University of Birmingham
Research at Birmingham

Methodology for overhead conductor replacement considering operational stress and aging characteristics

Vasquez , Wilson; Jayaweera, Dilan

DOI:
10.1109/PESGM.2018.8586012

License:
None: All rights reserved

Document Version
Peer reviewed version

Citation for published version (Harvard):
Vasquez , W & Jayaweera, D 2018, Methodology for overhead conductor replacement considering operational stress and aging characteristics. in *2018 IEEE Power & Energy Society General Meeting (PESGM).* Power& Energy Society, IEEE General Meeting, Institute of Electrical and Electronics Engineers (IEEE), IEEE PES General Meeting , United States, 5/08/18. https://doi.org/10.1109/PESGM.2018.8586012

Link to publication on Research at Birmingham portal

Publisher Rights Statement:
© 2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.
•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
•User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 14. Aug. 2024

Methodology for Overhead Conductor Replacement Considering Operational Stress and Aging Characteristics

Wilson A. Vasquez, Dilan Jayaweera
School of Electronic, Electrical and Systems Engineering
University of Birmingham
Birmingham, United Kingdom
Email: WAV535@student.bham.ac.uk, d.jayaweera@bham.ac.uk

Abstract—**This paper presents a novel methodology for the prioritization of overhead conductor replacement considering operational stress and aging characteristics. The time sequential Monte Carlo technique is used to assess the reliability of a distribution network over a planning period. To incorporate the influence of high operating temperatures and aging characteristics into the reliability assessment, up-times of aging conductors are sampled using the interval-by-interval method, Arrhenius life-temperature relationship, and thermal model IEEE 738-2006. Aging conductors are ranked for replacement based on the financial losses caused by their failures throughout the planning period. The methodology was tested using the IEEE 33-bus distribution network model. Results indicate that failures of aging conductors affect significantly system reliability indices. Furthermore, it was determined that financial losses of aging conductors depend on the conductor location and network's protection scheme. The proposed methodology may help utilities improve both asset replacement plans and system reliability.**

Index Terms- **Arrhenius relationship, conductor replacement, distribution network, reliability assessment, thermal aging.**

I. INTRODUCTION

Reliability of power systems has been of primary concern for utilities since the deregulation of electricity markets. Energy regulators may impose financial penalties if utilities fail to deliver desirable levels of service quality. Power system reliability is affected by equipment aging. Aged assets tend to fail more frequently, increasing the number and duration of interruptions [1]. There are several factors responsible for accelerating equipment aging process, such as insulation deterioration of electrical components, overheating, corrosion, and fatigue damage of mechanical parts. Although the development of asset management techniques in the electric power industry has increased in the last years, it has been identified that assets are not being replaced at a proper rate in some developed countries where electricity networks have equipment that is operating close to, or even beyond, its lifetime [2]. Utilities' budget constraints may affect asset replacement plans.

The application of reliability assessment in asset replacement planning has been explored in [3-4]. A reliability based framework for cost-effective replacement of power transmission equipment was proposed in [3]. Critical components are identified by performing system reliability assessment and Pareto analysis. The replacement of critical components is based on a comparison between the cost of unreliability due to deferring the replacement and the saving on reinvestment cost. On the other hand, the authors of [4] proposed a reliability model of aging cable and a methodology for distribution cable replacement. The reliability model was incorporated into a sequential Monte Carlo procedure. Cable replacement lists were obtained using reliability indicators.

Strategies for overhead conductor replacement have been investigated in [5-8]. An approach to estimate the remaining life of transmission line conductors using visual inspection and age information is presented in [5]. Field and laboratory tests of aged ACSR (Aluminum Conductor Steel Reinforced) conductors, such as corrosion detection and tests of fatigue, tensile strength, torsional ductility, and electrical performance, are presented in [6]. The authors of [7] proposed a method to calculate conductors' remaining useful life using progressive degradation curves. In a recent study [8], analytical models were used to predict conductors' tensile failure probabilities, and optimum time intervals for conductor replacement were recommended. Even though those strategies may provide good criteria for conductor replacement decisions, the influence of aging conductors' failures on power system reliability and replacement plans has not been investigated.

