Condition Monitoring of Power Transformer: A Practical Approach

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***Abstract*- Power transformer is important and expensive component in the electric power system. At electricity utilities still maintenance approach is time and age based only. This paper describes how various observed, measured, testing conditions used for calculation of 'health indices' to support reference for asset management programmes to management and asset cares. Power transformers are important assets in electrical network, considering cost and reliability. The conditions of these assets have to be known, in order to avoid any possible outages and to choose the appropriate maintenance operation that could be done. The health index of a power transformer is one single overall indicator that represents its condition and is derived by a weighting process of all available indicators.**

This paper presents a case study on several power transformers having different capacity and discussing the benefits of using health index and failure probability as overall diagnostic tools. Moreover, a remaining lifetime calculation based on the transformer failure probability is defined.

Keywords- Condition monitoring, Aging rate, Health index, Probability of Failure (PoF), End of Life (EoL)

I. INTRODUCTION

Indian power grid is one of the major power networks across the world. After independence there was large investment and development in power sector. Many assets are very old and at the end of life considering their original design. Still many assets are providing functional duties without any major problem.

The transformer is a static device so the efficiency will be more. The natural failure rate is less therefore replacement rate is also very slow. This is another reason for use of asset for longer life span. From last decade regularity bodies and asset management policies emphasised on to reduce asset maintenance cost, simultaneously improve reliability and efficiency. In this situation understand the present condition and future performance of assets is important. Time frame of assets to be replace and which are the different consequences, financial as well as operational, are the paramount questions.

But after 2014 all over the world "Asset management" standard ISO 55001:2014 provides the guidelines to power utilities. Asset owners are already focusing on asset optimum use, efficiency, operational parameters, maintenance strategy etc. but asset management emphasizes scientific and systematic approach to take care of assets. In any high voltage substation transformer cost will be 60% that of total substation cost [4]. During normal operation of transformer it will experiences various stresses like, thermal, chemical, environmental, operational etc. [5].Consequently transformer age approaches to end of life and probability of failure increases.

Additionally regular overloading and short-circuit incidents on aged transformers may lead to unexpected premature failures, resulting in damage to customer relationships due to interruption of power supply.

The major consequences of failure of power transformer are,

a) Loss of cost and remaining life of existing asset.

b) Unexpected financial burden for replacement of power transformer.

c) Environmental effect due to oil leakage and Safety policy violation due to fire /flashover.

The existing process of asset condition monitoring techniques involves monitoring dissolved gas analysis, oil screening test, FFA of oil, various testing results such as, thermal image, partial discharge, sweep frequency response analysis, dielectric frequency response analysis etc.[4] [6]. Each individual parameter data stated above have a different effect on the transformer. This effect does not have a linear effect on transformer age. It may be exponential. So this evaluation method for deciding present health status of the transformer is not enough. Conventional methods are not compatible to calculate health condition of transformer combining all available inputs.

This limitation has been overcome and expressed in this paper to calculate the condition assessment of power transformers using "Health Index" (HI) technique. DNO common network asset indices methodology is adopted for calculation of health index in this paper. Weighting factor is defined for each input parameter considering the physical, environmental, operational, location conditions of transformers used for HI calculation in this paper.

Health Index (HI) "is a way of combining complex condition information to give a single numerical value as a comparative indication of overall condition."

This health index calculation technique gives a health score of existing transformers along with Probability of Failure (PoF) and End of Life (EoL) data.

II. DEVELOPING HEALTH INDEX

With the available theoretical available data "ideal health score" is calculated. In actual practice the transformer duty and location factors affects the expected life. Normal theoretical life and expected life are important for calculation of aging rate as age is depends on functional and operational parameters. Initial health score is function of aging rate and defined health score for new asset i.e. 0.5 as per methodology adopted. Additional information such as measured and observed conditions are collected for final calculation of health index. These conditions are needed to be fixed by weighting method, generally called as calibration. This approach to development of health indices summarised in the schematic diagram below [3].

