A CASE STUDY OF RELIABILITY CALCULATIONS AND FAILURES ANALYSIS FOR POWER TRANSFORMERS

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Abstract

This paper describes the case study of the reliability of subtransmission transformers (63/20 Kv) installed in MAZANDARAN province, operated in subtransmission system. The information obtained from Mazandaran Regional Electric Company. Failures of transformers in subtransmission systems not only reduce reliability of power system but also have significant effect on power quality since one of the important components of any system quality is reliability of that system.

To enhance utility reliability, failure analysis and rates, failure origin and physical damage causes must be study. The results of study on 60 substation including more than 110 transformers installed in subtransmission system show that the failure mode of transformers can be represented by Weibull distribution. Weibull statistics have been widely used and accepted as a successful mathematical method to predict the remaining life time of any equipment. Analysis show that the protective operation is the highest number of failures but the highest Average Time of Fault *(ATF)* is related to insulation problems. Useful conclusions are presented both for power systems operators and manufactures for improving the reliability of transformers. The methodology used in this study also applied to other equipment in electrical system such as oil switches, capacitor and insulators.

INTRODUCTION

An AC power system is a complex network of many components such as synchronous generators, power transformers, transmission lines, distribution network and loads. The operational availability of power transformer is such a strategic importance for power utility companies. Serious failures in power transformers owing to insulation breakdown cause considerable financial lose due to power outage and cost of replacement or repair [1]. Most power utilities have developed inspection methods and scheme for transformer condition assessment and they traditionally collect data and information on failure cases [2]. These information shows that in smaller transformers aging related failures are dominant. In the medium MVA rating class, tap changer failures constitute the highest failure rate. In the large transformers insulation coordination failures is the most common cause in the early service life of transformer [3].

Appropriate maintenance of newer and refurbishment of the older units can minimize general aging and significantly extend the life time of transformers [4].

Knowledge of the reliability of transformer and other electrical equipment is an important consideration in the design of power systems. To evaluate the reliability of a power system, it is necessary to have accurate reliability data on transformers, together with similar data on other types of electrical components. The condition of components directly affects the condition of system with respect to adequacy and security [5].

Because reliability of power transformers is such an important attribute of a modern power system as well as its impact on system economy, a good deal of effort goes into the specification and testing of reliability.
The purpose of this paper is to describe methods for estimating the main reliability parameters from operation records. The style of information is one of the means of demonstrating economic justification for spares, redundancy, or improved maintenance programs .

TRANSFORMER FAILURE CAUSES

Problems normally are caused either by insulation oil problem, overloading and/or excessive heat and humidity or bushing and insulator problems contamination and deterioration lead its insulating oil decay, and eventually lead to premature transformer failures. From the records it may be stated that some of the causes are due to contaminated oil. This is when they contain moisture or other foreign substances that are not products of oil oxidation. One or a combination of the following can cause elevated temperature: excessive load, excessive ambient temperature, cooling system problems, sludge oil, dark colored exterior paints [7].

Load and ambient temperature are closely related in their effect on transformer operating temperature. For a constant transformer load higher ambient temperature led to higher operating temperatures. A number of cooling system problems can cause high operating temperature: closed radiator valves, dirty or kludged cooling fins, broken or improperly set cooling fans/pumps, and cooling control circuit failure [7].

DATA PREPRATION

Records of failures reports from 2000 to 2004 on the transformers installed in MAZANDARAN province in the north of Iran by Mazandaran Regional Electric Company. For the purpose of this study data where collected including the number of outages caused by transformers failure , the outage duration , number of units , voltage level , failure cause and restoration time if any .

GEOGRAPHICAL LOCATION

The nature of Mazandaran province is under the influence of geographical latitude, Albroz heights, elevation from sea level, distance from the sea, southern wildernesses of Turkmenistan, local and regional wind currents, and diverse vegetation cover.
From geographical point of view Mazandaran province is divided into two parts i.e. coastal plain and Alborz mountainous area. Alborz mountain range has surrounded the coastal strip and coastal plains of the Caspian Sea like a high wall. Due to permanent breeze of the sea and local winds in southern and eastern coasts of the Caspian Sea, there have been formed sandy hills that have caused the appearance of a low natural barrier between the sea and plain.
High and low average temperature in these two weather region are about: 10.9 ºc in winter, 26 ºc in summer and the annually average temperature is 17.7 ºc. Annually average humidity is about 75.5%. Figure 1 illustrates the geographical location of the Mazandaran province.

