poor condition. Fuses blow periodically. • One or more of the OLTC operating components is in imminent danger of failure. Requires immediate corrective action.
E	• Corrosion, water ingress, or insects/rodent damage / degradation beyond repair. Components have failed or are damaged / degraded beyond repair.

3.3.16 Overall OLTC condition

Condition Rating	Description
A	- OLTC external components, including control cubicle and mechanism, are all in good condition, and free from corrosion, deformation, cracks and obstruction. - No external corrosion or rust on the OLTC tank, cover plates, welded seals, flanges, valve fittings, pressure relief diaphragms, relays and fittings associated with the OLTC. - No oil leakage or water ingress at any interfaces, tank gaskets, cover plates, welded seams, flanges, valve fittings, pressure relief diaphragms, relay and fittings associated with the OLTC. - OLTC contacts and leads are in good functional condition. - Operation counter readings are $\leq 25\%$ of replacement value.
B	- Normal signs of wear of OLTC external components, including control cubicle and mechanism, and are free from corrosion, deformation, cracks and obstruction. - Minor oil leaks evident, no moisture ingress likely. - OLTC contacts and leads are in good functional condition. - Operation counter readings are between 25 – 50% of contact replacement value.
C	- Increased wear of OLTC external components, including control cubicle and mechanism, and some corrosion, deformation forming. - Clear evidence of oil leaks but rate of loss is not likely to cause any operational or environmental impacts. - Operation counter readings are between 50 – 75% of contact replacement value.
D	- Significant wear of OLTC external components, including control cubicle and mechanism, and significant corrosion, deformation forming. - Major oil leakage and probable moisture ingress. If left uncorrected it could cause operational and/or environmental problems. - Operation counter readings are between 75 – 100% of contact replacement value.
E	- Components have failed or are damaged / degraded beyond repair. - Oil leakage or moisture ingress that has caused damage / degradation beyond repair. - Operation counter readings are $>100\%$ of contact replacement value, contacts are required to be replaced immediately.

OLTC operation counter limit before contact replacement:

Brand	Type	Operation count
Reinhaussen	B, BC and C	25000
	D	50000
	F	35000
	M	40000
	V	70000
ACEC		20000
Ferranti		20000
English Electric		30000
All other brands		60000

3.4 Health index formulation

The power transformer is rated against set criteria for each condition parameter. The ratings are converted to a factor and multiplied by the given weight to obtain a health index score. The following table contains the associated weight for each condition criterion:

#	Condition Criteria	Weight (W _i)	Condition Rating	Factors (S _i)	Maximum Score (T _i)
1	Bushing external condition	1	A, B, C, D, E	4, 3, 2, 1, 0	4
2	Main tank and control cubicle	1	A, B, C, D, E	4, 3, 2, 1, 0	4
3	Conservator, Radiators and cooling system	1	A, B, C, D, E	4, 3, 2, 1, 0	4
4	Overall transformer condition	1	A, B, C, D, E	4, 3, 2, 1, 0	4
5	Maintenance history	1	A, B, C, D, E	4, 3, 2, 1, 0	4
6	DGA oil analysis	11	A, B, C, D, E	4, 3, 2, 1, 0	44
7	Furan oil analysis	58	A, B, C, D, E	4, 3, 2, 1, 0	232
8	Transformer winding resistance	2	A, B, C, D, E	4, 3, 2, 1, 0	8
9	Transformer ratio test	1	A, B, C, D, E	4, 3, 2, 1, 0	4
10	Transformer DDF test	2	A, B, C, D, E	4, 3, 2, 1, 0	8
11	HV Bushing DDF test	5	A, B, C, D, E	4, 3, 2, 1, 0	20
12	LV Bushing DDF test	2	A, B, C, D, E	4, 3, 2, 1, 0	8
13	Insulation resistance	1	A, B, C, D, E	4, 3, 2, 1, 0	4
14	Oil quality test	3	A, B, C, D, E	4, 3, 2, 1, 0	12
15	OLTC control cubicle and mechanism components	6	A, B, C, D, E	4, 3, 2, 1, 0	24
16	Overall OLTC condition	4	A, B, C, D, E	4, 3, 2, 1, 0	16
		100			400

All 16 scores are entered into the formula below to convert to a rating out of 100:

$$HI = \left(\frac{\sum_{i=1}^N (S_i \times W_i)}{\sum_{i=1}^N T_i} \right) \times 100$$

where: $\sum_{i=1}^N T_i = 400$

$N = 16$

3.5 Health index results and condition assessment

An overall health index for a power transformer can be derived from the above methodology. The overall health index is then compared to the Health Index Scale in Section 2.3 to determine to the overall condition of the asset. The resultant overall condition will dictate the strategic asset management requirements of the asset.