Refurbishment of Existing Overhead Transmission Lines

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1. Summary

The basis of the refurbishment activities is to reduce the probability of failure of existing transmission lines.

The paper will detail the opportunities for utilities to restore the design working life of existing transmission lines by refurbishment activities. Definitions associated with uprating, upgrading, life extension, refurbishment and increased capacity and the associated probability of failure and consequences of failure are discussed. A brief overview of conductors & overhead earthwires, joints, supports, foundations, earthing, insulators and fitting degradation mechanisms, diagnostic techniques and refurbishment activities will be provided.

The refurbishment activities are then described in the context of ranking transmission lines on the basis of the probability of failure and the consequence of failure. A simple economic model is discussed to define the optimal point to carry out transmission line refurbishment activities. The determination of the optimal point of transmission line refurbishment requires an understanding of the marginal costs and the long run average costs of the refurbishment of the transmission line.

2. Keywords

transmission lines, overhead lines, maintenance, asset management, refurbishment, technical assessment, risk assessment, economic assessment.

3. Introduction

Within the next decade most developed countries with major electrical infrastructure are confronted with three coinciding critical issues. Firstly, most of the electrical infrastructure was constructed after 1945, which result in the age of the assets being over 50 years. Secondly, the design life of much of the electrical infrastructure is in many cases about 50 years and has matured beyond the engineering serviceability and or economic life and requires some form of life extension. Thirdly, the need to increase capacity of the existing electrical infrastructure places extraordinary demands on utilities to establish strategies to uprate existing electrical infrastructure.

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Transmission lines fall into part of the critical elements of electrical infrastructure that require uprating, upgrading, life extension, refurbishment and or extended utilisation. An additional influencing consideration is that transmission line uprating, upgrading, life extension and or refurbishment will invariably require extended outages that are, in general difficult to secure in competitive and deregulated electricity markets.

This paper will discuss transmission line refurbishment and present example case studies. Refurbishment of conductors, earthwire, joints, supports foundations, earthing, insulators, and fittings will be discussed. An elementary risk assessment model based on the age, operating experience, operating environment and system configuration will be presented. The paper will also provide strategies to determine optimum economic and serviceability triggers for transmission lines refurbishment.

The paper will be an extension of the work carried out by Study Committee B2 Overhead Lines, Working Group 13 who published in December 2000, Brochure 175 on the “Management of Existing Overhead Transmission Lines.”

4. Definitions

The terms uprating, upgrading, life extension and refurbishment are defined [1] as follows and is based on the risk of failure which is defined [1] as,

\[
\text{risk of failure} = \text{probability of failure} \times \text{consequences of failure} \quad (1)
\]

<table>
<thead>
<tr>
<th>term</th>
<th>description</th>
<th>failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>uprating</td>
<td>increasing the electrical characteristics of a line due to, for example, a requirement for higher electrical capacity or larger electrical clearances.</td>
<td>no change</td>
</tr>
<tr>
<td>upgrading</td>
<td>increasing the original mechanical strength of an item due to, for example, a requirement for: higher meteorological actions.</td>
<td>decrease</td>
</tr>
<tr>
<td>refurbishment</td>
<td>extensive renovation or repair of an item to restore their intended design working life.</td>
<td>decrease</td>
</tr>
<tr>
<td>life extension</td>
<td>extensive renovation or repair of an item without restoring their original design working life.</td>
<td>decrease</td>
</tr>
</tbody>
</table>

Table 1 Definitions [1]

In addition, it is considered necessary to define the additional term of increasing capacity, which is a combination of refurbishment and or upgrading and or uprating of an overhead transmission line. Increasing capacity will in general, decrease the risk failure.

5. Technical Assessment

Degradation mechanisms, diagnostic techniques and refurbishment activities have been the subject of considerable research activities and publications [1,2] and a brief overview of conductors & overhead earthwires, joints, supports, foundations, earthing, insulators and fittings will be provided. The overview will also be presented in context of risk of failure.

