Reliability Enhancement of Line Conductor of a Transmission System using Artificial Neural Network

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Abstract:

Reliability of line conductor of a transmission system depends upon its tensile strength which is affected by factors like conductor weight, wind pressure and heat dissipation due to continuous energy loss that takes place in the transmission line conductor. The reliability assessment is based on the principle of degradation of tensile strength of line conductor leading to elongation of transmission line conductor or increase in sag. The transmission line conductor holds the reliability until its sag is lesser than the threshold value of sag. In the present work the mathematical relations have been developed to assess the effect of each of the above factors on decay in tensile strength followed by increase in size of sag and therefore on loss of reliability of line conductor. It is suggested that the reliability of line conductor in the transmission system can be enhanced by transmitting the power at higher level of voltage. The mathematical results both for assessment and enhancement of reliability of a line conductor have been confirmed through Artificial Neural Network (ANN). The ANN is based on the principle of back propagation.

Keywords — *Transmission Line, Tensile Strength, Sag, Span, Conductor Weight, Wind Pressure, Conductor Temperature, Ageing, Reliability, Artificial Neural Network.*

I. INTRODUCTION

Reliability of transmission line conductor bears greater significance with reference to uninterrupted and assured supply of power to the load centre besides supporting the growing load demand so the enhancement in reliability of line conductor will boost the performance of transmission system. For the purpose it is required to have a close study of factors which badly affects the reliability of transmission line conductor. The reliability of a transmission line conductor is at a stake when the sag of the transmission line conductor exceeds a predetermined value or the clearance of the line conductor with respect to ground breaches the standard value as per rule 77 of 1956 Indian Electricity Rules. The causes which lead to increase in sag includes (i) sustained application of conductor weight on line conductor (ii) sustained application of wind pressure on the line conductor (iii) sustained heating of line conductor due to energy loss occurring in line conductor because of the resistance of line conductor possesses certain resistance/ km length of conductor.

Thus all the three factors explained above have cumulative effect which grows with time and is the fundamental basis of ageing of line conductor. It can therefore be said that the reliability of transmission line conductor is affected by ageing caused by above explained three factors.

In [1] the authors have presented new method to evaluate the reliability of power system using ANN. This method gives more accurate results with simple modeling and short computations as well as proposed ANN can be easily adapted with any change in the generation and transmission systems.
In [2] the authors have given a report which describes an enhanced test system (RTS-96) by adding a number of enhancements for use in bulk power system reliability evaluation studies. They also presented data which is required by reliability models of power systems.

In [4] the author has described repairable system and life data methods for assessing preventive maintenance of power line with minimal repair and replacement.

In [5] the authors have focused on the operation behavior of ageing overhead lines with special regard to the sag calculation line. The sag calculation is based on the deflection of the suspension insulators and the phase to earth clearance.
In [6] the authors have worked out the thermal-mechanical behavior of line conductor with a realistic model of the irreversible elongation behavior and sag calculations.

In [7] the authors have developed a probability based numerical method for evaluating the tensile strength of ACSR conductors through modeling of the tensile properties of conductors.

In [8] the authors have described the development of a data driven algorithm to predict remaining useful life of the system.

In [9] the author has given the equations for the determination of sag curves of an overhead line based on a given catenary constant.
The paper aims to provide the method to assess the reliability of line conductor and a method to enhance the same.

Next the reliability of transmission line is enhanced by reducing the effects of all the three factors by making transmission line to operate at nearly 10% higher voltage than the rated voltage. This is because working at higher voltage causes conductor weight to decrease, wind pressure effect to decrease due to decrease in projected area of conductor and heat dissipation to decrease as the current being transmitted is reduced at higher voltage. Further the enhancement of reliability is validated through ANN.

The paper is organized in six sections. Section 2 gives reliability assessment of line conductor affected by conductor weight, wind pressure and conductor heating, section 3 deals with approach for reliability enhancement. Section 4 deals with validation of reliability assessment and enhancement using ANN. Section 5 provides the conclusion followed by references.

II. RELIABILITY OF LINE CONDUCTOR

A transmission system for any level of transmission voltage consists of sending end transformer, line post and line insulator, line conductor and receiving end transformer. The present work focuses on assessment of reliability of a line conductor in a transmission system. Let the transmission system be as given in fig.1.