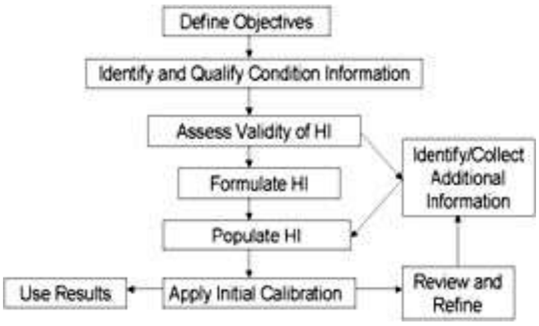


Fig.1. Flow chart for HI

A. Health scores-

Health score of each asset defined here is representated in a numeric presentation. The health score is calculated from combining complex input data such as transformer age, duty, environmental, functional, and operational parameters. The concept is illustrated in schematically in figure 2.[3]

Fig.2. Concept of HI

B. Initial Aging Rate (β_1)-

The rate of change of the health Score is not linear. For distribution assets, the degradation processes involved are all accelerated by the products of the process. Hence the rate of degradation increases as the processes proceed, i.e. it is an exponential function which, for a given asset, can be written as follows: [1]

$$HI_{t1} = HI_{t0}.exp\{\beta 1\,(t_1 - t_0)\} \qquad (1)$$

Where,
HI_{t1} = Health score at time t_1
β_1 = Initial aging rate

To determine the rate of change of the health Score, the value of β1 must be determined. The initial aging rate is a function of health score of new asset(i.e. 0.5) and the end of an asst's normal expected life (i.e. 5.5). Therefore, a different value of β1 must be calculated for each single asset based on its duty (load) and operating environment (e.g. indoor, outdoor, proximity to the coast etc.) as follows:[2]

$$\beta 1 = \frac{ln\left(\frac{H_{Expected\ Life}}{H_{new}}\right)}{Expected\ Life} \qquad (2)$$

Where,
β1 = Initial ageing rate

Hnew = Health Score of a new asset = 0.5

Hexpected life = Health Score at the end of the expected life = 5.5

C. Probability of Failure (PoF)-

The probability of failure is depends on the HI of asset. For high health score the probability of failure of asst is very high and asset is near to its end of life. It involves the degradation parameters and illustrated as,

$$PoF = k\cdot\left(1 + HS\cdot c + \frac{(HS\cdot c)^2}{2!} + \frac{(HS\cdot c)^3}{3!}\right) = k\cdot\sum_{i=0}^{3}\frac{(HS\cdot c)^i}{i!} \qquad (3)$$

Where,
HS = Health score
PoF = Probability of Failure per annum
k & c = Constants

D. Initial Health Score-

The Initial Health Score is obtained from new asset health and aging rate as mentioned in bellow expression,[2]

$$Initial\ Health\ Score = H_{new} * e^{(\beta 1 * age)} \qquad (4)$$

Where,

Hnew = New asset health score (0.5)
β1 = Initial Ageing Rate
Age = Current age of the asset in year

E. Normal Expected Life-

The Normal Expected Life is defined depending on asset manufacturing year and OLTC type. It will be finalised after discussion among asset care individuals and not fixed as per methodology.

F. Expected Life-

Expected Life is derived from Normal Expected Life, stated above and asset's location factor (environmental conditions where asst is installed) and duty factor (functional duties of asset).[2]

$$Expected\ Life = \frac{Normal\ Expected\ Life}{(Duty\ Factor * Location\ Factor)} \quad \textbf{(5)}$$

G. Current Health Score-

Having calculated an initial Heath Score for all assets, we can now consider the available condition information in order to improve on, or override, the initial Health Score value.
In order to calculate the Current Health Score, the Initial Health Score is multiplied by a Health Score Modifier. The Health Score Modifier is derived from a number of Health Score Factors which are derived from condition information. For each condition measure, a Minimum and Maximum Health Score is also calculated, with the final Health Score being within these minimum and maximum boundaries.

