Failures of transformers in sub-transmission systems not only reduce reliability of power system but also have significant effects 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 its rates, failure origin and physical damage causes must be studied. This paper describes a case study of the reliability of sub-transmission transformers (63/20 KV) installed in Mazandaran province, operated in sub-transmission system. The information obtained from Meandering Regional Electric Company. The results of study and analysis on 60 substation including more than 110 transformers installed in sub-transmission system show that the failure modes 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. Useful conclusions are presented both for power systems operators and manufactures for improving the reliability of transformers.

Keywords: Failure, Transformer, Reliability.

1. 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. Most power utilities have developed inspection methods and scheme for transformer condition assessment and they traditionally collect data and information on failure cases [1]. This information shows that in smaller transformers aging related failures are dominant. In the medium power rating class, tap changer failures constitute the highest failure rate. Also In the large transformers insulation coordination failures are the most common cause in the early service life of transformer [2].

Appropriate maintenance of newer and refurbishment of the older units can minimize general aging and significantly extend the life time of transformers [3]. 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.

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 [4, 5 & 6].

The purpose of this paper is outage analysis and description of methods for estimating the main reliability parameters of power transformers by using of operational records. The style of information is one of the means of demonstrating economic justification for spares, redundancy, or improved maintenance programs.

2. TRANSFORMER FAILURE CAUSES

Transformer problems normally are caused by insulation oil degradation, overload, thermal stress, humidity in oil/paper and bushing defective and etc. 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. 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 temperature. A number of cooling system problems can cause high operating temperature: closed radiator valves, dirty cooling fins, broken or improperly set cooling fans/pumps, and cooling control circuit failure [3].

3. DATA PREPARATION

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 and anything else.
4. GEOGRAPHICAL LOCATION

The nature of Mazandaran province is under the influence of geographical latitude, Alborz heights, elevation from sea level, and 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 °C in winter, 26 °C in summer and the annually average temperature is 17.7 °C. Annually average humidity is about 75.5%. Figure 1 illustrates the geographical location of the Mazandaran province.

5. 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 study. Furthermore, transformers must be deenergized for some periodical tests and services. Therefore an outage will occur and it will decrease the component and ultimately system reliability. So we consider that causes as outages/failures.
In this part, we divide the outage 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 outages/faults that are most likely to occur in transformers. Table 1 shows the distribution of each failure mode. Also the details of the failures and corresponding percentages are shown in figure 2.

Table 1. Classification of outage/failure origins: TTF = Total Time of Fault (Outage), ATF = Average Time of Fault (Outage).

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

Figure 2: The percentage of any type of failures.

Results of table 1 show that protective operation is the highest failure mode, but average times of the fault is the lowest, due to their causes are temporary and are removed after a little time. In other hand insulation problems are not too much but they have the highest average time of faults. The 5th group is consists of development interruption, bushing faults, tap changer faults, operator failures, lightning, unknown operation errors and etc. The most
number of faults of this group are 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 reduced this type of failures.

![Bathtub Curve](image)

**Figure 3: Component failure rate as a function of operating time, bathtub curve.**

### 6. 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 have a bathtub curved failure rate. It can be divided into three failure modes as shown in figure 3. [7, 8]

These modes are:

**Early Failures**: These occur during the first year of energization and usually are caused by inherent defects due to poor materials, workmanship or processing procedures or manufacturer’s quality control beside installation problems.

**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. This part of curve called useful life time period and failure rate is nearly constant.

**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.
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 possible 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 2 summarizes the operating time for the failed transformers \( (t) \), the number of failures cause to unit outage \( (m_i) \), the cumulative number \( (N) \) and the relative cumulative frequency \( (F'(t_i)) \). The histogram of this data is shown in figure 4.

Table 2. The number and relative cumulative frequency of failures.