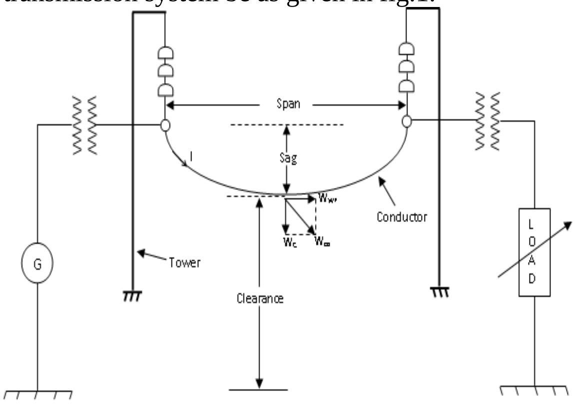


Fig.1 Line Conductor Sag in Transmission Line

Reliability of line conductor is decided by its tensile strength. But the tensile strength of line conductor depends on conductor weight, wind pressure and conductor heating. It is therefore the effect of each these parameters on tensile strength and thus on reliability is required to be assessed.

A. Effect of Conductor Weight on Tensile Strength of Conductor

Due to gravity the conductor weight (wc) acts downward and causes tension upon the conductor, it is reacted by the tensile strength of the conductor. Since the application of conductor weight is a continuous process, the tensile strength of the conductor suffers degradation due to ageing with time and is given by

$$T_{s\,w_c}(t) = T_{si} \times e^{-\alpha w_c t} \qquad (1)$$

$T_{s\,w_c}(t) =$
Working tensile strength affected by conductor weight at time 't',

B. Effect of Wind Pressure on Tensile Strength of Conductor

The pressure in the atmosphere varies with time over the year. It is assumed that it remains constant over a quarter and ultimately the mean of means of four quarter remains constant over the year. It is therefore assumed that the mean of pressures over the four quarters acts constantly upon the conductor throughout the year. Such mean pressure which is the mean of mean pressure over four quarters is known as equivalent constant pressure that acts uniformly over the years. This is to take account of effect of wind pressure on the conductor weight.
The effect of wind pressure in terms of weight on conductor,
w_{wp} = Projected Area * Wind Pressure

$$= (D \times l) \times P_w \qquad (2)$$

D = Conductor diameter (mm)
l= Length of Conductor (m)
P_W =Wind Pressure on Conductor (kg/m2) and

$$P_w = \frac{P_{w1} + P_{w2} + P_{w3} + P_{w4}}{4} \qquad (3)$$

Here Pw1, Pw2, Pw3 and Pw4 are average pressures over four quarters of a year.
The effect of weight due to wind pressure on tensile strength of line conductor with time is given by

$$T_{s\,w_{wp}}(t) = T_{si} \times e^{-\alpha w_{wp} t} \qquad (4)$$

$T_{s\,W_{wp}}(t)$=Working tensile strength affected by weight due to wind pressure at time 't'.

C. Equivalent Effect of Conductor Weight and Weight due to Wind Pressure on the Tensile Strength of Line Conductor

Because the wind is assumed to create pressure on the conductor at a uniform rate it is taken as an integral part of the weight of conductor. It is therefore the value of sag corresponding to mean value of weight due to wind on line conductor is considered to find initial sag. Also successive increase in sag is considered due to joint effect of conductor weight and wind pressure as net weight of line conductor per metre length basis. The net weight of conductor is obviously more than weight of conductor alone (without wind pressure). It will therefore cause fast decay in tensile strength and rapid growth in sag and finally earlier decay in reliability of conductor.

Therefore for the assessment of increase in sag resulting from decay in tensile strength due to conductor weight and wind pressure, the resultant effect of conductor weight and wind pressure on the conductor is given by

$$w_{eq} = \sqrt{w_c^2 + w_{wp}^2} \quad (5)$$

Where,

w_{eq}= Equivalent weight of conductor (kg/m)

w_c= Weight of conductor (kg/m)

w_{wp} = Weight due to wind pressure(kg/m)

Now the tensile strength of the conductor at any instant 't' i.e. $T_{s\,Wwp}(t)$ is given by

$$T_{s\,w_{eq}}(t) = T_{si} \times e^{-\alpha w_{eq} t} \quad (6)$$

Here,

$T_{s\ Weq}(t)$ =Working tensile strength affected by conductor weight and wind pressure at time't',

α= Elasticity constant

t = Time in years,

T_{si} = Initial Tensile Strength

D. *Effect of Conductor Heating on Tensile Strength of Conductor*

The effect of heating can be incorporated by estimating the decaying effect of heating caused by sustained energy loss in the conductor due to transmission of power. If it is assumed that there exists a steady temperature 'θ $_{steady}$' in the conductor uniformly present throughout the year after allowing for heat dissipation in atmosphere, then it expands the volume of conductor and leads to decay in tensile strength.

