Asset Health

&

Probability of Failure

Calculations for Transformers and Breakers

Western Area
Power Administration

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WAPA Health and Probability of Failure Calculations
For Transformers and Breakers

1. Introduction

The analysis using condition data determines the state or condition or Health Index (HI) of the asset and enables WAPA to collect standardized data that can be used to assist with optimizing maintenance and replacement strategies for assets within an asset class.

Acceptable methods for determining condition assessment include identifying and collecting condition data which may include review of manufacturer, specification or name plate data, field observations, analytic test data, destructive and/or non-destructive test data, supplementary field testing, historical records, operational records, etc. The process for determining condition assessment for an asset class includes: assembling a team of subject matter experts, who in-turn can then develop proposed condition factors (CF), corresponding weighting factors (WF) for each CF, and any required standardized test metrics, and then combining these CF metrics with a mathematical algorithm or formula to determine a Health Index (HI) value for each asset in that asset class. The SMEs should then follow up and perform a condition assessment test evaluation of a sample size from the corresponding selected asset class. The SMEs can then make any subsequent adjustments to the CFs and WFs so as to provide an initial or baseline set of initial CFs and WFs. The process then continues by collecting data for all assets in the selected class and analyzing each asset against the initial CFs. This initial Condition Assessment process concludes when Health indices are compiled for all the identified assets.

The entire condition assessment process must be documented and repeatable. Condition Assessment is a dynamic process. When new assets are added to the plant the condition assessment must be performed to capture the initial HI. When assets are retired, they should be removed from the condition assessment process. As assets are maintained or repaired, their individual condition data and condition assessment records must be updated to reflect the current asset condition.

When an asset's condition, age, and applied stresses are known, its probability of failure (POF) may be estimated. The POF is used to calculate the asset's risk level, and is also useful in predicting the relative remaining lives in a fleet of assets.

Risk is defined mathematically as the product of the probability and consequence of a future event. Risk-based asset management makes use of the calculated risks of asset failures to prioritize assets for replacement or other forms of risk reduction.

The probability of failure of an asset is based on its condition, age, the operational stresses it endures, and the characteristic life of the asset class.

2. Health Index

2.1 Development

The condition of an asset is measured by its HI. This HI is determined by evaluating several factors that are critical to the operational health of the asset. Each critical factor is weighted during the HI calculation so that the relative value of each factor can be adjusted.

2.1.1 For power circuit breakers, the critical factors are:

- Age
    - Current Age. This is based on the asset's date of manufacture. The asset's HI is reduced as its age increases.
- Maintenance History
    - Work Order History. This is evaluated by calculating the annual average number of repair work orders during the previous five year period. Only Maximo work orders for emergency (EM), corrective maintenance (CM) or reactive maintenance (RM) are counted. In addition, the total number of labor hours charged to these work orders for the asset is calculated. These elements are scored so that an increasing number of work orders or labor hours charged to the asset decreases its HI.
    - Recent PM Issues. This factor evaluates the results of routine preventative maintenance activities and decreases the asset's HI in proportion to the severity of problems discovered.
- Design and Obsolescence
    - Breaker Interrupt Rating. The breaker's HI is reduced if the breaker's bus fault duty is greater than 50% of its rated interrupting capacity.
    - Spare Parts Availability. The breaker's HI is reduced in cases where spare parts are difficult to obtain.
- Power System Stress
    - Breaker Operating Environment. The breaker's HI is reduced in cases where its operating environment results in a high level of operating stress (line breaker or reactive switching)

- Breaker Operations Count. The breaker's HI is reduced when it experiences greater than 50 operations on average per year over the previous five years.

2.1.2 Power transformers, mobile transformers, grounding transformers, phase shifting transformers, and oil-filled reactors, the critical factors are:

- Age and Design
  - Current Age. This is based on the asset's date of manufacture. The asset's HI is reduced as its age increases.
  - Design. The asset's HI is reduced if it is an autotransformer or phase shifting transformer. This is because industry experience has shown these two types of transformers to have a shorter lifespan than conventional two or three winding transformers.
  - Load Tap Changer (LTC) Issues. Because LTCs are generally susceptible to more mechanical and thermal problems than the transformers themselves, the transformer's HI is reduced if it has an LTC or if it has experienced recent problems with its LTC.
- Oil Condition
  - Dissolved Gasses. The transformer's HI is reduced if a recent dissolved gas analyses (DGA) show levels of total combustible gas in excess of 500 parts per million or a more frequent retest is recommended.
  - Oil Moisture. The transformer's HI is reduced if the level of moisture in the oil is greater than 0.5% by dry weight.
  - Furans. Furans are chemical compounds that are found in transformer oil when the insulating paper begins to deteriorate. The transformer's HI is reduced if measured Furan levels are greater than 0.18 parts per million.
  - Degree of Polymerization (DP). DP is another method of evaluating the life of the insulating paper in a transformer. It is determined by physically testing a sample of the transformer insulating paper. It can also be estimated from furan testing results. The transformer's HI is reduced if the DP level is less than about 600.

- Electrical Condition
  - Bushing Power Factor. This factor evaluates the results of routine power factor testing of the transformer bushings and decreases the transformer's HI in proportion to the severity of problems discovered.
  - Winding Insulation Power Factor. This factor evaluates the results of routine power factor testing of the transformer's internal windings and decreases the transformer's HI in proportion to the severity of problems discovered.
- Operational and Maintenance History
  - Through Fault History. This factor decreases the transformer's HI if it has a history of damaging through faults.
  - Work Order History. This factor is evaluated in the same way as for breakers. See description above.
  - Inspection Findings. This factor is evaluated in the same way as for breakers. See description above.
  - Loading and Temperature History. The transformer's HI is reduced if it has been loaded in excess of 50% of its nameplate rating or its winding temperatures have exceeded 100 degrees Centigrade.