5.1 Conductors and Overhead Earthwires [3]

Conductors are either homogeneous or non homogeneous. Homogeneous conductors suffer fatigue, corrosion and annealing degradation. In addition, non homogeneous conductors such as ACSR also
suffer deterioration of steel coating, sequentially followed by aluminium wire corrosion and then steel core corrosion.

The risks arising from the degradation mechanisms are localised elevated temperature rise, fatigue induced wire failure and corrosion induced broken wires. In all cases, wire failure will result in accelerated localised annealing and redistribution of mechanical loads which both will accelerate further wire failures. Wire unravelling resulting in compromised insulation and or whole of conductor separation are secondary symptoms of conductor degradation.

Diagnostic techniques are visual inspection, remote robot broken wire & coating deterioration detectors and intrusive testing of conductor samples removed from service. Refurbishment activities are generally limited to the costly replacement of conductor.

5.2 Joints

Joints are normally compression or helical and suffer corrosion, annealing and in some cases fatigue. The risk arising from the degradation is elevated joint electrical resistance and hence elevated temperature rise that will result in accelerated localised annealing and ultimate failure consisting of whole of conductor separation.

Corrosion and or annealing diagnostic techniques are joint electrical resistance measurement & statistical assessment of the sample resistance relative to a population of resistances of similar joints [2] and thermography at elevated conductor temperatures & assessment relative to similar joints. Fatigue of joints arises from deformations caused by the application of compression dies, which result in notches at successive compression interfaces.

The risk arising from joint annealing and fatigue is whole of joint separation. Refurbishment activities are generally limited to the costly replacement of conductor joints.

5.3 Supports

Supports consist of structures and in some cases inclusive of stays or guy wires. Structures may be wood pole, steel pole, concrete pole, composite pole or lattice steel towers. In general, the degradation mechanisms are wood fibre deterioration and or wood rot, concrete spalling and or cracking, corrosion, structural member permanent deformation and in the case of stay wires, corrosion and loss of joint strength.

The risks arising from the degradation mechanisms range from structure deformation to complete structural failure resulting in loss of line availability. Diagnostic techniques range from visual inspection, wood pole intrusive testing to coating thickness assessment. Refurbishment activities include supporting wood pole foundations, painting of steel structures, application of epoxy to damaged concrete structures, structural member replacement and complete structure replacement.

5.4 Foundations

Foundations range from a simple backfilled pole holes to complicated floating foundations and include grillage, micro pile, pile and pad & chimney. When correctly designed, excavated and constructed, foundations do not normally deteriorate and no significant loss of strength has been assessed arising from inspections and observations of foundation integrity. [1]

5.5 Earthing

Earthing generally consists of buried electrodes, which suffer environmental, and or electrolysis corrosion. The risk arising from corrosion is increased earth resistance, which will result in poor lightning performance, elevated structure step touch potential and extended fault protection clearing
times. Diagnostic technique is earth resistance measurement and refurbishment is normally limited to the replacement of buried electrodes.

5.6 **Insulators**

A large range of insulators of differing materials and differing designs have been employed on transmission lines throughout the world. Materials include glass, porcelain and in more recent times, composite of fibre glass rod with either EPDM or silicon covers and sheds. The designs range from cap & pin, long rod and line post. Insulators suffer varying electrical and mechanical degradation mechanisms and the most common are electrical puncture and radial cracking of porcelain insulators, glass erosion and steel pin erosion.

The risks arising from the degradation mechanisms are compromised line electrical performance and conductor insulator separation resulting in a dropped conductor. The latter is considered very serious as a dropped conductor may result in compromised public safety and or elevated mechanical loads at structures and the consequence risk of structure permanent deformation and or structure failure.

Some of the diagnostic techniques are visual inspection, voltage gradient measurement and testing of samples removed from service. Refurbishment activities are generally limited to the replacement of the insulators.