End-of-life failures of power system components are usually modeled using the method developed by Wenyuan Li [9]. Probability distribution functions, such as Normal and Weibull, are used to estimate the probability of transition to aging failure. A disadvantage of Li's method is that it can only be applied for composite power system reliability evaluation techniques, e.g., State Enumeration and non-sequential Monte Carlo. In addition, probability distributions do not incorporate the effect of components' operating conditions on failure probabilities.

This paper proposes a novel methodology for the prioritization of overhead conductor replacement considering operational stress and aging characteristics. The reliability of a distribution network is analyzed over a planning period using the time sequential Monte Carlo technique. To incorporate aging characteristics and operational stress into the reliability assessment, up-times of aging conductors are sampled through the interval-by-interval method, Arrhenius relationship, and thermal model IEEE 738-2006. Aging conductors are ranked for replacement based on the financial losses caused by their failures throughout the planning period.

The remaining parts of the paper are organized as follows. Section II presents the method to sample up-times of aging conductors. Section III introduces the method for prioritizing conductor replacement. The proposed methodology is described in Section IV. Section V gives information of the test system. Section VI presents the results and analysis. Finally, conclusions are given in Section VII.

II. TIME TO FAILURE OF AGING CONDUCTORS

To assess the reliability of a distribution network using the time sequential Monte Carlo technique, it is necessary to calculate the time to failure (TTF) and time to repair (TTR) for all system components. TTF is the time during which a component is kept in service. Likewise, TTR is the time during which a component is out of service. Inter-failure times (TTF) of a repairable component can be analyzed as a stochastic point process [10]. A sample path of a stochastic point process with a number of events $N(t)$ is depicted in Fig. 1. x_k and t_k represent the inter-failure time and specific time when a failure event occurs, respectively. The relationship between x_k and t_k is given by (1) and (2).

$$t_k = x_1 + x_2 + ... + x_k \tag{1}$$

$$t_k = x_k + t_{k-1} \tag{2}$$

If inter-failure times are described by an exponential probability distribution, the stochastic process is known as homogeneous Poisson process (HPP). In an HPP, repairable components have constant failure rates, and inter-failure times do not show aging trends [10].

Aging characteristics of repairable components may be taken into account in power system reliability assessment by modeling inter-failure times through a non-homogeneous Poisson process (NHPP) [11]. The NHPP is a general model that can handle both aging and reliability growth. There are several methods to calculate the inter-failure times, x_k, of a NHPP. In this study, the interval-by-interval method was used, and it is given by (3) and (4) [10].

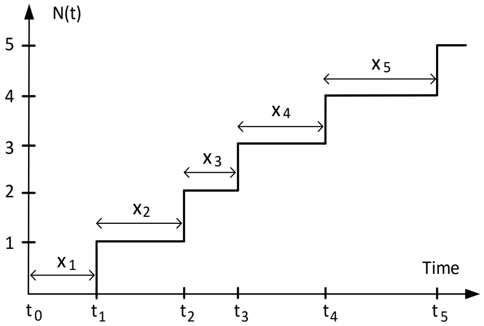


Fig. 1: Sample path of a stochastic point process [10]

$$x_k = \left(-\frac{\ln(U)}{\lambda}\right)^{\frac{1}{\beta}}, \qquad k = 1 \tag{3}$$

$$x_k = \left[\left(q\Big(\sum_{i=1}^{k-1} x_i\Big)\right)^{\beta} - \frac{\ln(U)}{\lambda}\right]^{\frac{1}{\beta}} - q\Big(\sum_{i=1}^{k-1} x_i\Big), k > 1 \tag{4}$$

The first failure time (x_1) follows a Weibull distribution with parameters β and $\lambda = 1/\alpha^{\beta}$ [4]. The parameter β is known as degree of aging. If the value of β is greater than one, the failure rate of a repairable component increases over the time. The failure rate is constant when β is equal to one. However, if β is less than one, the failure rate decreases over the time indicating reliability improvement. U is a uniformly distributed random number between [0,1]. The value of the repair adjustment factor, q, depends on the condition of the component after the repair process [10]. It was assumed $q = 1$ for the analysis of a NHPP.