For each asset, the critical factors and sub-factors are assigned scores ranging from 0 (worst) to 4 (best) based on the asset's most currently assessed condition. Each factor and sub-factor is also assigned a weight based on its relative importance. The HI is the weighted average of these factors and sub-factors expressed in a scale of 0 to 100, where 100 indicates a like-new condition.

The Condition Scoring Factors and initial assigned weights are shown the following figures.

For Circuit Breakers:

Breaker Condition Factors for Asset Management Health Index

5/19/2015

Age:		Factor Weight: 2	Score
Current Age			
	Based on initial	0 - 19 yrs	4
	circuit breaker	20 - 29 yrs	3
	in-service date	30 - 39 yrs	2
		40 - 49 yrs	1
		50 +	0

Maintenance History:		Factor Weight: 2	Score
Work Order History			
	Based on number	0 wo's/yr or	4
	of RM, CM, EM	0 - 10 hours/yr	4
	work orders or labor	.2 - .4 wo's/yr or	3
	hours in last 5 years	10 - 20 hours/yr	3
		.6 - .8 wo's/yr or	2
		20 - 40 hours/yr	2
		1 - 1.8 wo's/yr or	1
		40 - 100 hours/yr	1
	Subfactor Weight:	2 + wo's per year or	0
	2	100 + hours/yr	0
Recent PM Issues			
	Based on results of Doble	No issues	4
	tests, operating mechanism	Minor repairable issues	3
	condition, bushing condition,	Moderate repairable issues	2
	interrupter condition, timing	Moderate non-repairable issues	1
	tests, oil or gas leaks, etc.	Significant non-repairable issues	0
		Subfactor Weight: 2	

Design/Obsolescence:		Factor Weight: 2	Score
Breaker Interrupt Rating			
	Breaker interrupting rating	0 - 50% of interrupting rating	4
	as a percentage of maximum	51 - 80% of interrupting rating	2
	station bus fault duty	81 - 100% of interrupting rating	1
		100+ % of interrupting rating	0
	Subfactor Weight: 2		
Spare Parts Availability			
	Availability of critical	Parts easily available	4
	spare parts based on	Parts only available by special order	2
	Foreman's judgment -	Obsolete design for application	1
	or obsolete design	Parts unavailable or prohibitively expensive	0
	Subfactor Weight: 2		

Power System Stress:		Factor Weight: 2	Score
Breaker Operating Environment			
	Breaker application	Transfer breaker	4
		Bus tie or transformer breaker	3
		Line breaker	2
		Reactive switching	0
	Subfactor Weight: 2		
Breaker Operations Count			
	Averaged over	0 - 50 ops per year	4
	previous 5 years	51 - 100 ops per year	2
		100+ ops per year	0
	Subfactor Weight: 2		

For Transformers and Oil-Filled Reactors:

Transformer & Reactor Condition Factors for Asset Management Health Index

5/19/2015

Oil Condition: Factor Weight: 4

		Score
DGA Recommendation		
From Laboratory or	Retest 1 yr or TCG<500	4
Foreman/Engineer	Retest 6 mo or TCG 500-720	3
Subfactor Weight:	Retest 3 mo or TCG 720-1920	2
3	Retest 1 mo or TCG> 1920-4600	1
	Retest <1 mo or TCG>4600	0
Oil Moisture (115-kV)		
(% by dry weight or from	<.85% M/DW or Omicron Dirana <2.2%	4
Omicron Dirana tests)	.85 - 1.35	3
Subfactor Weight:	1.36 - 1.70 or Omicron Dirana 2.2 - 3.8%	2
3	1.71 - 2.65 or Omicron Dirana 3.8 - 4.8%	1
	>2.65% M/DW or Omicron Dirana > 4.8%	0
Furans (55 degree rise)		
From most recent DGA test	<.27 ppm or DP > 608	4
for 55 deg rise	.27 - .9 ppm or DP 461-607	3
transformer	.9 - 2.2 ppm or DP 349-460	2
Subfactor Weight:	2.2 - 4.4 ppm or DP 265-348	1
3	>4.4 ppm or DP < 264	0
Furans (65 degree rise)		
From most recent DGA test	<.2 ppm or DP > 608	4
for 65 deg rise	.2 - .5 ppm or DP 461-607	3
transformer	.5 - 1.1ppm or DP 349-460	2
	1.1 - 1.8 ppm or DP 265-348	1
	>1.8 ppm or DP < 264	0

Electrical Condition: Factor Weight: 4

		Score
Bushing Power Factor		
From most recent test	Good, no concerns	4
Subfactor Weight:	Deteriorated - monitor	3
3	Questionable - monitor	2
	Investigate to find problem	1
	Bad - remedial action needed	0
Winding Insulation Power Factor		
From most recent test	Good, no concerns	4
Subfactor Weight:	Deteriorated - monitor	3
3	Questionable - monitor	2
	Investigate to find problem	1
	Bad - remedial action needed	0

O&M History: Factor Weight: 2

		Score
Through Faults		
Operating history	No damaging through faults	4
from last 5 years	One or more damaging faults	0
Subfactor Weight:		
1		

O&M History: (continued)