Heat generated in line conductor (H $_{generated}$) is given by

$$H_{generated} = \frac{I^2Rt'}{4200}\ \text{kcal} \quad (7)$$

Where

I = Current flowing in conductor

R = DC resistance at 20 ^{0}C

t' = Time in second

The conductor temperature due to heat generated in the conductor is given by

$$\theta_2 = \frac{H_{generated}}{m_c s_c} + \theta_1 \quad (8)$$

Here,

θ_1 = Average atmospheric temperature

θ_2= Line conductor temperature

m_c = mass of conductor

s_c = specific heat of conductor

Heat dissipated to atmosphere per hour

The hot wire due to heat generated is exposed to atmosphere and transfers the heat to surrounding atmosphere on the basis of temperature level of atmosphere. Hence

$$Q_{dissipated} = m_a s_a \Delta\theta = m_a s_a (\theta_2 - \theta_1) \quad (9)$$

Here

$Q_{dissipated}$ = Heat dissipated to atmosphere

m_a = mass of air

s_a = specific heat of air

Steady temperature in the Line Conductor per hour

Since

$$H_{steady} = H_{dissipated} - Q_{dissipated} \quad (10)$$

Thus the steady temperature of line conductor is given by

$$\theta_{steady} = \frac{H_{steady}}{m_c s_c} + \theta_1 \quad (11)$$

The steady temperature (θ_{steady}) that results in the decay in tensile strength of line conductor is given by

$$T_{s\,H}(t) = T_{si} \times e^{-\beta\theta_{steady} t} \quad (12)$$

Where,

$T_{sH}(t)$ = Working Tensile Strength affected by conductor heating at time 't',

β = Coefficient of linear expansion

θ_{steady} = Steady temperature in line conductor

t = Time in years,

E. *Resultant Effect of Conductor Weight, Wind Pressure and Conductor Heating on the Tensile Strength and Sag of Line Conductor*

This too when the wind pressure is acting with conductor weight on line conductor to cause decay in tensile strength in addition to what is caused by heating. Thus include the effect of heating at any instant 't' the tensile strengths given by equation (4) and (6) would get super imposed. Conclusively the net value of tensile strength at time 't' is given by

$$T_{s\,net}(t) = T_{si} \times e^{-\left[\sqrt{(\alpha w_{eq} + \beta\theta_{steady})}\right] Ct} \quad (13)$$

where

$$C = \text{Super Imposition Factor} = \frac{\sqrt[3]{w_{eq}} \times F.O.S.}{\theta_{steady}} \quad (14)$$

Now, for every instant 't' there exists a sag corresponding to tensile strength, which is given by

$$S_{net}(t) = \frac{w_{eq} L^2}{8T_{s\,net}(t)} \quad (15)$$

As per the initial tensile strength the sag that remains in transmission line conductor at the time of installation is refers as initial sag (Si) and is given by

$$S_i = \frac{w_{eq} L^2}{8T_{si}} \quad (16)$$

The maximum value of sag beyond which the increase in sag is dangerous to humans and

animals passing below the transmission line is refer as sag threshold (S_{th}) and is given by
S_{th}=Distance from Ground to Insulator- Ground Clearance Limit
Threshold value of sag gives the limiting or threshold value of tensile strength ($T_{s\,th}$) of line conductor given by,

$$T_{s\,th} = \frac{w_{eq}\,L^2}{8S_{th}} \qquad (17)$$

Threshold Tensile Strength ($T_{s\,th}$) in fact marks the last point upto which the decay in tensile strength is permissible.
Thus conductor weight, wind pressure and conductor heating cause decay in tensile strength. This is reflected in increase in sag. This puts a question on the reliability of transmission line which no more remains reliable or the reliability lost is 100%.