Figure 1. Geographical location

BASIC CONCEPTS OF RELIABILITY ANALYSIS

In general, a bathtub curve may be used as an adequate representation of a transformer failure mode with varying life time. Accelerated life testing has shown that transformer do have a bathtub curved failure rate. It can be divided in to three failure modes as shown in figure 2.
These modes are:

1. EARLY FAILURES

These occur during the first year of energization and usually are cause by inherent defects due to poor materials, workmanship or processing procedures or manufacturer's quality control beside installation problems.

2. RANDOM FAILURES

These are not associated with early failures. They are produced by chance or operating conditions such as a failure from switching surges, lightning and operator faults.

3. WEAR OUT FAILURES

This type is the results of material wear out. Normally, the wear out mode becomes predominant only after 20 years of operation. This normal wear out period is followed by an increasing failure rate.

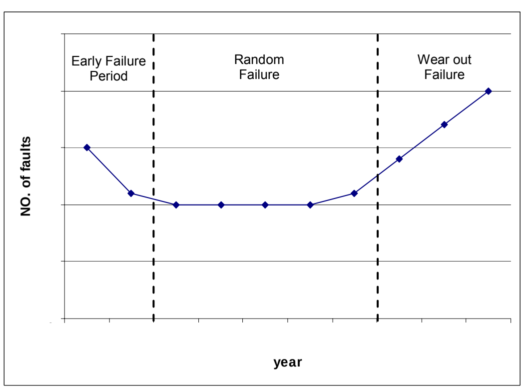

Figure 2. Component failure rate as a function of operating time, bathtub curve,

Different mathematical models can be used to simulate different failure modes. Obviously we are most interested in the random failure mode, since it is not only related to manufacturing quality control but also it is possibly related to the operating conditions of the units. Therefore, calculation and analysis are concentrated in the random failure mode which period is from 1 to 6 year of operation. One important methodology is to find a probability distribution function that can represent the operating time *t* in the random failure period.

Table 1.The number and relative cumulative frequency of failures

t	m_i	N	F\`
1<t≤2	67	67	0.162621359
2<t≤3	80	147	0.356796117
3<t≤4	101	248	0.601941748
4<t≤5	84	332	0.805825243
5<t≤6	80	412	1

Table 1 summarize the operating time for the failed transformers (t) , the number of failures (m_i) , the cumulative number (N) and the relative cumulative frequency $(F`(t_i))$.
The histogram of this data is shown in figure 3.

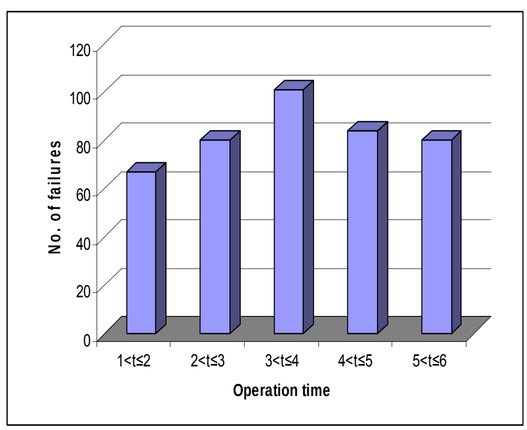

Figure 3. Number of failures due to operation time

RELIABILITY ANALYSIS

In the first step of reliability analyze we introduce the Weibull probability distribution and then we use current data to obtain the specific probability distribution. Weibull probability distribution is shown as equation [1]:

$$F`(t) = 1 - \exp(-\frac{t^m}{t_0}) \qquad [1]$$

In which m and t_0 must be determined. For achieving to a linear relation, (Ln) function must be use twice as below:

$$\ln\ln(\frac{1}{1-F`(t)}) = m\ln t - \ln t_0 \qquad [2]$$

Or :

Y=mX-A [3]

Where:

$$Y = \ln\ln(\frac{1}{1-F`(t)})$$

X=Ln t

A=Ln t_0

Table 2. Show calculated *X* and *Y* for failures data.

t	**m**i	N	F`	X	Y
1<t≤2	67	67	0.1626	0.6931	1.7289
2<t≤3	80	147	0.3568	1.0986	0.8180
3<t≤4	101	248	0.6019	1.3863	0.0821
4<t≤5	84	332	0.8058	1.6094	0.4941
5<t≤6	80	412	1.0000	1.7918	1.5272

The operating time *t* and its corresponding relative commutative $F`(t_i)$ are plotted on a Weibull probability paper as shown in figure 4.