A. Arrhenius Life-temperature Relationship

To incorporate the influence of high operating temperatures on TTF, the Arrhenius relationship may be used [4]. The lifetime of a component (L) is modeled as function of temperature (θ) through the Arrhenius relationship, as shown in (5).

$$L(\theta) = A \times \exp\left(\frac{B}{\theta}\right) \tag{5}$$

Where A and B are empirical constants. The parameter α of the interval-by-interval method is substituted by $L(\theta)$. In addition, for the analysis of overhead conductors, θ is replaced by the conductor temperature T_c, which may be estimated using conductor thermal models.

B. Thermal Model of Overhead Conductors

Conductor temperature depends on ambient weather conditions, electrical current, conductor material properties, conductor diameter, and conductor surface conditions [12]. The standard IEEE 738-2006 was used for the calculation of T_c. The iterative process to solve (6) is described in detail in [12].

$$q_c + q_r = q_s + I^2 \times R(T_c) \tag{6}$$

Where q_c and q_r are the convection and radiation heat losses, q_s is the solar heat gain, R is the conductor resistance, and I is the electrical current.

III. RANKING OF AGING CONDUCTORS BASED ON FINANCIAL CONSEQUENCES

Reward and penalty schemes have been implemented in some countries to deliver desirable levels of service quality. These schemes are complex regulation instruments that alter companies' revenues [13]. Financial rewards or penalties are established based on the comparison between companies' actual performance and performance standards established by electricity regulators. Quality indicators, such as Energy

Not Supplied (ENS), System Average Interruption Frequency Index (SAIFI), and System Average Interruption Duration Index (SAIDI), may be subject to financial incentives [13].

The method for the prioritization of conductor replacement takes into account two financial consequences: revenue losses under incentive schemes and failure repair costs [4]. C represents the total financial losses caused by an aging conductor over a time period.

$$C = SAIFI_{cond}SAIFI_{inc} + SAIDI_{cond}SAIDI_{inc} + N_f C_f \tag{7}$$

Where $SAIFI_{cond}$ and $SAIDI_{cond}$ are the customer-interruptions and customer-minutes-lost caused by an aging conductor, $SAIFI_{incentive}$ and $SAIDI_{incentive}$ are monetary values of one customer interruption $(\$/SAIFI)$ and one customer minute lost $(\$/SAIDI)$, C_f is the failure repair cost, and N_f is the number of failures of a conductor.

IV. DESCRIPTION OF THE PROPOSED METHODOLOGY

The methodology for the prioritization of overhead conductor replacement is based on the probabilistic reliability assessment of a distribution network. The reliability assessment takes into account both aging characteristics and operational stress of overhead conductors. The time sequential Monte Carlo simulation technique is used to analyze the network performance over a planning period. The TTF of aging conductors is calculated using the interval-by-interval method, Arrhenius relationship, and thermal model IEEE 738-2006. It is assumed that the TTF of non-aging conductors follows an exponential distribution. Likewise, the TTR of aging and non-aging conductors follows an exponential distribution. After completing the reliability assessment, aging conductors are ranked based on the financial penalties and repair costs caused by their failures during the planning period. Fig. 2 illustrates the flow chart of the methodology. The main steps for the methodology implementation are described below:

Input data: Before starting the simulation, it is necessary to enter the location and topology of the network, physical and electrical data of conductors, weather data, historic and forecasted load profiles, conductor failure data, and parameters of the thermal model, Arrhenius model, and load flow.

Historic Period: Conductors are classified as aging or non-aging components based on their current remaining tensile strength, which depends on the operational stress. To determine the remaining tensile strength, the experimental model described in [14] is used. Hourly conductor temperatures are calculated using historic load profiles and weather data. Group conductor temperatures in orderly levels, e.g., 100°C, 105°C, 110°C, etc., and determine their frequency at each level. Then, calculate the remaining tensile strength only for conductors that operated at temperatures higher than 90°C. It is assumed that if the remaining tensile strength is $\geq$95% of its initial value, conductors are non-aging components. If the remaining tensile strength is between 90% and 95% of its initial value, conductors are classified as aging components.

