Optimum Return Period of an Overhead Line Considering Reliability, Security and Availability with Respect to Extreme Icing Events

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Abstract— **The paper presents a basis for computing the optimum return period of an overhead line under extreme icing events. The return period of the climatic loads is directly related to the expected line failure rate and hence, the reliability. A mathematical model is developed for a parallel line configuration to ensure that the line cost is balanced against the present value of the future failure cost. The future failure cost consists of two components; (1) cost of line replacement and (2) cost of energy not supplied. It is shown clearly that the optimum failure rate (hence the design return period) is significantly influenced by the duration of the line repair (hence the line security) after a line has failed. The line should be designed for a higher return period if the expected duration of repair is long. The sensitivity analysis shows that the optimum return period is strongly dependent on the repair rate and is less influenced by the unit cost of unsupplied energy.**

1.0 INTRODUCTION

In overhead line design, the reliability is provided by assigning a fixed return period to the extreme climatic loading events such as wind, ice and combined wind and ice. This implies some expected failure rate during the service life of a line. On the other hand, the security of a line is deterministic and is provided in two ways (1) designing structures for adequate longitudinal capacity and (2) inserting a number of containment structures (anti-cascading towers) at a fixed interval

In the power network, the reliability includes system adequacy (sufficient generation to meet the load demand) and system security implying that the system is able to respond to transient disturbances (faults or unscheduled removal of components). This is contrary to the structural design of overhead lines where both reliability and security are treated separately.

2.0 METHODOLOGY

A methodology is developed based on a probabilistic system model where various system state contingencies are evaluated under extreme icing events and the corresponding impacts assessed in terms of a cost-risk model. The cost-risk model explicitly integrates the line reliability and security in optimizing the total line cost. It is well known that two lines

designed with same reliability level can have very different availabilities should the failure modes and the extent of the failure zones be different. Haldar et al (2007, 2010) have used finite element models to estimate the extent of the cascade zone of overhead lines.

3.0 RESULTS AND DISSCUSSIONS

Based on a parallel line configuration it is shown clearly that the optimum design return period is significantly influenced by the duration of the line repair once it has failed. For an expected long duration of line repair (lower line security), the line should be designed for a higher return period. Figure 1 presents the result for a base case where the repair rate is 365 occurrences per year (one day repair duration) and the unit cost of energy is $20/kWhr. The sensitivity analysis shows that optimum failure rate is less sensitive to the unit cost of energy compared to the repair rate.
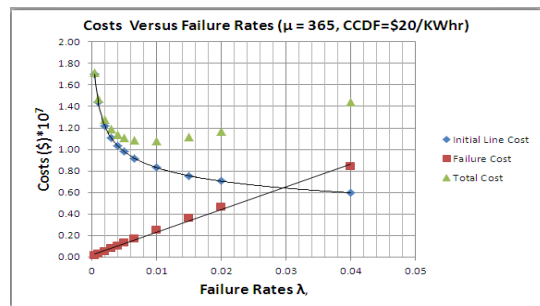

Figure 1- Costs versus Line Failure Rates

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I. NOMENCLATURE

Reliability, Availability, Security, Overhead Lines, Icing Events,

II. INTRODUCTION

In overhead line design, the reliability is provided by assigning a fixed return period to the extreme climatic loading events such as wind, ice and combined wind and ice. This implies some expected failure rate during the service life of a line. On the other hand, the security of a line is provided in two ways (1) designing structures for adequate longitudinal capacity and (2) inserting a number of containment structures (anti-cascading towers) at a fixed interval (e.g. normally every 20 to 25 structures). The containment structures are designed for unbalanced residual static loads (RSL) due to (1) ice shedding and (2) the loss of a phase conductor (with or without ice) or the loss of a critical hardware at suspension or "dead end" locations.

Considering a line being a part of the complex power network, the most common deterministic security criterion used in bulk electric power system (BEPS) planning is the N-1 criterion where there should be no outage if there is loss of a single BEPS component (such as a generating unit or a transmission line). Some utilities also use N-2 criterion or N-1-1 criterion where it is assumed that the system should be able to withstand the simultaneous loss of two components (N-2) or the forced outage of a single component in conjunction with scheduled maintenance of another component (N-1-1).

In the power network, the reliability includes system adequacy (sufficient generation to meet the load demand) and system security implying that the system is able to respond to transient disturbances (faults or unscheduled removal of components). This is contrary to the structural design of overhead lines where both reliability and security are treated separately.

III. SCOPE

The purpose of this paper is to present a systematic methodology to determine the optimum failure rate (design return period) of an overhead line by balancing the reliability based initial line cost against the present value of the future failure costs**.** The failure cost depends on the extent of the line damage (severity) and therefore, the security level provided in the line design.
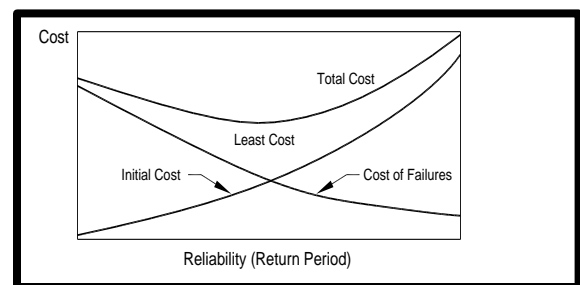.

