3.2.1. **Dissolved Gas Analysis Factor (DGAF).** The DGAF is a representative factor of the oil-paper insulation condition from the dissolved gases perspective. The DGAF is an integer score value from zero to four, which indicates the degree of danger or degradation of the oil-paper system based on DGA. A score of zero indicates a poor DGA condition, while a score of four indicates a healthy DGA condition. In order to calculate the DGAF, a scoring system for each of the seven key gas elements is used to indicate the extent of the respective dissolved gases in the oil sample. Table 8 indicates the score system which is used for the key gas elements. Based on the score value, the DGAF is calculated using [26]

$$DGAF = \frac{\sum_{i=1}^{7} S_i \times W_i}{\sum_{i=1}^{7} W_i} \quad (1)$$

where S_i is the score outcome of each of the seven key gas elements based on Table 8, and W_i is the key gas associated weight or significance factor. The DGAF will be a real positive number that will be converted to an integer value from zero to four based on the DGAF scoring system shown in Table 9. As an example, the DGAF for the key gas elements of the samples, shown in Table 4 (from UTILA), will be computed as per the explained procedure. Table 10 shows the obtained DGAF values for these samples.

Table 8: DGAF score and weight system [26]

Hydrogen		*Methane*		*Ethane*		*Ethylene*		*Acetylene*		*Carbon Monoxide*		*Carbon Dioxide*	
$W_1=2$		$W_2=3$		$W_3=3$		$W_4=3$		$W_5=5$		$W_6=1$		$W_7=1$	
ppm	S_1	*ppm*	S_2	*ppm*	S_3	*ppm*	S_4	*ppm*	S_5	*ppm*	S_6	*ppm*	S_7
<155	1	<103	1	<92.5	1	<75	1	<5	1	<500	1	<2,750	1
<225	2	<145	2	<95.5	2	<85	2	<15	2	<850	2	<3,500	2
<365	3	<240	3	<96.5	3	<95	3	<25	3	<1,050	3	<4,500	3
<585	4	<400	4	<97.5	4	<105	4	<35	4	<1,250	4	<6,000	4
<700	5	<600	5	<100	5	<130	5	<60	5	<1,400	5	<7,000	5
>700	6	>600	6	>100	6	>130	6	>60	6	>1,400	6	>7,000	6

Table 9: DGAF final scoring system [26]

DGAF Calculated	*DGAF Final*
< 1.2	4
< 1.5	3
< 2	2
< 3	1
≥ 3	0

Table 10: Computed DGAF for UTILA Data Subset

Sample	*Hydrogen*		*Methane*		*Ethane*		*Ethylene*		*Acetylene*		*Carbon Monoxide*		*Carbon Dioxide*		*DGAF Calc.*	*DGAF Final*
	ppm	S_1	*ppm*	S_2	*ppm*	S_3	*ppm*	S_4	*ppm*	S_5	*ppm*	S_6	*ppm*	S_7		
1	15.6	1	14.4	1	2.5	1	0.3	1	0	1	1019.6	3	2619.3	1	1.11	4
2	19.9	1	15.6	1	3	1	0.4	1	0	1	1240.8	4	3323.2	2	1.22	3
3	7.9	1	0	1	0.7	1	0.5	1	0	1	132.5	1	1770.7	1	1.00	4
4	9.6	1	2.8	1	7.1	1	20.6	1	0	1	126.4	1	2126.5	1	1.00	4
5	19.2	1	2.4	1	2.3	1	6.5	1	34.8	4	237.6	1	3654.1	3	1.94	2
6	27.1	1	236.8	3	202.1	6	628.1	6	27.7	4	230.5	1	4810.7	4	4.00	0
7	18.7	1	2.5	1	41.4	1	55	1	58.2	5	165.8	1	5123.8	4	2.28	1

3.2.2. **Oil Quality Factor (OQF).** The OQF represents the health condition of the transformer oil. The OQF value is also an integer value which ranges from zero to four. An OQF of four indicates an excellent level of oil quality, while an OQF of zero indicates a very poor level of oil quality. Computation of the OQF is based on the scores and weights of the six oil quality parameters respectively. The OQF calculation is done using [26]

$$OQF = \frac{\sum_{i=1}^{6} S_i \times W_i}{\sum_{i=1}^{6} W_i} \tag{2}$$

Table 11 indicates the weights (W_i) and score values (S_i) for the oil quality parameters. The OQF will be a real positive number that will be converted to an integer score from zero to four based on the OQF scoring system shown in Table 12. The computed OQF values for the UTILA data subset (of Table 4) is shown in Table 13.

Table 11: OQF score and weight system [26]

Water		*Acidity*		*BDV*		*DDF*		*Color*		*IFT*	
W_1=4		W_2=1		W_3=3		W_4=3		W_5=2		W_6=2	
ppm	S_1	*mgKOH/g*	S_2	*kV*	S_3	-	S_4	-	S_5	*mN/m*	S_6
≤30	1	≤0.05	1	≥45	1	≤0.1	1	≤1.5	1	≥25	1
≤35	2	≤0.1	2	>35	2	≤0.5	2	≤2	2	>20	2
<40	3	<0.2	3	>30	3	<1	3	<2.5	3	>15	3
≥40	4	≥0.2	4	≤30	4	≥1	4	≥2.5	4	≤15	4

Table 12: OQF final scoring system [26]