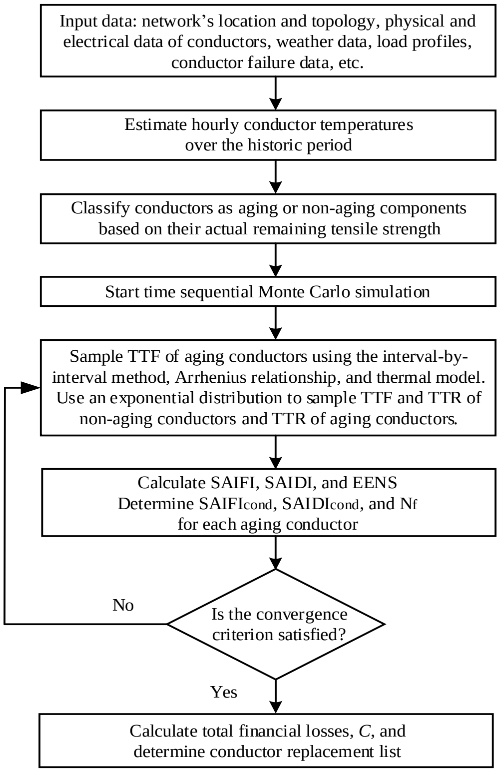


Fig. 2: Flow chart of the methodology

Planning Period: Start the time sequential Monte Carlo simulation for the pertinent planning period. Sample TTF of aging conductors combining the interval-by-interval method, Arrhenius model, and thermal model. Sample TTF and TTR of non-aging conductors as well as TTR of aging conductors using an exponential distribution. Calculate system reliability indices SAIFI, SAIDI, and EENS, as well as $SAIFI_{cond}$, $SAIDI_{cond}$, and N_f for each aging conductor. Repeat the simulation until the convergence criterion is satisfied. In this study, the coefficient of variation of the EENS was used as the convergence criterion [15]. Finally, calculate the financial losses (C) for each conductor and determine the replacement list.

V. SYSTEM INFORMATION

A. Test System

The test system is an 11-kV radial distribution network. The system, depicted in Fig. 3, has 33 buses (bus 1 is the substation), 32 line sections (L1, L2,..., L32), and 5 tie-lines. The system maximum demand, hourly load profile, and load growth were taken from [16], [17], [18]. For the reliability assessment, it was assumed that a breaker is located at the start of the main feeder (L1), and switches are allocated in all other line sections.

B. Conductor and Weather Information

Mechanical specifications of ACSR conductors, such as average tensile strength of aluminum strands, rating factors, and strength of steel strands at 1% elongation, were found in

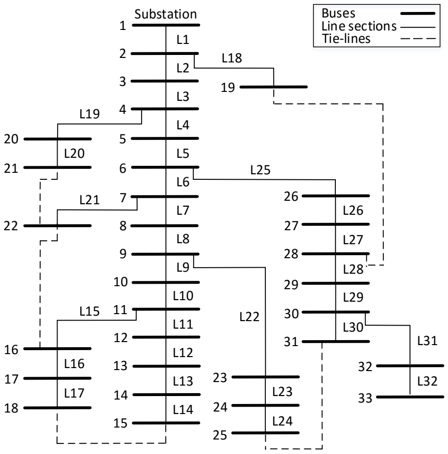


Fig. 3: Test system

international standards ASTM B498, ASTM B230, and ASTM 232. Average hourly values of wind speed, wind direction, and ambient temperature of 2010 were found in [19].

VI. RESULTS AND ANALYSIS

The calculation of up-times (TTF) of aging conductors was analyzed. Up-times depend on conductor temperature (T_c) and degree of aging (β). Ten consecutive average up-times were calculated considering different β values (1.1 and 1.3) and constant temperatures (110°C and 120°C). After completing a simulation of 10^3 trials, the results are depicted in Fig. 4. It can be seen that either temperature increments or higher β values can reduce significantly average up-times of aging conductors, which leads to more frequent failures.

Two scenarios were analyzed for the methodology implementation. Scenario 1 and Scenario 2 comprise historic periods of 30 and 35 years, respectively. Fig. 5 shows the estimated remaining tensile strength of line sections L1-L5 for both scenarios. It can be seen that the remaining tensile strength of L1 and L2 is between 90% and 95% of its initial value in Scenario 1; and therefore, these conductors are classified as aging components. Likewise, L1, L2 and L3 are aging components in Scenario 2.

A 10-year planning period was considered for the reliability assessment of the test system. The estimated values of A and B are 1.067×10^{-14} and 1.322×10^{4}, respectively [16]. Several simulations were performed to analyze the influence of β on the system performance. Table I shows the resulting system reliability indices SAIFI, SAIDI, and EENS. One may notice that either higher β values or more aging conductors affect the system reliability indices. For instance, when β equals 1.4 and 2.2, the corresponding SAIDI values are 6.24 and 7.39 (hr/cust./yr) in Scenario 1 and 6.77 and 8.38 (hr/cust./yr) in Scenario 2.