F. Reliability Assessment of Line Conductor

The reliability of transmission line is then given by

$$(\%)\text{Reliability} = \left(\frac{K_2}{S_{net}(t)} - K_1\right) \times 100 \qquad (18)$$

Where,

$$K_1 = \frac{S_i}{S_{th} - S_i}$$

$$K_2 = S_{th}\left(\frac{S_i}{S_{th} - S_i}\right) = S_{th} \times K_1$$

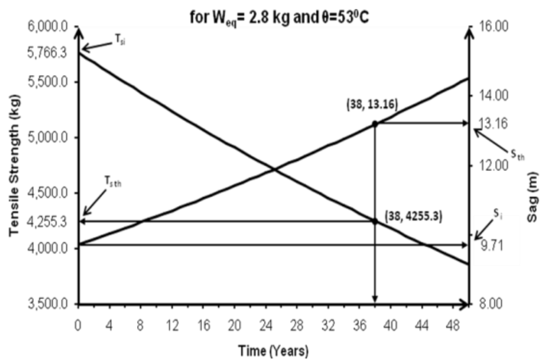
Case Study

A 400kV transmission line conductor's reliability on the basis of its tensile strength and sag w.r.t. time 't' is has been observed. Line conductor used having 16434kg as ultimate tensile strength, 2.004kg/m as conductor weight, 31.77mm as diameter and 400m to be the span between two successive towers. Considering uniform wind pressure act on line conductor by averaging theory. Current flowing through the line conductor is 700A and conductor resistance is 0.05596mΩ. Other data are chosen as per the Indian Electricity Rules of 1956. The table 1 gives the values of tensile strength, sag and reliability at successive intervals of four year.

Table 1

Years	Tensile Strength (kg)	Sag (m)	Reliability (%)
0	5766.3	9.71	100
4	5583.67	10.03	87.92
8	5406.82	10.36	76.24
12	5235.58	10.70	64.92
16	5069.76	11.05	53.97
20	4909.19	11.41	43.36
24	4753.71	11.78	33.08
28	4603.15	12.17	23.14
32	4457.36	12.56	13.50
36	4316.19	12.97	4.18
38	4247.29	13.18	-0.38

The manner in which the line conductor's tensile strength, sag and reliability are affected with ageing (as the time grows) due to joint effect of conductor weight, wind pressure and conductor heating is graphically shown in Fig.2 and 3.



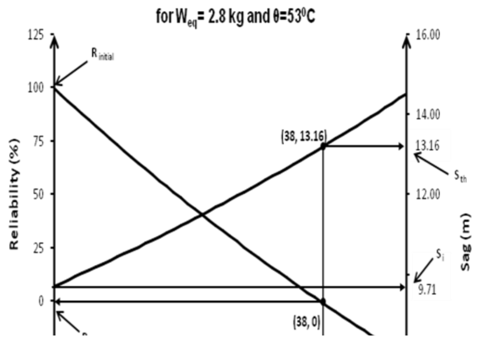


Fig.3 Assessment of Reliability and Sag of Line Conductor

It is obvious "from the graphical analysis for assessment of reliability of line conductor" that sag is increased due to sustained application of conductor weight, wind pressure and conductor heating on 400 kV line conductor of the transmission line. This results decay in tensile strength of line conductor. Thus conductor weight, wind pressure and conductor heating cause to reach its threshold value i.e. 13.16m in 38 years. The reliability of line conductor is therefore lost at the end of 38 years.

III. PROPOSED APPROACH FOR RELIABILITY ENHANCEMENT OF LINE CONDUCTOR

For a given power demand if the power is transmitted at higher voltage the current to be transmitted would get low. This requires conductor of small diameter/ cross-section leading to low conductor weight, low power loss and low effect of wind pressure. Hence the time to attain threshold sag by conductor would be elongated and the reliability of conductor would enhance.

A. Case Study

A 450kV transmission line conductor's reliability on the basis of its tensile strength and sag w.r.t time 't' has been observed. Line conductor used having 27.46 mm as conductor diameter, 592 mm2 as area of cross section of conductor, 1.987 kg/m as conductor weight, 16434 kg as ultimate tensile strength and 400m to be the span between two successive towers. Consider uniform wind pressure to act on line conductor by averaging theory. Current flowing through the line conductor is 622.22A and conductor resistance is 0.05643mΩ. Other data are chosen as per the Indian Electricity Rules of 1956.