<table>
<thead>
<tr>
<th>( t )</th>
<th>( m_i )</th>
<th>( N )</th>
<th>( F'(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;( t \leq 2 )</td>
<td>67</td>
<td>67</td>
<td>0.162621359</td>
</tr>
<tr>
<td>2&lt;( t \leq 3 )</td>
<td>80</td>
<td>147</td>
<td>0.356796117</td>
</tr>
<tr>
<td>3&lt;( t \leq 4 )</td>
<td>101</td>
<td>248</td>
<td>0.601941748</td>
</tr>
<tr>
<td>4&lt;( t \leq 5 )</td>
<td>84</td>
<td>332</td>
<td>0.805825243</td>
</tr>
<tr>
<td>5&lt;( t \leq 6 )</td>
<td>80</td>
<td>412</td>
<td>1.000000000</td>
</tr>
</tbody>
</table>

7. RELIABILITY ANALYSIS

In the first step of reliability analysis, we introduce the Weibull probability distribution [9].

![Figure 4: Number of failures vs. operation time.](image)
Therefore we use current data to obtain the specific probability distribution. Weibull probability distribution is shown as equation (1):

\[ F'(t) = 1 - \exp\left(-\frac{t^m}{t_0}\right) \quad (1) \]

In which \( m \) and \( t_0 \) must be determined where \( t_0 \) is the scale and \( m \) is the shape parameter. For achieving to a linear relation, (ln) function must be used twice as below:

\[ \ln \ln \left(\frac{1}{1 - F'(t)}\right) = m \ln t - \ln t_0 \quad (2) \]

or:

\[ Y = mX - A \quad (3) \]

Where:

\[ Y = \ln \ln \left(\frac{1}{1 - F'(t)}\right), \quad X = \ln t \quad \text{and} \quad A = \ln t_0. \]

Table 3. Shows calculated \( X \) and \( Y \) for failures data.

<table>
<thead>
<tr>
<th>( t )</th>
<th>( m_i )</th>
<th>( N )</th>
<th>( F' )</th>
<th>( X )</th>
<th>( Y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (&lt;)t(\leq)2</td>
<td>67</td>
<td>67</td>
<td>0.1626</td>
<td>0.6931</td>
<td>-1.7289</td>
</tr>
<tr>
<td>2 (&lt;)t(\leq)3</td>
<td>80</td>
<td>147</td>
<td>0.3568</td>
<td>1.0986</td>
<td>-0.8180</td>
</tr>
<tr>
<td>3 (&lt;)t(\leq)4</td>
<td>101</td>
<td>248</td>
<td>0.6019</td>
<td>1.3863</td>
<td>-0.0821</td>
</tr>
<tr>
<td>4 (&lt;)t(\leq)5</td>
<td>84</td>
<td>332</td>
<td>0.8058</td>
<td>1.6094</td>
<td>0.4941</td>
</tr>
<tr>
<td>5 (&lt;)t(\leq)6</td>
<td>80</td>
<td>412</td>
<td>1.0000</td>
<td>1.7918</td>
<td>1.5272</td>
</tr>
</tbody>
</table>

The operating time \( t \) and its corresponding relative commutative \( F'(t_i) \) are plotted on a Weibull probability paper as shown in figure 5. From figure 5 the distribution parameters \( (m \quad \text{and} \quad t_0) \) of Weibull distribution function can be estimated as follow: \( m = 2.8076 \) and \( t_0 = \exp(4.01) = 55.14 \).

The theoretical probability function of operating time \( t \) has the form:

\[ F(t) = 1 - \exp\left(-\frac{t^{2.8076}}{55.14}\right) \quad (4) \]
Theoretical distribution curve \( F(t) \) of failed transformers is shown in figure 6 that \( t \) is operating time. To determine the accuracy of this theoretical function, the new corresponding values for previous data must be recalculate and compare with basic data. Table 4. Shows \( F'(t) \), \( F(t) \) and their absolute deference \( D_n \).

\[ D_n = \max | F(t) - F'(t) | \]  

Therefore: \( D_n = 0.0647 \).