		Score
Work Order History		
Based on number	0 /yr or	4
of RM, CM, EM	0 - 10 hours/yr	4
work orders or labor	.2 - .4/yr or	3
hours in last 5 years	10 - 30 hours/yr	3
	.6 - .8/yr or	2
	30 - 60 hours/yr	2
	1 - 1.8 or	1
Subfactor Weight:	60 - 150 hours/yr	1
2	2 + per year or	0
	150 + hours/yr	0
Inspection Findings		
Visual and IR findings	No issues	4
from most recent	Minor repairable issues	3
inspections, including	Moderate repairable issues	2
oil leaks	Moderate non-repairable issues	1
Subfactor Weight:	Significant non-repairable issues	0
2		
Loading and Temperature History		
From recorded operating	Max Load < 50% nameplate or	4
history and inspection	Max winding temp < 100 C	4
records	Max Load 50 - 90% nameplate or	3
	Max winding temp < 105 C	3
Subfactor Weight:	Max Load 90 - 100% nameplate or	2
2	Max winding temp < 110 C	2
	Max Load 100 - 120% nameplate or	1
	Max winding temp < 115 C	1
	Max Load > 120% nameplate or	0
	Max winding temp > 115 C	0

Age, Design and Other Factors: Factor Weight: 2

		Score
Current Age		
Based on initial	0 - 19 years	4
transformer/reactor	20 - 29 years	3
in-service date	30 - 39 years	2
Subfactor Weight:	40 - 49 years	1
2	50 + years	0
Design		
Subfactor Weight:	2 or 3 winding transformer	4
2	oil-filled reactor	4
	autotransformer or phase shifter	2
LTC Issues		
	No LTC	4
Subfactor Weight:	Yes - no LTC problems	3
2	Yes - minor LTC problems	2
	Yes - moderate LTC problems	1
	Yes - major LTC problems	0

2.1.3 The equations for the Health Index calculation are:

$$HI = \frac{\sum_{m=1}^{n} \alpha_m \left(FS_m \times FW_m\right)}{\sum_{m=1}^{n} \alpha_m \left(FS_{m.max} \times FW_m\right)}$$

and

$$FS = \frac{\sum_{p=1}^{q} \beta_p \left(SFS_p \times SFW_p\right)}{\sum_{p=1}^{q} \beta_p \left(SFS_{p.max} \times SFW_p\right)} \times 4$$

Where:

α_m = Data availability coefficient for Factor score (=1 when data available, =0 when data unavailable)

β_p = Data availability coefficient for the Subfactor condition parameter (=1 when data available, =0 when data unavailable)

n = Number of Factors

q = Number of Subfactors within the Factor

FS_m = Factor Score

SFS_m = Subfactor Score

FW_m = Factor Weight

SFW_p = Subfactor Weight

2.2 Verification

If a Health Index calculation methodology is developed or provided by an outside vendor, it is advisable to conduct an audit to verify the processes and data by WAPA SMEs or other WAPA personnel with the same level of expertise as the vendor. Site audit forms have been developed that may be used for random sampling to verify an outside vendor's Health Index approach for circuit breakers and transformers.

Since WAPA's Health Index approach and calculations for circuit breakers and transformers were developed and reviewed by WAPA's SMEs, maintenance foremen and field engineers, the use of a separate site audit was not considered to be necessary.

3. Alternative Health Index

Although the HI is a good overall indicator of the condition of an asset, certain critical sub-factors can be masked in the averaging process. In the Alternative HI, only the worst sub-factor score in each factor is used to determine the weighted average.

$$Alt\ HI = \frac{\sum_{m=1}^{n} \alpha_m (FS_m \times FW_m)}{\sum_{m=1}^{n} \alpha_m (FS_{m.max} \times FW_m)}$$

Where for each *FS*, $FS_m = SFS_{p.min}$

It is yet clear whether the HI or Alternative HI is the more accurate indicator of overall asset health. However, the Alternative HI for transformers is useful in determining the asset probability of failure due to loading.

4. Probability of Failure

As stated previously, the probability of failure (POF) of an asset has three components: age, condition, and stress. The following paragraphs explain the relationships that determine the asset POF for transformers and power circuit breakers.

4.1 The Effect of Age on Probability of failure

All assets wear out over time and have a characteristic replacement age. Using a statistical method called Life Data Analysis, the expected service lives of an asset class can be predicted. The result of this analysis is the Unreliability of the asset class, or the probability that an asset will fail or be removed from service before it reaches a certain age. The analysis is based on historical data for the retirement and failure ages of assets. WAPA is fortunate to have a good source of retirement and failure age data in its Maximo computerized maintenance management system.