From figure 4 the distribution parameters (*m* and t_0) of Weibull distribution function can be estimated as follows:

m = 2.3076

And

$t_0 = \exp(3.25) = 25.79$

The theoretical probability function of operating time *t* has the form:

$F(t) = 1 - \exp(-t^{2.3076}/25.79)$ [4]

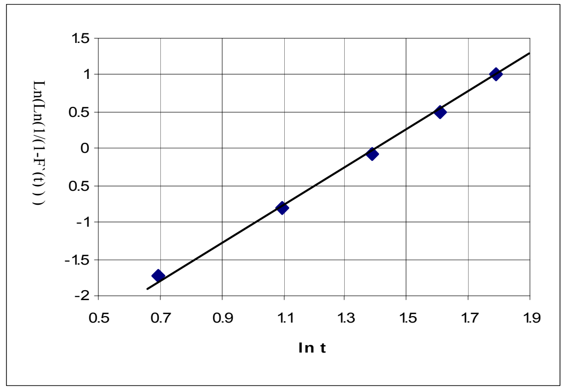

Figure 4 . The relative commutative function plotted in Weibull distribution paper

Theoretical distribution curve *F(t)* of operating time *t* of failed transformers shown in figure 5.

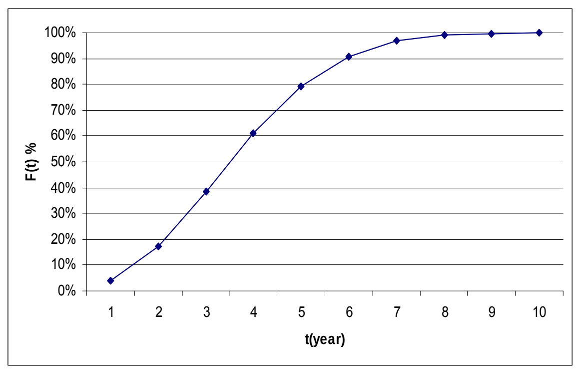

Figure 5. Theoretical distribution curve of operating time of failed transformers

To determine the accuracy of this theoretical function, the new corresponding values for previous data must be recalculate and compare with basic data.

Table 3. Show *F`(t)* and *F(t)* and their deference (D_n) .

The maximum difference between *F(t)* and *F`(t)* is the measure of how good the fit is let the maximum difference be denoted by :

$D_n = \max | F(t) - F`(t) |$ [5]

Therefore:

D_n=0.063

Table 3. F(t) and F`(t) and their difference

t	mi	N	F`	F	D_n
1<t≤2	67	67	0.1626	0.1794	0.0167
2<t≤3	80	147	0.3568	0.4011	0.0443
3<t≤4	101	248	0.6019	0.6350	0.0331
4<t≤5	84	332	0.8058	0.8178	0.0120
5<t≤6	80	412	1.0000	0.9267	0.0633

This deference, which is a random variable which in turn varies with the sample selected, is then compared with the critical value D_n^α , which is defined as:

$$P(D_n < D_n^\alpha) = 1 - \alpha \qquad [6]$$

Critical values D_n^α at various significant levels are tabulated in Probability Tables for various values of *n*.

If the observed $(D_n < D_n^\alpha)$ the proposed distribution is acceptable at the selected significance level *α*.

For *α=0.05* and *n>50* from probability tables we have :

$$D_n^\alpha = \frac{1.36}{\sqrt{n}} \qquad [7]$$

In this case *n=412* so:

$$D_n^\alpha = 0.067 \text{ and } (D_n < D_n^\alpha)$$

Therefore the Weibull distribution is verified.
The results show that the studied power transformers are in conformity with the Weibull distribution for the mathematical failure model.

RELIABILITY LEVEL AND FAILURE RATE

The operating time test known as "definite time and tail cut test" was used to calculate the Mean Time To Failure *(MTTF)* and the Failure Rate *(F_r)*.
The failure rate function % has the form:

$$H(t) = (\frac{m}{t_0})t^{m-1} \qquad [8]$$

It can be obtain from the distribution parameters *m*, t_0 of *F(t)* . in this case :

$$H(t) = (0.0894)t^{1.3076}$$

The *MTTF* is *M* equal to exception of operation time and has the form:

$$M = (t_0)^{1/m}\Gamma(1 + 1/m) \qquad [9]$$

Where :

$$\Gamma(n) = \int_0^\infty t^{n-1}e^{-t}dt$$

MTTF is calculated and shown as below :

MTTF=8.36

For comparison and analysis, two different approaches for calculating the average failure rate $F_{r,\,av}$. The first approach uses the average value given as:

$$F_{r,av} = \frac{1}{T}\int_0^T H(t)dt \qquad [10]$$

The results of this approach are tabulated in table 4.