OQF Calculated	*OQF Final*
< 1.2	4
< 1.5	3
< 2	2
< 3	1
≥ 3	0

Table 13: Computed OQA for UTILA data subset

Sample	*Water*		*Acidity*		*BDV*		*DDF*		*Color*		*IFT*		*OQA*	*OQA*
	ppm	S_1	*mgKOH/g*	S_2	*kV*	S_3	-	S_4	-	S_5	*mN/m*	S_6	*Calc.*	*Final*
1	3	1	0.005	1	99	1	0	1	0	1	42	1	1.00	4
2	2	1	0.005	1	84	1	0	1	0	1	43	1	1.00	4
3	1	1	0.133	3	76	1	0.005	2	3	4	20	3	2.00	1
4	11	1	0.046	1	75	1	0.001	1	1	1	23	2	1.13	4
5	7	1	0.042	1	55	1	0.002	2	3	4	18	3	1.87	2
6	4	1	0.029	1	82	1	0.002	2	2	2	18	3	1.60	2
7	4	1	0.057	2	74	1	0.002	2	3	4	18	3	1.93	2

3.2.1. **Furan Factor (FFA).** One of the main numerical factors that indicates the extent of the paper insulation degradation is the FFA. Calculation of the FFA is based on the scoring system shown in Table 14. The FFA is an integer score value that ranges from zero to four. Similarly, a value of four indicates a healthy paper condition, while a value of zero indicated a very poor paper condition. The calculated FFA values for the UTILA data subset are shown in Table 15.

Table 14: FFA scoring system [26]

Furan - ppm	*FFA*
< 0.1	4
< 0.25	3
< 0.5	2
< 1	1
≥ 1	0

Table 15: FFA for UTILA data subset

Sample	*Furan*	*FFA*
	ppm	*Final*
1	0.01	4
2	0.01	4
3	0.28	2
4	4.45	0
5	0.54	1
6	2.18	0
7	2.73	0

3.2.2. **Final Health Index (HI) value.** Based on the final insulation parameter scores (DGAF, OQF and FFA), a cumulative calculation for the HI is done. Each factor is assigned with a weight value (W_{DGAF}, W_{OQF} and W_{FFA}) that indicates the significance of the factor in the overall health of the transformer.

The cumulative calculation for the transformer HI is done using the following formula [26]

$$HI\ (\%) = 100 \times \frac{(DGAF \times W_{DGAF}) + (OQF \times W_{OQF}) + (FFA \times W_{FFA})}{4(W_{DGAF} + W_{OQF} + W_{FFA})}\ \% \qquad (3)$$

The final HI values for the UTILA data subsets are shown in Table 16. The overall HI computation is illustrated as a block diagram shown in Figure 4.

Table 16: Final HI for UTILA data subsets

Sample	*DGAF*	*OQF*	*FFA*	*HI (%)*
	$W_{DGAF} = 10$	$W_{OQF} = 6$	$W_{FFA} = 5$	
1	4	4	4	100.00
2	3	4	4	88.10
3	4	1	2	66.67
4	4	4	0	76.19
5	2	2	1	44.05
6	0	2	0	14.29
7	1	2	0	26.19

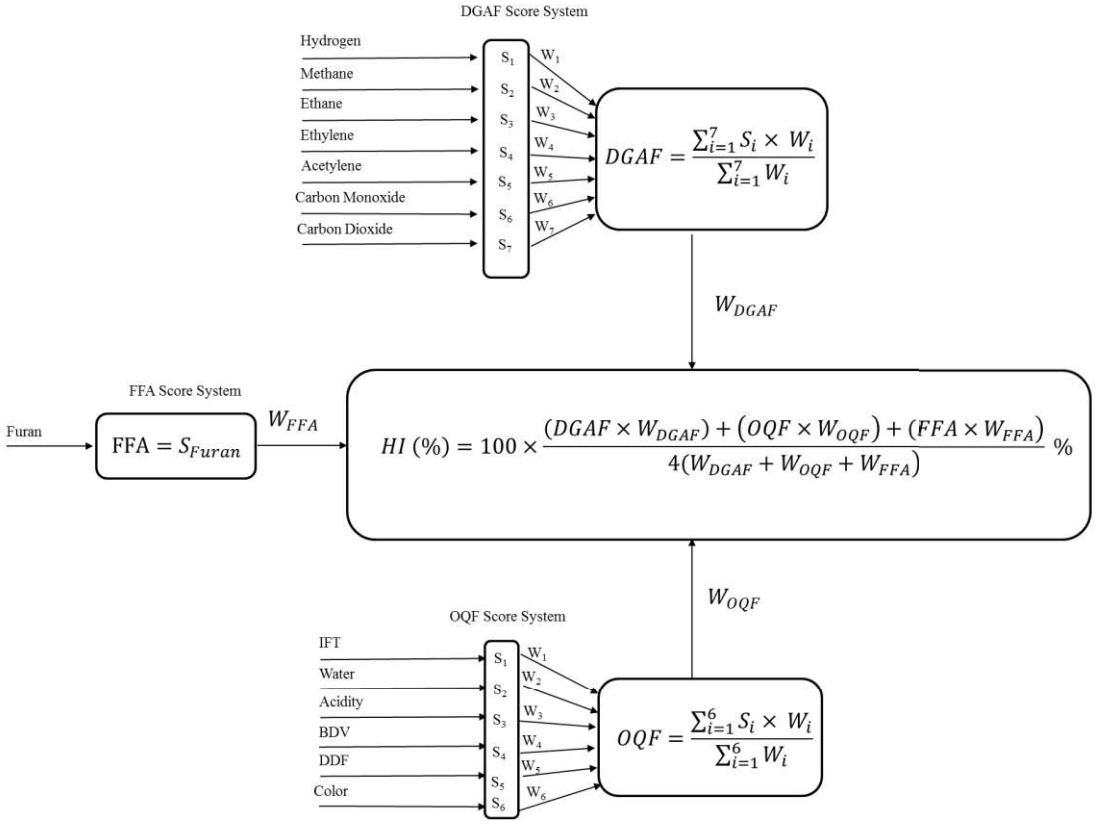

Figure 4: Overall HI computation using [26]