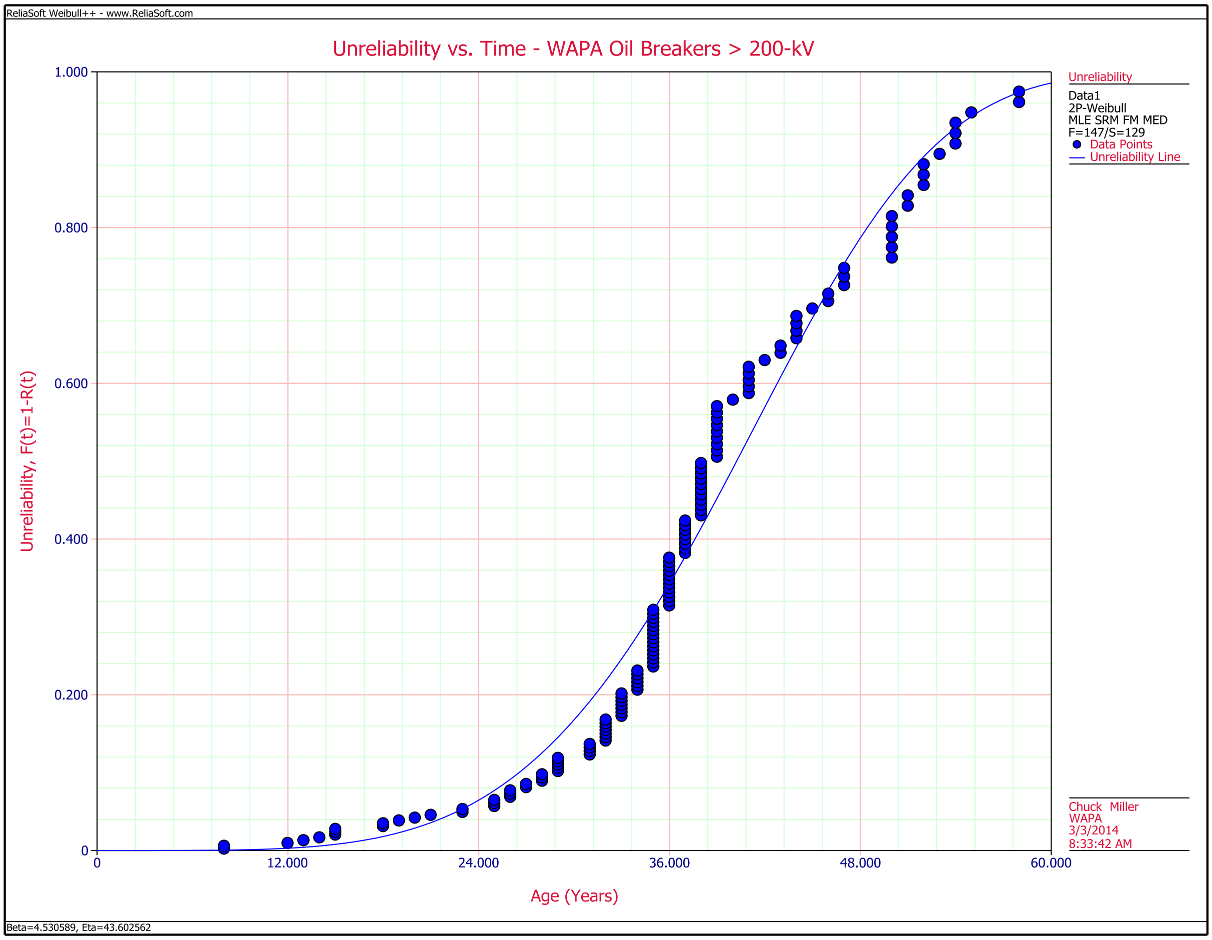
Several methods are available to estimate failure rates and failure probabilities from retirement and replacement age data. The Weibull analysis is the most well-known. In practice, there are software packages such as Weilbull++ by Reliasoft and Availability Workbench by Isograph that can develop failure distribution curves like the ones shown below from equipment failure and replacement data. WAPA has purchased the Weibull++ software for this purpose. It is administered by the Design and Engineering office (A7900) at CSO.

Depending on the specific data set, the software will determine whether the data is best described by a Weibull, Gumbel, Gamma, Logistic, or other statistical distribution representing the best fit to the data. These curves represent the probability that an asset will fail or be removed from service prior to a specific age (Unreliability). A related calculation will be described later that can provide the probability that an asset will fail or be removed from service in the next year, given that it has survived to the present year. Both calculations are useful for asset management.

WAPAs fleet of retired assets includes both assets that have failed in service and those which were permanently removed from service for other reasons. These other reasons include assets that had become increasingly expensive to maintain, assets that had become functionally obsolete, and assets whose performance ratings had become inadequate for their application due to system growth or other changes.

Since the data used for WAPA’s asset life data analysis includes both failed assets and those removed from service for other reasons, the resulting calculated probability of asset failure actually represents the probability of asset replacement. For the sake of simplicity, however, we will continue to use the term “probability of failure” and “Unreliability” to mean the probability that the asset will be replaced for all reasons.

The chart below shows a typical Unreliability analysis of one group of WAPA’s high voltage circuit breakers. The dots are actual data from Maximo, and the solid line is a mathematical approximation of the same data based on the Weibull distribution. The Weibull distribution was found to provide the best representation for WAPAs high voltage gas and oil circuit breakers (115-kV and above). The analysis of WAPA’s retirement data for circuit breakers for voltages greater than 100-kV showed that the assets can be adequately described by two Weibull equations, one for oil breakers and the other for gas breakers.



The Weibull equation for the probability of failure prior to a specified age (Unreliability) is:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

Where:

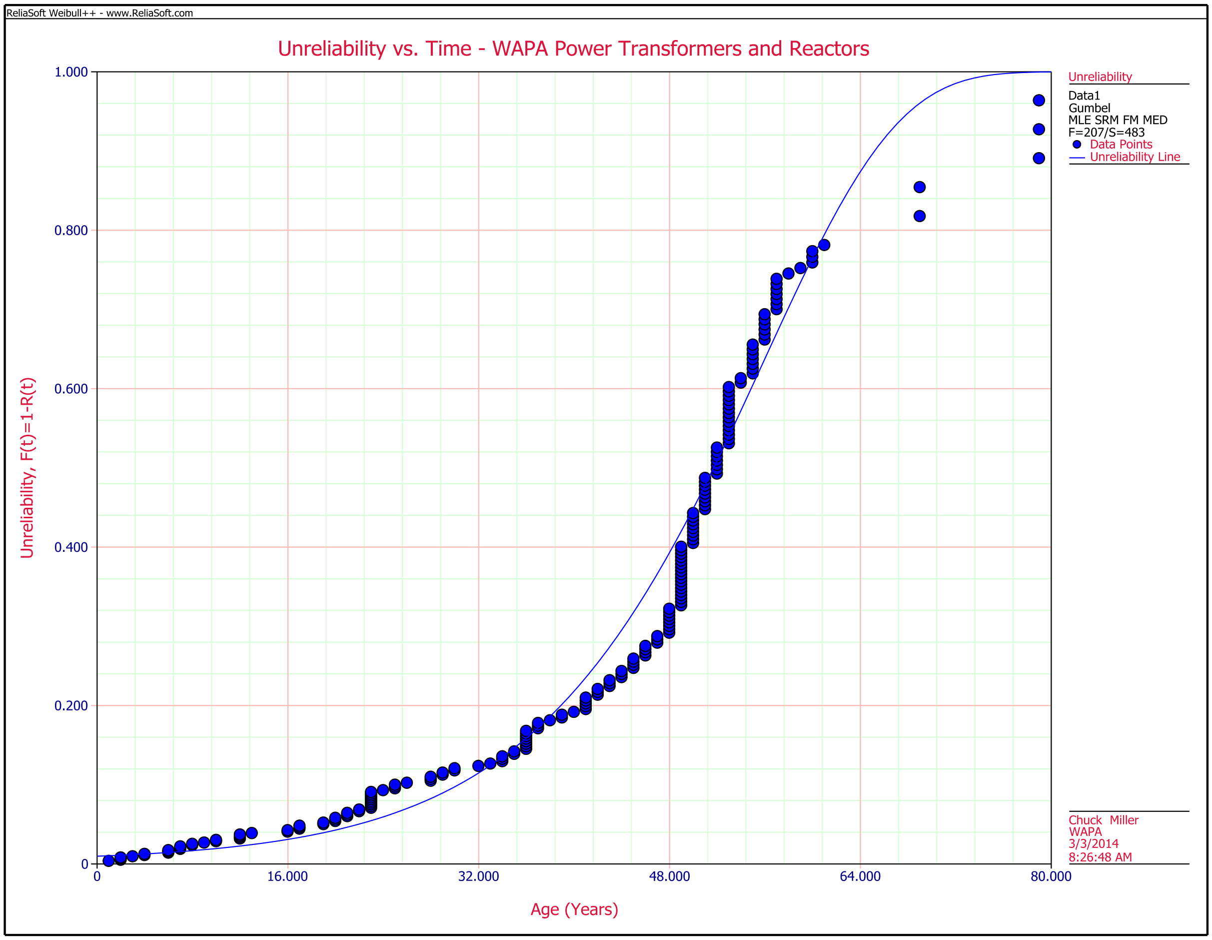
F(t) is the Unreliability, or the probability that an asset will be removed from service prior to age t.

t = age of the asset

η = characteristic life

β = shape parameter (or slope)

For transformers and oil-filled reactors, the Gumbel distribution provided the best fit for WAPA's data as shown in the chart below.



The Gumbel distribution equation for Unreliability is described as:

$$F(t) = 1 - e^{-e^{z}}$$

Where:

$$z = \frac{(t - \mu)}{\sigma}$$

And:

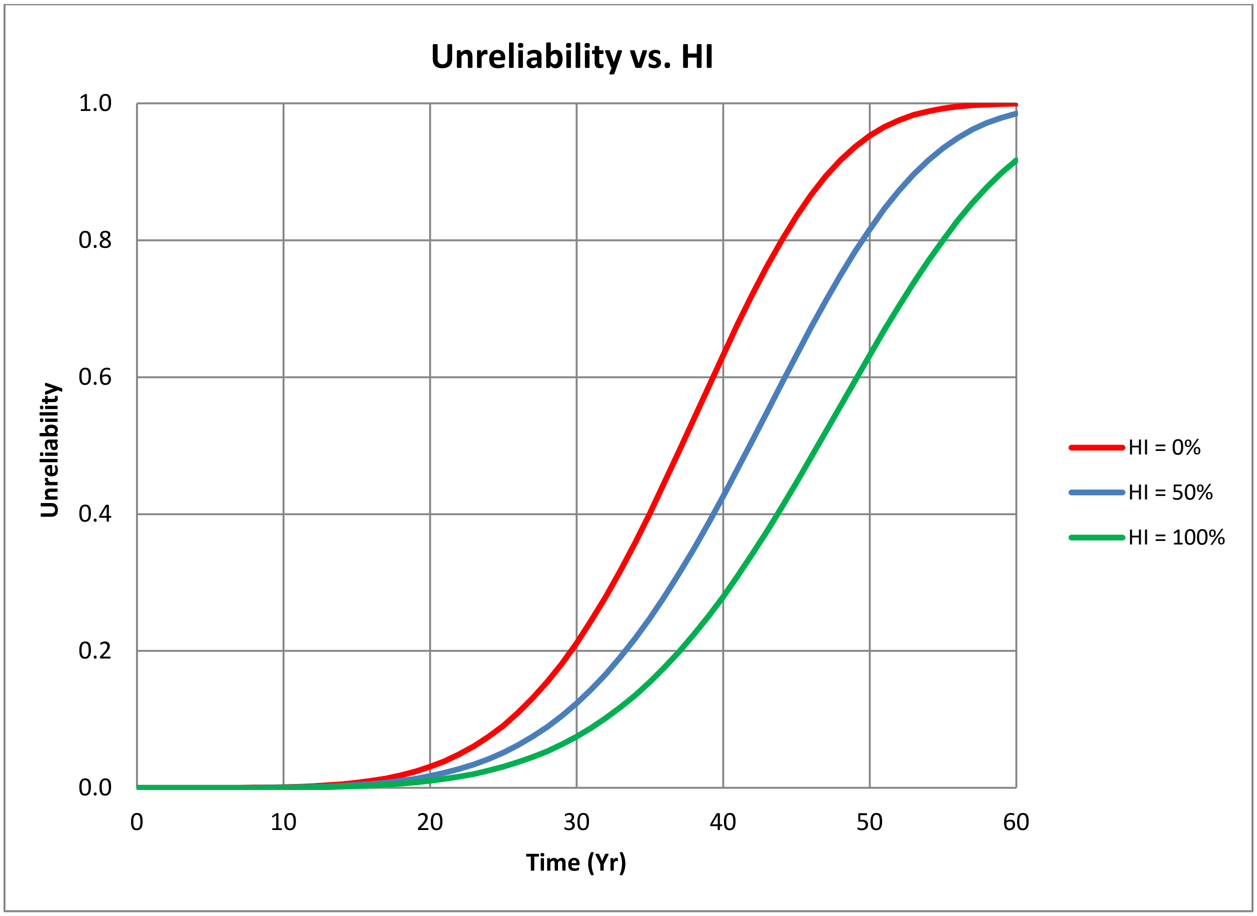
t = age of the Asset

μ = location parameter

σ = scale parameter (slope)

4.2 The Effect of Condition on Probability of Failure

In WAPA's analysis, the asset's condition affects the POF by shifting the Unreliability curve left or right as a function of the HI. The chart below illustrates the effect of HI on a typical Unreliability plot. The POF is unchanged for a HI of 50% and reduced or increased for HI values above or below 50%.



As may be seen on the chart, a breaker with a high Health Index will have a lower probability of failure than a breaker of the same age and but with a low Health Index. A high Health Index has the effect of making a breaker appear younger in terms of its probability of failure.

In order to calculate the effect of Health Index on the probability of failure, we have redefined the Weibull Unreliability equation so that the characteristic life factor, η, is modified by the Health index.

$$F(t) = 1 - e^{-\left(\frac{t}{\eta + b(HI - .5)}\right)^{\beta}}$$

where

t = age of the Asset

η = characteristic life parameter

β = shape parameter (or slope)

b = Health Index shift factor

A similar equation is used for Transformers where

$$F(t) = 1 - e^{-e^{z}}$$

$$z = \frac{t - \mu - b(HI - .5)}{\sigma}$$

and

t = age of the Asset

μ = location parameter

σ = scale parameter (slope)

b= HI shift factor

For both Breakers and transformers, the Health index shift factor, β, determines the amount of influence the Health Index has on the Unreliability. Note that for a HI shift factor of zero, the equation reverts to the original equation presented in 4.1.

For Breakers, the effect of the HI on probability of failure varies with the breaker's age and shift factor. The shift factor determines the amount of influence the HI has on the Unreliability curve. With a shift factor of 20, the effective age of a 25 year old breaker can vary up to plus or minus seven years. For a 50 year old breaker, the effect is plus or minus twelve years. For transformers, a shift factor of 10 shifts the effective age by plus or minus 5 years at all ages. The initial shift factors were chosen arbitrarily and will be evaluated and adjusted as the program matures.

The Gumbel and Weibull unreliability equations described above have been implemented in WAPA's Maximo. The parameters and shift factors have been defined as variables so the equations can be modified to represent different asset classes.

4.3 Conditional Reliability

Life distribution curves produced for assets predict the probability that the asset will fail (or no longer be in service) prior to reaching a certain age. For assets currently in-service, it is much more useful to be able to predict the probability of asset failure in the near future. Assuming that an asset is still in service, the probability that it will fail within a specified future period is called the Conditional Probability of Failure and is defined by the following equation:

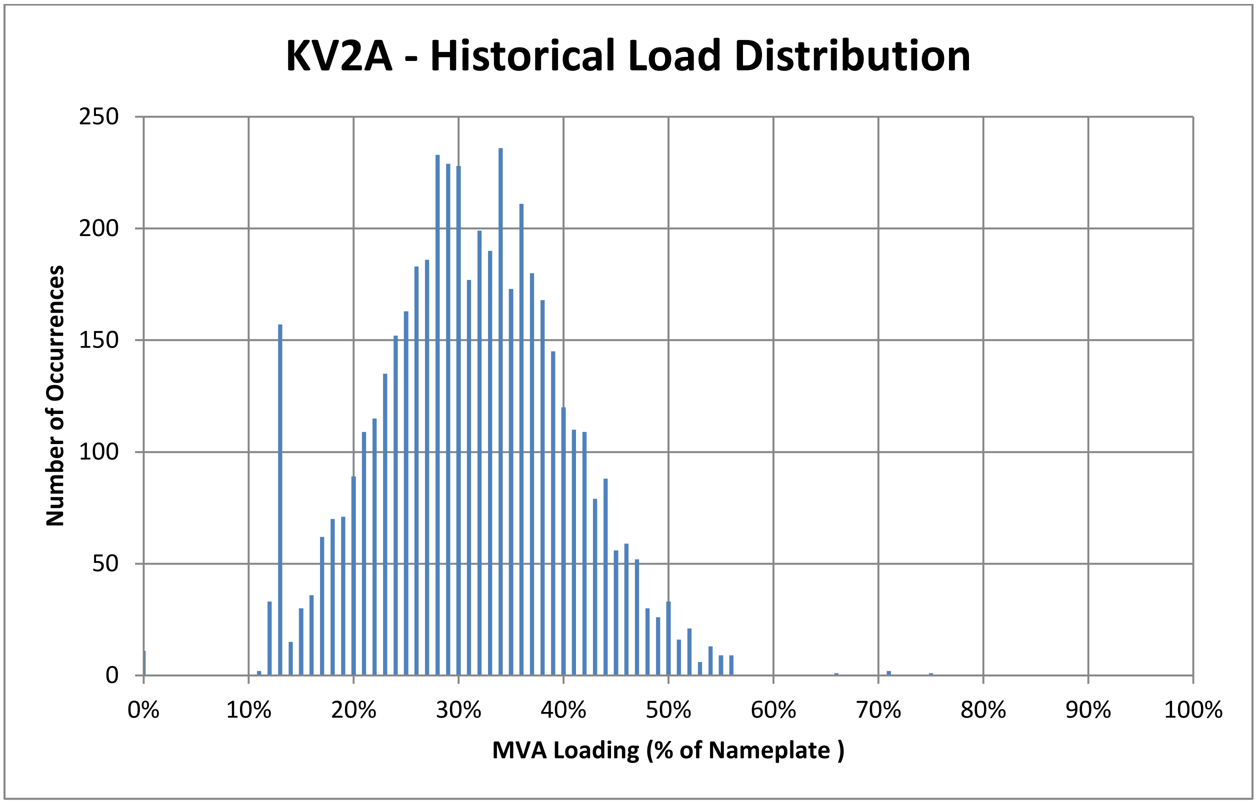
$$F_c(t) = \frac{F(t+1) - F(t)}{1 - F(t)}$$