5.7 **Fittings**

Fittings consist of conductor suspension and tension fittings, structure attachment fittings, vibration dampers, conductor spacers & spacer dampers. Fitting degradation is normally limited to fatigue and or corrosion.

The risks arising from the degradation mechanisms are fatigue induced fitting failure, conductor wire damage, and fitting separation. Diagnostic techniques are normally limited to visual inspection and destructive testing of samples removed from service. Refurbishment activities are generally limited to the replacement of the fittings.

6 **Transmission Line Risk Ranking**

As mentioned the risk of failure is a function of the probability of failure and the consequence of failure. Transmission line risk ranking provides a mechanism to minimize the net present value of annual expenditures over an investment period for identified transmission line refurbishment activities.

6.1 **Probability of Failure**

The probability of failure is a function of the capacity of the components & elements to withstand loads; the probability of the loads exceeding the components & elements safety limits and the components & elements residual life.

The design load, \( Q \) is based on the probability design criteria of IEC 60826 [4] and for a particular component or element is described [5] as,

\[
Q = Q_T \cdot \gamma
\]

where

\[
Q_T = \text{limited load associated with return period } T
\]

\[
\gamma = \text{load factor}
\]

The required strength, \( R \) is described as,

\[
R = R_C \cdot \phi
\]
where \( R_C \) = characteristic or guaranteed strength
\( \phi \) = compound strength factor

The basis of the design criteria for components and elements of the transmission line is \( Q < R \) and for the purposes of this paper and elementary probability of failure, \( P_F \) is defined as

\[
P_F = R \cdot Q^{-1} = 1
\]  \hspace{1cm} (4)

Assuming constant load factor \( \gamma \) over time, the design loads \( Q \), remains unchanged, the component or element strength degradation mechanisms are linear time dependent function and the environmental & operation experience for a particular component or element may be described by indices, then the probability of failure indice, \( P_F \) may be defined by,

\[
P_F = 0.01 \cdot n^{-1} \cdot \phi_{1-n} \cdot (A \cdot L^{-1}) \cdot E_n \cdot O_n
\]  \hspace{1cm} (5)

where
\( n \) = number of component or element considered
\( A \) = age of the transmission line in years
\( L \) = design life of component or element in years
\( E_n \) = environmental index
\( O_n \) = operational index

Examples of environmental and operational indices are as follows,

<table>
<thead>
<tr>
<th>index</th>
<th>description</th>
<th>indice</th>
</tr>
</thead>
<tbody>
<tr>
<td>environmental</td>
<td>light pollution</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>medium pollution</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>heavy pollution</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>extra heavy pollution</td>
<td>4</td>
</tr>
<tr>
<td>operational</td>
<td>good performance of component or element</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>average performance of component or element</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>poor performance of component or element</td>
<td>3</td>
</tr>
</tbody>
</table>

**Table 2 Component and Element Environmental & Operational Indices**

### 6.2 Engineering Consequence of Failure

The consequence of a transmission line failure is influenced by the criticality of the line, whether the failure is likely to result in a risk to the public, the failure restoration duration and the likelihood of permanent damage to the transmission line and other transmission elements and these parameters may also be described as indices Therefore an elementary definition of consequence of failure defined as line security, \( S \) and may be given by,

\[
S = C \cdot R \cdot \mathfrak{R} \cdot \Delta
\]  \hspace{1cm} (6)

where
\( C \) = criticality line index
\( R \) = public risk exposure index
\( \mathfrak{R} \) = restoration duration index
\( \Delta \) = permanent damage index

Examples of the transmission line operational indices are as follows,

<table>
<thead>
<tr>
<th>index</th>
<th>Description</th>
<th>indice</th>
</tr>
</thead>
<tbody>
<tr>
<td>criticality line</td>
<td>part of interconnected network</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>radial double circuit line</td>
<td>2</td>
</tr>
</tbody>
</table>
Table 3  Transmission Line Operational Indices