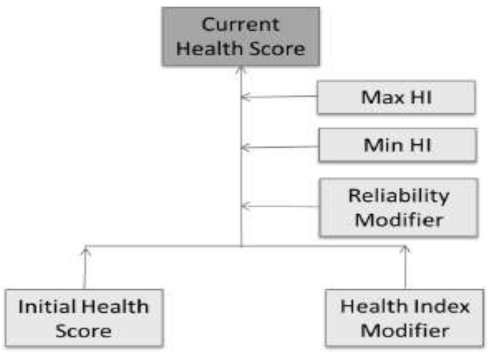


Fig.3 Current Health Score schematic diagram

H. Health Score modifier-

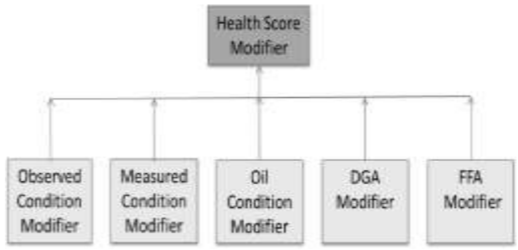


Fig.4 Health Score modifier schematic diagram

I. Reliability Modifier-

The reliability modifier is a direct input for each transformer and is used to reflect any reliability issues that exist with the unit. These may be reliability issues due to the make/model of the asset, or may reflect a particular asset that has a history of reliability issues.[2]

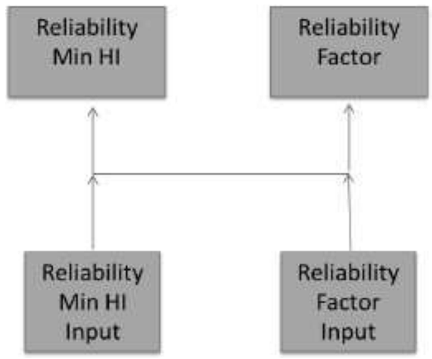


Fig.5 Reliability modifier schematic diagram

J. Future Health Score-

The ageing rate is first recalculated for calculation of future health score. The initial Health Score was calculated using an initial ageing rate based on the asset expected life, duty and location. The Current Health Score also takes into account the condition information and, as such, recalculating the ageing rate using the asset age and the Current Health Score gives a more accurate indication of the expected future ageing of an asset.
The Forecast Ageing Rate (β2) is calculated as follows:

$$\beta 2 = \frac{ln\left(\frac{H_{current}}{H_{new}}\right)}{Asset\ age} \quad (6)$$

Where,
β2 = Forecast Ageing Rate
Hnew = Health Score of a new asset = 0.5
Hcurrent = Current Health Score

$$HI_{future} = HI_{current}.exp\{\beta 2\,(t_2 - t_1)\} \quad (7)$$

Where,
Hfuture = Future Health Score.

Hcurrent = Current Health Score.
β2 = Forecast Ageing Rate.
t2 = Future year
t1 = Current year

K. End of Life-

The number of years to end of life is calculated based on a defined Health Score relating to end of asset life. In this case end of life does not relate to the point at which an asset fails, but to the point at which the probability of failure becomes unacceptable.

The number of years to end of life is calculated using the following equation.[1]

$$H_{future} = H_{current}.exp\{\beta_2.(t_2 - t_1)\} \quad (8)$$

Where ,
Hfuture =Future Health Score i.e. the end of life health index
Hcurrent =Current Health Score
β2 = Forecast Ageing Rate
t2 =Years to end of life
t1 =Current year

III. CALIBRATION SELECTION

Calibration factors are decided for different inputs to calculate required output. Reference for this health score calculation is DNO common network asset indices methodology [1].