Table 4. *H(t)* and $F_{r,av}$ of transformers for 5 years

H(t) percenr per year					$F_{r,av}$ T=5
t=1	t=2	t=3	t=4	t=5	
0.089	0.221	0.376	0.547	0.733	0.317

The second approach assuming the distribution function is an exponential distribution then the failure rate F_r is constant and the following formula can be used for calculating F_r :

$$F_r = M\sum_{i=1}^{M}\frac{t_i}{M\sum_{i=1}^{M}t_i + (n-M)T} \qquad [11]$$

Where *T* is the test period (5 year) , t_i is the operating time of failed transformers and *n-M* is the total number of good transformers.

Presented formulas in this part are useful for the comparison of transformers in different areas or different manufactures.

FAILURES ANALYSIS

When a failure occurs it is necessary to investigate the causes to improve production technology and maintenance programs. Some of the most important causes of failures in power transformers are cited in the first of this stuady. In this part of study we divide the failures causes into five groups:

1) Periodical test
2) Services
3) Protective operation
4) Insulation problems
5) Others (bushing faults, development, lightning, etc.)

The purpose of this classification is to identify faults that are most likely to occur in transformers.
Table 5. Show the distribution of each failure mode.

Table 5. Classification of failure origins
TTF = Total Time of Fault
ATF = Average Time of Fault (TTF/NO.)

Description	Failures		Duration	
	No.	%	TTF	ATF
Periodical Test	48	12%	80:39:00	1:40:49
Services	56	14%	88:16:00	1:34:34
Protective Operation	206	50%	264:22:00	1:17:00
Insulation Problems	16	4%	107:40:00	6:43:45
Others	86	21%	113:23:00	1:19:06
Total	412	100%	654:20:00	-

The details of the failures and corresponding percentage shown in figure 6.

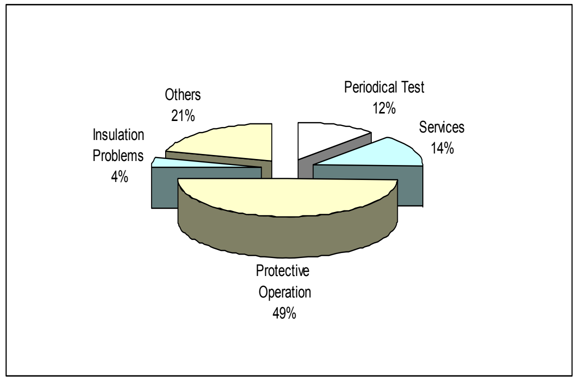

Figure 6. The percentage of any type of failures

The table results show that Protective operation is the highest failure mode, but Average Time of these Faults (ATF) is the lowest, because the causes are usually transient.
In other hand insulation problems are not too much but they have the highest average time of faults.
The 5th group is consists development interruption, bushing faults, tap changer faults, operator faults, lightning, unknown operation errors and etc.
The most faults of this group is related to Tap Changer failures. The main causes of the Tap changers failures start from sparking and erosion of the Tap Changer contacts. Moving parts malfunctioning can also lead to a failure. Eroded contacts produce sparking and sticking. In off-load Tap Changers long period without operation, leads to a corrosion and sludge build up which causes jamming of the moving parts and consequently, a failure of the Tap Changer. Therefore maintenance and periodical test and services can be reducing this type of failures.

CONCLUSION

1.The failure mode of subtransmission transformer can be represented by Weibull distribution. For most transformers the empirical cumulative frequency *F`(t)* versus *t* on the Weibull probability paper exhibits a remarkable linearity .

2. The MTTF for all subtransmission transformers installed in 2000-2004 in Mazandaran province is 8.36 years. And the average failure rate ($F_{r, av}$) is 0.317/year.

3. The classified causes of subtransmission transformer failures are: Periodical test, Services,

Protective operation, Insulation problems, others (bushing, development, etc.)

4. Protective operations have the highest number of faults and insulation problems have longest interrupts duration.

5. Appropriate maintenance of newer and refurbishment of the older units can minimize general aging and significantly extended the life of transformers.

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