The table 2 gives the values of tensile strength, sag and reliability for increased transmission voltage at successive intervals of four year.

Table 2

Years	Tensile Strength (kg)	Sag (m)	Reliability (%)
0	5766.3	9.018	100
4	5578.12	9.322	89.63
8	5396.082	9.637	79.60
12	5219.984	9.962	69.90
16	5049.633	10.298	60.52
20	4884.841	10.645	51.44
24	4725.428	11.004	42.65
28	4571.216	11.376	34.16
32	4422.037	11.759	25.94
36	4277.727	12.156	17.99
40	4138.126	12.566	10.29
44	4003.081	12.990	2.85
46	3937.22	13.207	-0.77

With increased transmission voltage, the manner in which the conductor weight, wind pressure and conductor heating affects the tensile strength, sag and reliability of line conductor with ageing (as the time grows) is graphically shown in fig. 4 and 5.

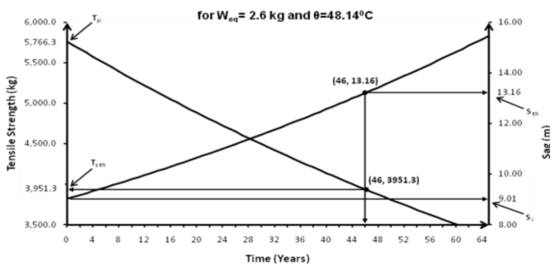


Fig.4 Assessment of Tensile Strength and Sag of Line Conductor with Increased Transmission Voltage

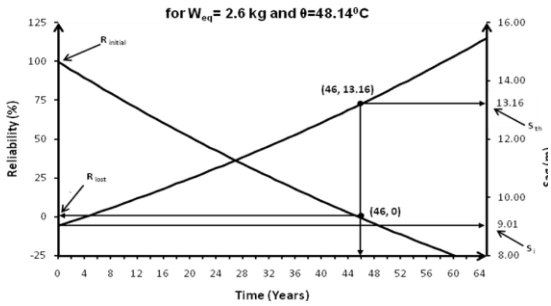


Fig.5 Assessment of Reliability and Sag of Line Conductor with Increased Transmission Voltage

It is obvious "from the calculation and graphical analysis for assessment of reliability of line conductor affected by increased transmission voltage" that sag grows at a slower rate due to increased transmission voltage which is affecting the net weight of line conductor of the transmission line and conductor heating. It is therefore noticed that the sag of conductor takes 46 years viz-a-viz 38 years to reach its threshold value i.e. 13.16m completely. Also it loses its reliability at the end of 46 years i.e. when the sag approaches 13.16m.

B. Result

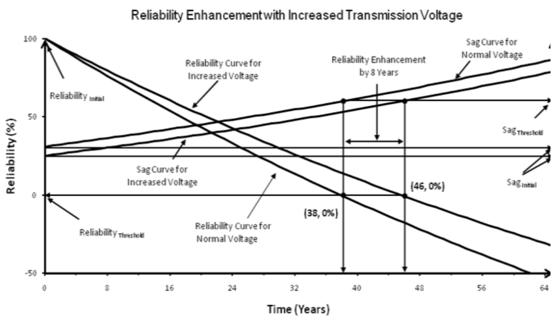


Fig.6 Enhancement in Reliability of Line Conductor with Increased Transmission Voltage

The enhancement in reliability is shown in fig. 6. The threshold value of sag was reached in 38 years under normal voltage (i.e. 400kV) conditions but when the voltage was raised up to 450kV the threshold value of sag was reached in 46 years. The reliability of transmission line conductor therefore got improve in term of age by 8 years. Which is approximately 17.4% more than what it posses without increase of voltage.

IV. VALIDATION OF RELIABILITY AND ITS ENHANCEMENT THROUGH ANN

On MATLAB platform architecture the ANN has been organized and its training has been shown in the training window as in figure 7.