TABLE I. LOCATION FACTOR

Altitude Factor		
Ref	Distance	Factor
1	≤ 100m	1
2	> 100m and ≤ 200m	1
3	> 200m and ≤ 300m	1.05
4	> 300m	1.1
5	Default	1

Distance from Coast Factor		
Ref	Distance	Factor
1	≤ 1km	1.1
2	> 1km and ≤ 5km	1.05
3	> 5km and ≤ 10km	1
4	> 10km and ≤ 20km	1
5	>20km	1
6	Default	1

Corrosion Factor		
Ref	Proximity with	Factor
1	DUMPING GROUND	1.05
2	CHEMICAL PLANT	1.05
3	RAILWAY YARD	1
4	QUARY	1
5	SEWARAGE PLANT	1.1
6	INDUSTRIAL BELT	1
7	CHEMICAL PLANT + SEWARAGE PLANT	1.15
8	DEFAULT	1

TABLE II. DUTY FACTOR

Duty Factor 1		
Ref	Average % Utilisation	Factor
1	≤ 70%	1
2	> 70% and ≤ 85%	1.05
3	> 85% and ≤ 100%	1.1
4	> 100%	1.4
5	Default	1

Duty Factor 2		
Ref	Maximum % Utilisation	Factor
1	≤ 100%	1
2	> 100% and ≤ 110%	1.05
3	> 110% and ≤ 120%	1.2
4	> 120%	1.4
5	Default	1

Tapchanger Duty		
> From	<= To	Avg. No Daily Tap Operations
0	7	≤ 7
7	14	> 7 and ≤ 14
14	21	> 14 and ≤ 21
21	100	> 21
None		Default

TABLE III. OBSERVED CONDITIONS

Main Tank Condition			
Ref	Observed Condition	Description	Factor
1	No Wear	The asset is as new	0.95
2	Normal Wear	The asset component is fit for continued service. There is little deterioration	1
3	Some Deterioration	e.g Minor corrosion but no leakages	1
4	Substantial Deterioration	e.g. major corrosion or Welding defects leading to Oil leakage from main tank	1.1
5	Default	No data available	1

Cooler Condition			
Ref	Observed Condition	Description	Factor
1	No Wear	The asset is as new	0.95
2	Normal Wear	All Fans working	1
3	Some Deterioration	All Fans working but noisy	1
4	Substantial Deterioration	one or more fans not working	1.05
5	Default	No data available	1

TABLE IV. MEASURED CONDITIONS

Oil Ave Temp			
Ref	Measured Condition	Description	Factor
1	Normal	upto 65 degrees	1
2	Moderate	65 to 75 degrees	1.05
3	High	Above 75 degrees	1.1

4	Default	No data available	1
Oil Max Temp			
Ref	Measured Condition	Description	Factor
1	Normal	Less than 75 degrees	1
2	Moderate	75 to 85 Degrees	1.05
3	High	Greater than 85 degrees	1.1
4	Default	No data available	1
Winding Ave Temp			
Ref	Measured Condition	Description	Factor
1	Normal	Less than 75 degrees	1
2	Moderate	75 to 90 degrees	1.05
3	High	Greater than 90 degrees	1.1
4	Default	No data available	1

TABLE V. OIL TEST MODIFIER

Moisture Condition State Calibration (Mineral Oil)		
> Moisture (ppm)	<= Moisture (ppm)	Moisture Score
-0.01	15	0
15	30	2
30	40	4
40	50	8
50	10000	10

Acidity Condition State Calibration (Mineral Oil)		
> Acidity (mg KOH/g)	<= Acidity (mg KOH/g)	Acidity Score
-0.01	0.1	0
0.1	0.15	2
0.15	0.2	4
0.2	0.3	8
0.3	10000	10

Breakdown Strength Condition State Calibration (Mineral Oil)		
> BD Strength (kV)	<= BD Strength (kV)	BD Strength Score
-0.01	30	10
0	40	4
0	50	2
0	0000	

TABLE VI. FFA TEST MODIFIER

FFA Test Factor		
> FFA value (ppm)	<= FFA value (ppm)	FFA Test Factor
-0.01	2	1
2	3.3	1.1
3.3	6.2	1.25
6.2	7	1.4
7		1.6

TABLE VII. DGA TEST MODIFIER

Hydrogen Condition State Calibration		
> Hydrogen (ppm)	<= Hydrogen (ppm)	Hydrogen Condition State
-0.01	20	0
20	40	2
40	150	4
150	200	10
200	10000	16