<table>
<thead>
<tr>
<th>index</th>
<th>Description</th>
<th>indice</th>
</tr>
</thead>
<tbody>
<tr>
<td>public risk exposure</td>
<td>areas not frequented by the public</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>areas frequented by the public</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>public gathering areas</td>
<td>3</td>
</tr>
<tr>
<td>restoration duration</td>
<td>less then 1 day</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>more than 1 day and less than 3 days</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>greater than 3 days</td>
<td>3</td>
</tr>
<tr>
<td>permanent damage</td>
<td>Unlikely</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Possible</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>most likely</td>
<td>3</td>
</tr>
</tbody>
</table>

6.2  Engineering Risk of Failure

Risk of failure of a transmission line based on an assessment components & elements and the consequences of a failure and has been previously described as equation (1) or in terms equations (5) and (6) the risk of failure indice, \( F_R \) may be given by,

\[
F_R = P_F \cdot S
\]  

(7)

7  Economic Assessment [6]

For the purposes of the discussion, it is assumed that the time value of money is not a consideration, then the optimum time to refurbish a transmission line is at that point of the long run lowest average cost per unit of production.

The production of a transmission line is defined as the availability and the cumulative production is therefore proportional to the service life. The life costs of a transmission line are capital expenditure, very low relative operating and maintenance costs, no risk costs during the economic life and low...
probability of disposal and hence zero disposal costs. The optimal refurbishment point is the point of
tangency of the long run average costs with the cumulative cost curve as illustrated in Figure 1.

The optimal refurbishment point also represents when marginal cost of continuing to operate the asset
is equal to the long run average cost of refurbishment. Considering a point prior to the optimal
refurbishment, which may represent the first failure and trigger refurbishment then, the cost streams
are illustrated in figure 2. The long run average cost of refurbishment is shifted to the left to the point
where the cost of early refurbishment activities will equal the maximum savings in delaying
refurbishment.

Hence, the key to understanding the economic point of optimal refurbishment of the transmission line
is an understanding of the marginal costs associated with the existing transmission line and the long
run average costs of the refurbishment of the transmission line.

![Figure 2 Initial Component or Element Failure of Transmission Line Cost Streams](image)

A range of transmission line refurbishment options would be considered in the context of the marginal
costs and the long run average costs to minimize the net present value of annual expenditures over the
intended design working life. The intended design working life would be defined by the extend of the
transmission line refurbishment works carried out.

The annual expenditures is defined [1] as

\[
\text{annual expenditures} = \text{planned expenditures} + \text{risk of failure} \quad (8)
\]

where

\[
\text{planned expenditures} = \text{recurrent costs and capital investments} \quad (9)
\]

The risk of failure cost would the be loss of revenue, fault and emergency restoration costs, public
damage restoration costs and any likely litigation costs arising from damages.

8 Case Studies

8.1 132 kV Double Circuit Transmission Line

The case study is based on a radial line to a 132/33 kV transmission substation by a 132 kV double
circuit lattice steel transmission line. The average demand at the substation is 120 MVA and the
average cost of loss of supply is $13,000 per hour. The transmission line average design life is 40
years and was constructed in 1956. The age of the transmission line is 47 years. The transmission line traverses heavily polluted areas and in recent times has suffered a number of single circuit outages as a result of classical pin corrosion of cap & pin, ball and socket porcelain insulators. The risk of repetitive outages is high.

Furthermore, the lattice steel towers galvanising has deteriorated and the towers require painting. Conductor residual life assessment of the fully greased 54/7/3.00 mm ACSR has been carried out and no significant degradation has taken place. The earthwire is 7/3.00 SC/GZ and has suffered surface corrosion however has retained over 90% of the CBL.