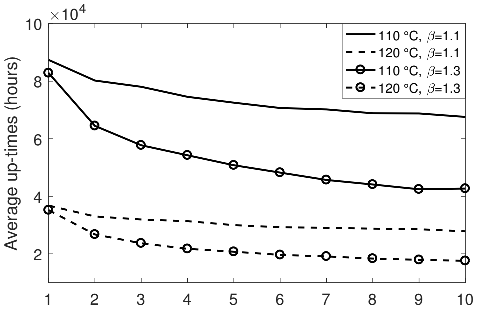


Fig. 4: Variation of average up-times

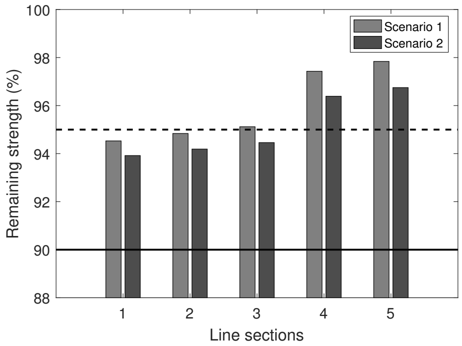


Fig. 5: Remaining tensile strength of line sections L1-L5

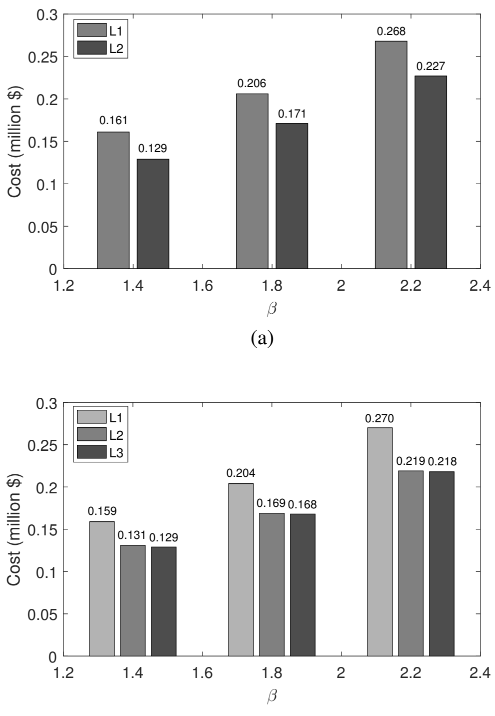
The SAIFI and SAIDI incentive rates used for the ranking method are 73,229.0 $(\$/SAIFI)$ and 2,462.0 $(\$/SAIDI)$ [20]. It was assumed that the failure repair cost is 3,000.0 $(\$/failure)$. Fig. 6 shows the total financial losses caused by each aging conductor during the planning period. It can be noticed that the total financial losses increase for higher values of β. This is because the TTF of aging conductors decreases when β increases, as mentioned before. Thus, the resulting conductor replacement lists for both scenarios are given below:

- Scenario 1: L1, L2.
- Scenario 2: L1, L2, L3.

There were two main factors that affected the conductor replacement lists. First, the test system has a radial configuration; and therefore, line sections located at the beginning of the main feeder (L1-L3) are exposed to high loading levels, i.e., faster thermal aging. Second, the protection scheme of the system determines that failures of conductors that are located near to the substation and connected to the main feeder make a significant contribution to the SAIDI value. For instance, when $\beta = 1.4$, the total values of $SAIDI_{cond}$ represent the 26% and

TABLE I: System reliability indices

Scenario 1 (two aging conductors)			
β	$SAIFI$ $(interr./cust./yr)$	$SAIDI$ $(hr/cust./yr)$	$EENS$ $(kWh/cust./yr)$
1.0	3.93	5.87	9.94
1.4	4.06	6.24	10.58
1.8	4.20	6.73	11.43
2.2	4.41	7.39	12.56
Scenario 2 (three aging conductors)			
1.0	4.07	6.22	10.94
1.4	4.24	6.77	11.92
1.8	4.47	7.45	13.16
2.2	4.78	8.38	14.81



(a)

(b)

Fig. 6: Financial losses caused by aging conductors: a) Scenario 1, b) Scenario 2

35% of SAIDI in Scenario 1 and Scenario 2, respectively.