Methane Condition State Calibration		
> Methane (ppm)	<= Methane (ppm)	Methane Condition State
-0.01	10	0
10	20	2
20	130	4
130	250	10
250	10000	16

Ethylene Condition State Calibration		
> Ethylene (ppm)	<= Ethylene (ppm)	Ethylene Condition State
-0.01	10	0
10	20	2
20	180	4
180	300	10
300	10000	16

Ethane Condition State Calibration		
> Ethane (ppm)	<= Ethane (ppm)	Ethane Condition State
-0.01	10	0
10	20	2
20	90	4
90	150	10
150	10000	16

Acetylene Condition State Calibration		
> Acetylene (ppm)	<= Acetylene (ppm)	Acetylene Condition State
-0.01	1	0
1	5	2
5	20	4
20	100	8
100	10000	10

TABLE VIII. HEALTH SCORE MODIFIERS

Health Score Modifier Tapchanger

Setting Item	Value
Health Score Factor 1 Divider	1.5
Health Score Factor 2 Divider	1.5
Health Score Max. No Factors	2
Max Boundary	1

Health Score Modifier Tapchanger

Setting Item	Value
Health Score Factor 1 Divider	1.5
Health Score Factor 2 Divider	1.5
Health Score Max. No Factors	2
Max Boundary	1

TABLE IX. FUTURE HEALTH SCORE

Setting Item	Value
Recalculated Ageing Rate Ratio Limit (B)	1.25
As New HI	0.5
Future Year	2
Future Year Health Score Max HI	15
Recalculated Ageing Rate Ratio Start Year (B)	10

IV. PRACTICAL APPROACH_CASE STUDY

Total 211 no. of transformers having various MVA capacity, voltage level, different insulation medium, different types of OLTC included in this model. A health Score is calculated for each transformer and its associated tapchanger. The spreadsheet model contains a detailed calculation sheet which provides the values for each step in the calculation.

TABLE X. DETAILS OF TRANSFORMER ID's

TX Asset ID	Health Index Asset Category	Asset Register Category
Transformer ID-1	33/11 kV	20MVA
Transformer ID-2	33/11 kV	20MVA
Transformer ID-3	33/11 kV	20MVA
Transformer ID-4	33/11 kV	20MVA
Transformer ID-5	33/11 kV	20MVA
Transformer ID-6	33/11 kV	20MVA
Transformer ID-7	33/11 kV	20MVA
Transformer ID-8	33/11 kV	20MVA
Transformer ID-9	33/11 kV	20MVA
Transformer ID-10	33/11 kV	20MVA
Transformer ID-11	33/11 kV	20MVA
Transformer ID-12	33/11 kV	20MVA
Transformer ID-13	33/11 kV	20MVA
Transformer ID-14	22/11 kV	10MVA
Transformer ID-15	22/11 kV	10MVA

TABLE XI. RESULTS FOR SAME ID's

Probability of failure

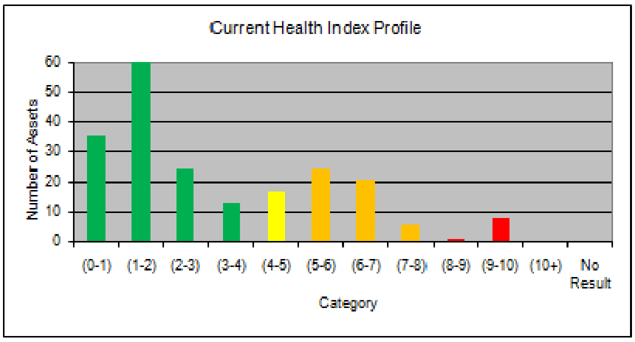
Current Health Score	Current Health Score Band	Future Health Score	Current PoF	Future POF (Y2)	Years to End of Life
1.93	(1-2)	2.26	0.00177	0.00177	18.7
5.50	(5-6)	6.08	0.00375	0.00481	8.71
2.38	(2-3)	2.71	0.00177	0.00177	19.7
1.65	(1-2)	1.91	0.00177	0.00177	22.0
4.50	(4-5)	5.10	0.00232	0.00313	10.0
3.51	(3-4)	4.15	0.00177	0.00192	10.5
3.73	(3-4)	4.17	0.00177	0.00194	14.8
4.03	(4-5)	4.48	0.00180	0.00229	14.0
3.49	(3-4)	3.71	0.00177	0.00177	10.7
1.64	(1-2)	1.94	0.00177	0.00177	19.4