This deference, which is a random variable which in turn varies with the sample selected, is then compared with the critical value \( D_n^\alpha \) that called Kolmogorov-Smirnov criteria, which is defined as:
\[ P(D_n < D_n^\alpha) = 1 - \alpha \]  

Critical values \( D_n^\alpha \) 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 \( \alpha \).

Table 4. \( F(t) \) and \( F'(t) \) and their differences

<table>
<thead>
<tr>
<th>( t )</th>
<th>( mi )</th>
<th>( N )</th>
<th>( F' )</th>
<th>( F )</th>
<th>( D_n )</th>
</tr>
</thead>
</table>
| 1
\( < t \leq 2 \) | 67   | 67   | 0.1626 | 0.1186 | 0.0439 |
| 2
\( < t \leq 3 \) | 80   | 147  | 0.3568 | 0.3249 | 0.0318 |
| 3
\( < t \leq 4 \) | 101  | 248  | 0.6019 | 0.5850 | 0.0168 |
| 4
\( < t \leq 5 \) | 84   | 332  | 0.8058 | 0.8065 | 0.0007 |
| 5
\( < t \leq 6 \) | 80   | 412  | 1.0000 | 0.9352 | 0.0647 |

For \( \alpha = 0.05 \) and \( n > 50 \) from probability tables we have:

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

In this case \( n = 412 \) so: \( D_n^\alpha = 0.067 \) 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.

8. 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 \% or hazardous function has the form:

\[ H(t) = \left( \frac{m}{t_0} \right) t^{m-1} \]  

It can be obtained from the distribution parameters \( m, t_0 \) of \( F(t) \). In this case:

\[ H(t) = (0.0509)t^{1.8076} \]

The MTTF or \( M \) is equal to exception of operation time and has the form:
\[ M = \left(t_0\right)^{1/m} \Gamma(1 + 1/m) \]  

(9)

Where:

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

MTTF is calculated and shown as: MTTF=3.71 (year)

For comparison and analysis, other approach is used for calculating the average MTTF with calculation of Failure rate \((F_{r,av})\). In this approach the average value given as below was used:

\[ F_{r,av} = \frac{1}{T} \int_0^T H(t)dt = T^{m-1}/t_0 \]  

(10)

The results of this approach are tabulated in table 5.

<table>
<thead>
<tr>
<th>(H(t)) percentage per year</th>
<th>(F_{r,av})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t=1)</td>
<td>(0.050)</td>
</tr>
<tr>
<td>(t=2)</td>
<td>(0.178)</td>
</tr>
<tr>
<td>(t=3)</td>
<td>(0.370)</td>
</tr>
<tr>
<td>(t=4)</td>
<td>(0.620)</td>
</tr>
<tr>
<td>(t=5)</td>
<td>(0.932)</td>
</tr>
<tr>
<td>(T=5)</td>
<td>(0.332)</td>
</tr>
</tbody>
</table>

By considering of the distribution function is an exponential distribution, the failure rate \(F_r\) will be constant and the following formula can be used for calculating \(MTTF\):

\[ MTTF = 1/F_{r,av} \]  

(11)

Where \(F_{r,av}\) is shown in Table 5 and therefore: \(MTTF=3.01\) (years).

There is a little difference between two value of \(MTTF\) from above approaches and its reason is the assuming of the constant failure rate in second approach.

9. CONCLUSION

In this paper, causes of sub-transmission transformer outages have been classified: Periodical test, Services, Protective operation, Insulation problems and others (bushing, development, etc.) Also the number and duration of transformers outage have been investigated and analyzed, according to following:
1. Protective operations have the highest number of faults and insulation problems have longest interrupts duration.

2. The failure mode of sub-transmission transformer can be represented by Weibull distribution. For most transformers the empirical cumulative frequency $F^r(t)$ versus $t$ on the Weibull probability paper exhibits a remarkable linearity.

3. The $MTTF$ for sub-transmission transformers installed during 2000-2004 in Mazandaran province is 3.71 years and the average failure rate ($F_{r,av}$) is 0.332%/year.

4. 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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