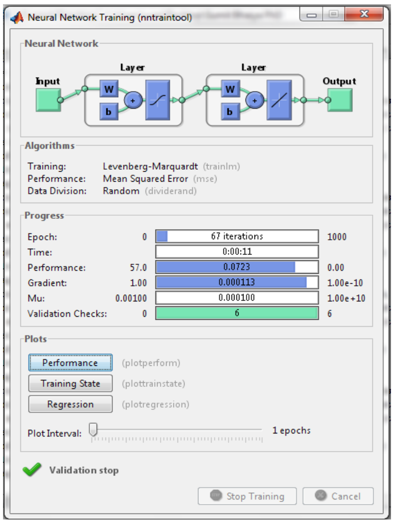


Fig.7 Training of ANN

The trained Neural Network (NN) is then validated and tested for its standardization shown in figure 8 so that the NN can be used for testing the reliability enhancement for the change in sag (S_L-S_H) corresponding to threshold value of sag threshold (S_H) when the conductor is operated at higher voltage.

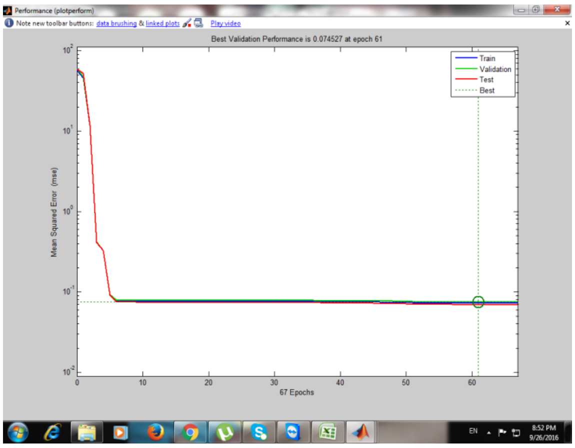


Fig.8 Testing and Validation of ANN

The output of ANN corresponding to difference in sag (S_L-S_H) at threshold value of sag (S_H) refers to reliability enhancement for S_L-S_H = 0.853m at S_H = 13.16m the value of reliability enhancement is equal to 17.1% shown in figure 9.

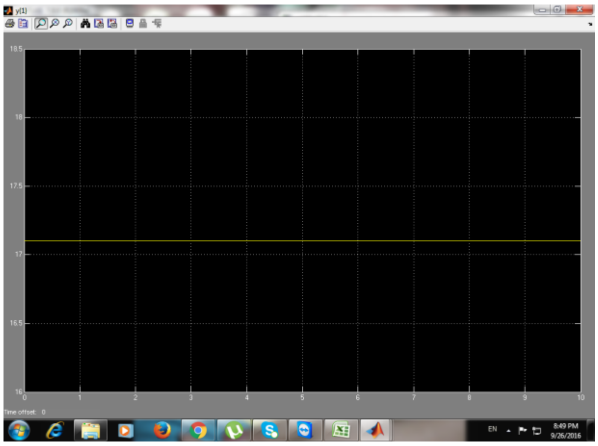


Fig.9 Reliability Enhancement Output for Difference in Sag 0.853

It is observed that the reliability due to operation at 450kV instead of 400kV is enhanced by 8years when worked out by mathematical model. This result is validated by ANN and that also shows the enhancement of reliability by 8years when the transmission system is operated at 450kV instead of 400kV.

V. CONCLUSION

Reliability assessment and enhancement has been suggested in this work for the line conductor of a transmission system. Mathematical formalism is developed to assess the reliability of line conductor. It is observed that factors like conductor weight, wind pressure and continuous dissipation of heat due to energy loss adversely affect the tensile strength of line conductor which therefore decays with time. It causes the line conductor to increase its length and hence the sag of the conductor increases. The transmission line losses its reliability when its sag exceeds beyond its threshold value i.e. 13.16m. The time duration in which the line conductor attains threshold level sag is the time till which the transmission line holds reliability and for all times beyond this point of time the line conductor loses its reliability. This time duration for the case of 400kV transmission line is 38 years. It is suggested that the reliability of transmission line or line conductor can be enhanced by making the transmission line to operate at 450kV instead of 400kV. It reduces the current through the conductor and therefore conductor of lower cross section can do the required work. Lower cross section reduces the conductor weight as well as the effect of wind pressure on the conductor. Which leads to reliability enhancement because the decay in tensile strength is slowed down. Finally low sized current flow through the conductor is responsible for low energy losses and therefore low heat dissipation. This also causes lower decay in tensile strength and hence reliability enhancement of line conductor takes place.

The results obtained by mathematical formalisms for reliability enhancement due to transmission at higher voltage is confirmed by ANN. Thus the suggested approach for reliability enhancement is validated. It is important to point out that both the approaches yields identical results for enhancement in reliability equal to 8 years.

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