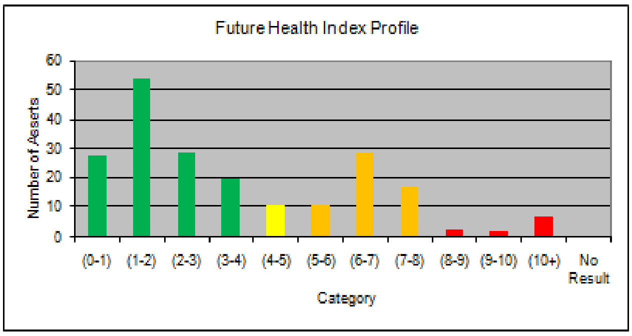
Reliability Modifier

Setting Item	Value
Factor Default	1
Min HI Default	0.5

6.58	(6-7)	7.30	0.00587	0.00769	4.28
3.49	(3-4)	3.90	0.00177	0.00177	15.9
3.14	(3-4)	3.53	0.00177	0.00177	17.1
4.98	(4-5)	5.46	0.00295	0.00368	11.6
10.00	(9-10)	11.11	0.01768	0.02353	0.0

V. CURRENT AND FUTURE HELATH SCORE PROFILE





Graph 1: Current and Future HI profile

Note: Future health score considered for after 2 years

VI. RESULT SUMMARY

For top results summary is tabulated bellow:

TABLE XII. CURRENT HEALTH SCORE

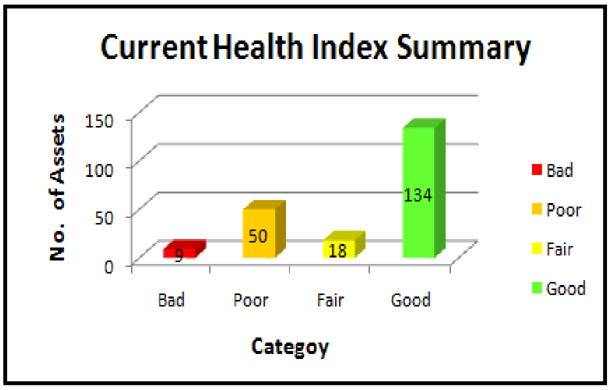
Current Health Score

TX Asset ID	Trans. Name	Transformer	Tap Changer	All Components
Transformer ID-11	20MVA-1	10.00	3.14	10.00
Transformer ID-90	10MVA-1	10.00	5.82	10.00
Transformer ID-124	20MVA-2	10.00	3.75	10.00
Transformer ID-140	10MVA-1	10.00	5.50	10.00

Transformer ID-148	20MVA -1	10.00	5.25	10.00
Transformer ID-45	20MVA -1	9.75	3.37	9.75
Transformer ID-111	10MVA -2	9.23	4.95	9.23
Transformer ID-94	10MVA -1	9.11	5.78	9.11
Transformer ID-193	10MVA -1	8.43	5.78	8.43
Transformer ID-114	10MVA -1	7.76	5.78	7.76
Transformer ID-20	10MVA -1	7.52	6.05	7.52
Transformer ID-47	10MVA -1	7.49	5.50	7.49
Transformer ID-40	10MVA -1	7.24	5.50	7.24

TABLE XIII. HI PROFILE

Current Health Index Profile	
Category	Number of Assets
(0-1)	35
(1-2)	62
(2-3)	24
(3-4)	13
(4-5)	17
(5-6)	24
(6-7)	21
(7-8)	6
(8-9)	1
(9-10)	8
(10+)	0
No Result	0
Total	211