This is the relationship that is used to calculate the asset's age-related POF for asset management purposes.

4.4 The Effect Operating Stress on Probability of Failure

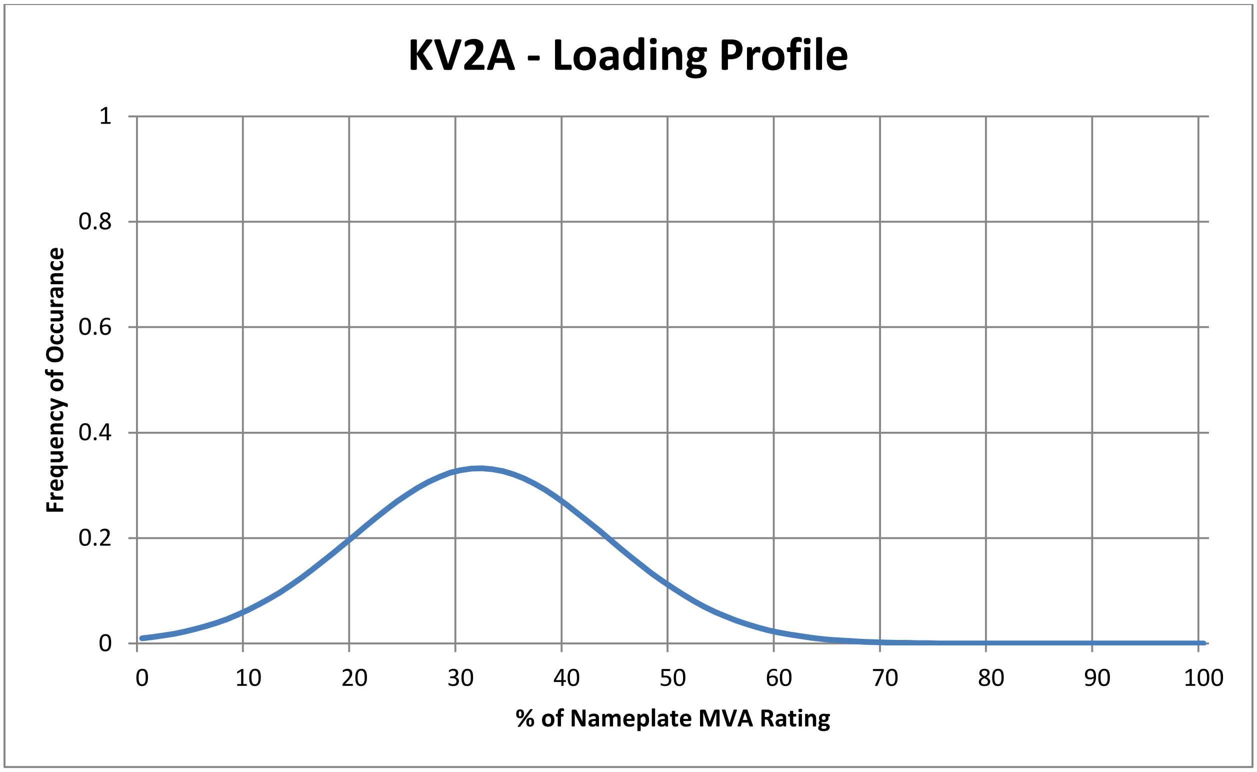
If an asset is in poor condition, it does not necessarily mean that it will fail. Failure occurs when the applied stress exceeds the asset's strength. An asset's strength is proportional to its health. The probability of failure for an asset due to stress is the probability of the applied stress exceeding the asset strength.

One method of determining the stress on a power transformer is to consider its historical loading pattern. A historical load profile may be obtained for a transformer asset such as the one shown below for the KV2A transformer. This profile shows the relative number of times that the transformer has experienced loading at various levels of its nameplate (maximum) MVA rating.