The probability of failure of the components or elements of the transmission line relative to other transmission lines is determined as follows,

<table>
<thead>
<tr>
<th>Component or Element</th>
<th>Design Life (years)</th>
<th>Degradation Indice</th>
<th>Environmental Indice</th>
<th>Operation Indice</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductors</td>
<td>40</td>
<td>1.175</td>
<td>3</td>
<td>1</td>
<td>3.525</td>
</tr>
<tr>
<td>Earthwires</td>
<td>40</td>
<td>1.175</td>
<td>3</td>
<td>2</td>
<td>7.050</td>
</tr>
<tr>
<td>Joints</td>
<td>40</td>
<td>1.175</td>
<td>3</td>
<td>1</td>
<td>3.525</td>
</tr>
<tr>
<td>Supports</td>
<td>60</td>
<td>0.783</td>
<td>3</td>
<td>2</td>
<td>4.700</td>
</tr>
<tr>
<td>Foundations</td>
<td>60</td>
<td>0.783</td>
<td>3</td>
<td>3</td>
<td>7.050</td>
</tr>
<tr>
<td>Earthing</td>
<td>40</td>
<td>1.175</td>
<td>3</td>
<td>3</td>
<td>10.575</td>
</tr>
<tr>
<td>Insulators</td>
<td>40</td>
<td>1.175</td>
<td>3</td>
<td>3</td>
<td>10.575</td>
</tr>
<tr>
<td>Fittings</td>
<td>40</td>
<td>1.175</td>
<td>3</td>
<td>2</td>
<td>7.050</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25.850</td>
</tr>
<tr>
<td>Probability of failure indice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31%</td>
</tr>
</tbody>
</table>

Table 4  132 kV Double Circuit Transmission Line Probability of Failure Case Study

The consequence of transmission line failure is determined as follows,

\[ C = \text{criticality line index} = 2 \]
\[ R = \text{public risk exposure index} = 1 \]
\[ R = \text{restoration duration index} = 3 \]
\[ \Delta = \text{permanent damage index} = 3 \]

hence the consequence of failure ranked relative to other transmission lines as 18. The risk of failure is ranked as \( F_R = P_F \times S = 0.31 \times 18 = 5.58 \).

The restoration of a failed insulator string is $3,000 and the duration is 8 hrs. The consequential cost of the risk is $107,000.

8.2  33 kV Sub Transmission Line Network

The case study is based on 33 kV wood pole transmission line radial lines to a number of small rural 33 kV transmission substations. The average peak demand at a substation is 10 MVA and the average sale price of energy is $0.11 per kW hour. The transmission line average design life is 40 years and most of the lines were constructed in 1950. The age of the transmission line 43 years. The transmission line traverses polluted areas that range from light to heavy and in recent times has suffered a number of outages as a result of fitting corrosion.

Furthermore, the wood poles have deteriorated and require replacement. Conductor residual life assessment of the 19/3.00 mm AAC has been carried out and no significant degradation has taken place.
The probability of failure of the components or elements of the transmission lines are 9, 46 and 64 % for pollution zones light, medium and heavy respectively.

The consequence of transmission line failure is determined as follows,

\[
\begin{align*}
C &= \text{criticality line index} = 3 \\
R &= \text{public risk exposure index} = 1 \\
\mathcal{R} &= \text{restoration duration index} = 1 \\
\Delta &= \text{permanent damage index} = 1
\end{align*}
\]

hence the consequence of failure is ranked relative to other transmission lines as 3. The risk of failure ranges from is 0.27 to 1.92 and the consequential cost of the risk is limited to loss of revenue for the restoration.

9 Conclusion

The paper detailed the opportunities for utilities to extend the life of existing transmission lines by refurbishment activities by providing

i. a brief understanding of the component & element degradation mechanisms, diagnostic techniques and refurbishment activities;

ii. an elementary indice method to assess the probability of failure and the consequence of failure to determine the risk of failure to allow a transmission line networks to be ranked; and

iii. an economic model to determine the optimum time for transmission line refurbishment activities.

The methodology is currently being used to model a number of transmission lines to test the validity of model and two examples of the methodology has been provided.

10. References