Graph 2: Current HI summary

TABLE XIV. HI BANDS

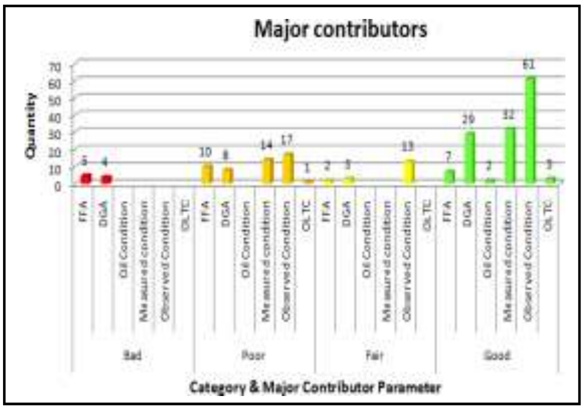
Category	Health Index
Bad	Above & including 8
Poor	Above & including 5.5 & below 8
Fair	Above 4 & below 5.5
Good	4 or Below

Detailed result for highest health score i.e. 10 tabulated herewith for Transformer ID-11.

TABLE XV. DETAILS FOR HIGH HI ASSET

Asset ID	Transformer ID-11
Transformer Name	20MVA-1
Current Health Score (All Components)	10
Current Health Score (Transformer)	10
Current Health Score (Tapchanger)	3.14
Years to End of Life (All Components)	0
Transformer Initial HI	
Expected Life	38.10
Duty Factor	1.00
Location Factor	1.05
Actual Age	27.00
Initial Health Score	2.74
Current Health Score	10.00
POF	
Current PoF	0.02
Future POF (Y2)	0.02
Tapchanger Initial HI	
Expected Life	33.33
Duty Factor	1.00
Location Factor	1.05
Actual Age	27.00
Initial Health Score	3.49
Tapchanger Health Score	
Observed Condition Modifier	1.00
Measured Condition Modifier	1.00
Oil Test Modifier	0.90
Health Score Factor	0.90
Health Score Max HI	10.00
Current Health Score	3.14

VII. MAJOR CONTRIBUTORS AND RECOMENDATIONS PRAPOSED



Graph 3: Major contributor's category wise

From above graph it is clear that in Bad category HI major contributors are FFA and DGA. For this category having major contributor FFA there is no recovery of cellulose electrical and mechanical properties by any maintenance process. So the recommendation is only repair or replacement of transformer. For DGA, investigation of cause for gas generation by Duval triangle method and corrective action is recommended. If not possible to take corrective action on site then repair, rewinding or replacement is recommended.

For Poor and Fair category HI the recommendations are summarised as bellow,

	Recommendations to Management
FFA	1. Procurement of transformer main tank online filtration portable machine. 2. Attending conservator air cell leakage abnormalities. Provision of budget for new air cell purchase and service order to attend same.
DGA	1. Procurement of online transformer oil DGA monitoring set.
Oil Condition	1. Procurement of transformer main tank online filtration portable machine. 2. Attending conservator air cell leakage abnormalities. Provision of budget for new air cell purchase and service order to attend same.
Measured condition	1. Procurement of smart breather, various online physical condition monitoring sensors. 2. Procurement of tan delta measurement kit & inclusion of same test as routine test for transformer.
Observed Condition	1. Procurement of new radiators for heavy leakage cases on priority basis.
OLTC	1. Procurement of Online filter (OFU) for OLTC unit. 2. Procurement of Dynamic resistance measurement (DRM) kit for OLTC contact healthiness check up.

VII. CONCLUSION

In this health score model we have formulated current health score, future health score (after 2 years), current and future PoF and end of life (EoL) for each asset. Now it is easy to take action on assets considering their health score banding. The spreadsheet is so designed that inputs can be changed as per change in observation status. The calculations are done automatically and results are available immediately. Also a number of asset additions are possible with this tool. This model will help as a reference to change maintenance strategy or replacement of any component / total asset from the network.

VIII. REFERENCES

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