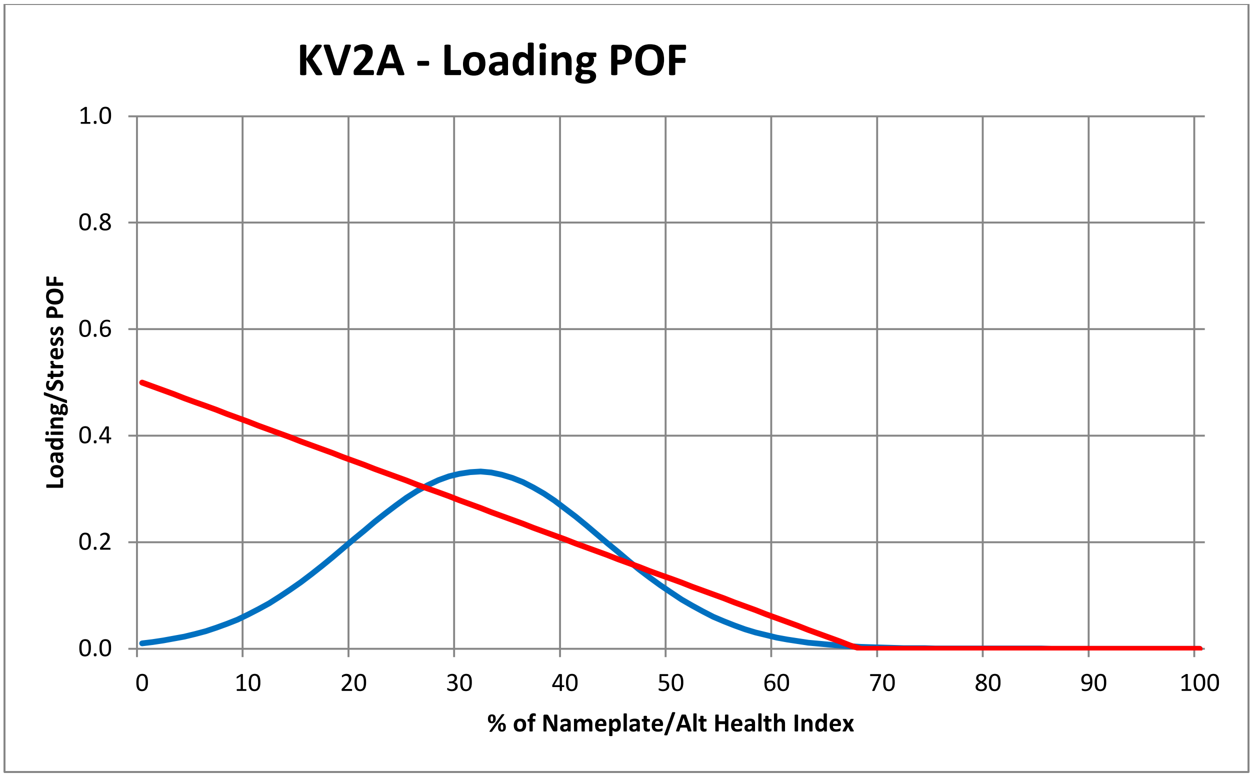
To simplify the mathematics, we assume that all transformers have a normally distributed load distribution (bell curve). With this assumption, we can obtain loading profiles for most transformers from WAPA's regional SCADA historian programs (PI and EDNA) in terms of the mean and standard deviation values of the historical MVA loading. In order to compensate for the normal seasonal variations, this data must be collected in whole year quantities.

As an example, an analysis of the loading data for years 2011, 2012, and 2013 for transformer KV2A reveals a mean loading of 31.8% of the transformer's nameplate MVA rating and a standard deviation of 12% of the transformer's nameplate MVA rating. The curve in the following graph shows the normalized load profile for KV2A.



In order to relate transformer loading to probability of failure, we must make several assumption about how a transformer responds to loading. First we make the assumptions that a healthy transformer can withstand a high level of loading, but an unhealthy transformer can only withstand a limited level of loading. Specifically, we will simplify this by assuming that a transformer's loading-related POF will vary in a linear fashion from zero to .5 based on its HI. The upper limit (POF=0) of this line will be set near the upper end of the load distribution which represents three standard deviations of the loading profile. This means that 99.7% of the historical loading has been equal to or less than this percentage of the nameplate rating. In order to accommodate transformers with unusual loading patterns, we will arbitrarily set the maximum value of this point to 75%.

The following chart illustrates the POF curve for our example transformer KV2A. For this example, the transformer POF varies from zero for a HI of 68 or greater to .5 for a HI of zero. The POF of .5 means that there is a 50% probability that the transformer will fail due to loading in the next 12 months if the HI is zero.



Because any one of the HI subfactors could signal an impending transformer failure, we have chosen to represent transformer health with the Alternative Health Index for the calculation of Loading POF. The Alternative Health Index is described in Section 3.

4.5 Asset POF

Neither the age (modified by condition) nor the loading approach to POF is an ideal model of the failure likelihood of the transformer. The Age POF is obviously heavily weighted toward the asset's age and condition, and the Loading POF is dependent on an accurate HI determination. Both indicators are useful when averaged together. For our transformer POF analysis, we have taken an average of the two POF calculations to give the overall Asset POF.

Since circuit breakers are not significantly affected by loading, we have chosen only the Age POF modified by the Health Index to represent the Asset POF. Also, since reactors and grounding transformers are always fully loaded when in service, we use only the Age POF and HI for these assets.

In all cases, the Asset POF is multiplied by Consequence to determine asset Risk.

The equation for Asset POF is given by:

$$\mathrm{POF(Asset)} = [\mathrm{POF(Age)} + \mathrm{POF\ (Loading)}]\ /\ 2$$

The equation for Risk is given by:

$$\mathrm{Risk} = \mathrm{POF(Asset)\ x\ Consequence}$$