VII. CONCLUSION

The paper proposes a novel methodology for the prioritization of overhead conductor replacement considering operational stress and aging characteristics. The time sequential Monte Carlo technique is used to assess the network performance over a planning period. The time to failure of aging conductors is sampled using the interval-by-interval method, Arrhenius relationship, and thermal model IEEE 738-2006 to incorporate the influence of elevated temperatures and aging characteristics into the reliability assessment. Then, aging conductors are ranked for replacement taking into account the financial losses caused by their failures throughout the planning period.

The proposed methodology was tested using the IEEE 33-bus radial distribution network. Simulation results established that failures of aging conductors affect significantly system reliability indices. The financial losses of aging conductors depend on the conductor location and network's protection scheme. With the increasing penetration of renewable generation and electric vehicles into power systems as well as improper operation of controllable demands, it is more likely to expose lines and transformers to overloading conditions. In that context, the proposed methodology may help utilities improve both asset replacement plans and system reliability.

REFERENCES

[1] W. Li, E. Vaahedi, and P. Choudhury, "Power system equipment aging," 2006.

[2] IEC, "Strategic asset management of power networks," 2015.

[3] S. Awadallah, M. Jovica, and P. Jarman, "Reliability based framework for cost-effective replacement of power transmission equipment," *IEEE Trans. Power Syst.*, vol. 29, no. 5, pp. 2549–2557, 2014.

[4] M. Buhari, V. Levi, and S. Awadallah, "Modelling of ageing distribution cable for replacement planning," *IEEE Trans. Power Syst.*, vol. 31, no. 5, pp. 3996–4004, 2016.

[5] Y. Tsimberg, K. Lotho, and C. Dimnik, "Determining transmission line conductor condition and remaining life," US, Apr. 2014, pp. 1–5.

[6] D. Harvard, G. Bellamy, and P. Buchan, "Aged acsr conductors part i testing procedures for conductors and line items," *IEEE Trans. Power Delivery.*, vol. 7, no. 2, pp. 581–587, 1992.

[7] D. Harvard, M. Bissada, and C. Fajardo, "Aged acsr conductors part ii prediction of remaining life," *IEEE Trans. Power Delivery.*, vol. 7, no. 2, pp. 588–595, 1992.

[8] I. Hathout, K. Callery, and T. Tang, "Fuzzy probabilistic expert system for overhead conductor assessment and replacement," US, 2015, pp. 1–5.

[9] W. Li, *Risk assessment of power systems*. Wiley, 2005.

[10] H. Kim and C. Singh, "Reliability modeling and simulation in power systems with aging characteristics," *IEEE Trans. Power Syst.*, vol. 25, no. 1, pp. 21–28, 2010.

[11] L. Crow, "Reliability analysis for complex, repairable systems," AMSAA, 1975.

[12] IEEE, "Standard for calculating the current-temperature of bare overhead conductors," pp. 1–59, 2006.

[13] E. Fumagalli, L. Lo, and F. Delestre, *Service quality regulation in electricity distribution and retail*. Springer, 2007.

[14] J. Harvey, "Effect of elevated temperature operation on the strength of aluminum conductors," *IEEE Trans. Power Appar. and Syst.*, vol. 91, no. 5, pp. 1769–1772, 1972.

[15] R. Billinton and W. Li, *Reliability assessment of electric power systems using Monte Carlo methods*. Springer, 1994.

[16] W. Vasquez, D. Jayaweera, and J. Jativa, "Advanced aging failure model for overhead conductors," Italy, Sep. 2017, pp. 1–6.

[17] R. T. Force, "Ieee reliability test system," *IEEE Trans. Power Appar. and Syst.*, vol. 98, no. 6, pp. 2047–2054, 1979.

[18] "Annual energy outlook," U.S. Energy Information Administration, 2014.

[19] (). Noaa u.s. climate normals (1981-2010), [Online]. Available: https://www.ncdc.noaa.gov/cdo-web/search?datasetid=NORMAL_HLY.

[20] "Default price-quality paths for electricity distributors from 1 april to 31 march 2020," Commerce Commission, 2014.