Figure 1: Typical Optimization Problem

Figure 1 depicts the graphical representation of the two costs. The initial line cost will increase as the reliability increases while the future failure cost will decrease with increasing line reliability. It is expected that an optimum reliability can be found by balancing these two costs. A methodology is developed based on a probabilistic system model where various system state contingencies are evaluated and its impact assessed in terms of a cost-risk model. Figure 1 also shows the point where the total cost is at minimum. An example problem is illustrated to show the application of the methodology in determining the optimum design return period of a new line to extreme icing events.

IV. DEFINITIONS

Mechanical System

Reliability: Reliability of a line is defined as the probability that the line will perform its required function under specified conditions for a specified period of time, normally defined as the service life.

Security: Security is often referred as the line's ability to withstand a catastrophic loss particularly a cascade failure. One way to mitigate this failure, at present, is to design suspension structures for adequate residual static longitudinal load, (RSL) as well as to insert anti-cascading towers ("stop towers") at certain intervals (normally every 20 to 25 towers).

Power System

The primary function of an electric power system is to supply electrical energy to its customer economically with an adequate degree of reliability and service continuity. Billinton and Allan (2007) describe the system reliability in terms of system adequacy and system security. Figure 2 presents this in graphical form.
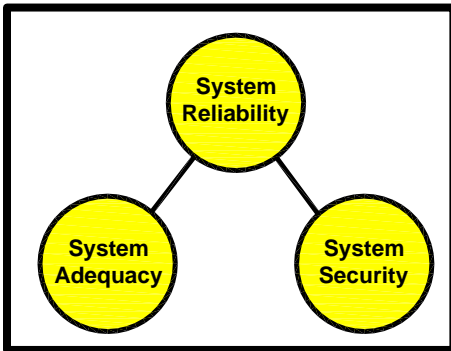

Figure 2: System Reliability (Billinton and Allan, 1996)

System Adequacy refers to the system capacity to respond to its customer requirements (load demand) taking into account line constraints (voltage and thermal limits) as well as component outages.

System Security refers to the ability of the system to respond against transient disturbances (faults or unscheduled removal of components).

The system adequacy is linked to "long term" planning criteria (steady state) while security relates to "short term" disturbances on the system (dynamic situation).

Basically in line design, the security criterion is deterministic and treated separately from the reliability criterion which is often probabilistic. However, it is the author's opinion that the structural design of a continuously operated system (such as a power line), should link the reliability and security through an **availability** model which can provide the probability of the line component (as part of a power network) in the operating state at some points in the future.

Availability of a repairable system (such as a transmission line) is a function of both failure and repair rates which are directly related to the design return period of the climatic loads and the duration of the repair respectively (hours, days etc. after a failure). The availability issue is normally left to the system planner to ensure that N-1 criterion or similar criterion is satisfied for the power system. However by not linking these two parameters (reliability and security) in line design quantitatively, the current method of determining the design return period may not be an optimum one.

It is well known that two lines designed with same reliability level can have very different availabilities should the failure modes and the extent of the failure zones be different. Haldar et al (2007, 2009, and 2010) have used finite element models to estimate the extent of the cascade zone of overhead lines. The model included multiple tower failures. The purpose was to estimate the cascade failure zone and the expected number of tower losses to link the number of tower failures to repair time. Although the numerical model for cascade requires some improvement, the current study will further explore the extent of the line damage and its effect on the repair rate and line availability.

V. METHODOLOGY

It is well known that the overestimation of the design wind and ice loads will significantly affect the initial cost of a line, while the underestimation of these loads would certainly impose a significant "future" failure costs. The future failure costs under extreme ice loads include the expected replacement cost (ERC) of the failed section of the line and the cost of expected energy not supplied (ECOST). The cost due to electrical losses in the conductor is not included.

The expected energy not supplied (EENS) is determined through a probabilistic model which considers the unavailability of the line based on the line failure rate (hence the return period) and the line repair rate (hence the security) explicitly under an extreme icing event. The security based design links the extent of the failure zone (number of towers failed) to the repair duration (hours, days etc.) This concept will be discussed further at the end of this section.

Simple Cost Equation

A methodology is developed based on a probabilistic system model where various system state contingencies are evaluated and the corresponding impacts assessed in terms of a cost-risk model. The mathematical expression is presented below

$$C_T = C_I + \text{PV (Future failure cost)} \qquad [1]$$

where

C_T = total line cost based on a specific design return period, T and the present value of the future failure cost;

C_I = initial cost which is a function of the line failure rate, λ , and the corresponding design return period of the climatological loading parameters such as wind, ice etc.

PV (future failure cost) = present value of future failure costs including repair/upgrade costs and the cost of unsupplied energy after a failure event.

Line cost model

The line cost model includes the costs of materials and construction. Based on historical information, the line cost model for various design ice thicknesses is first developed. Later, these ice thicknesses can be related to the design return periods using a Gumbel distribution. The failure rate, λ is directly related to the return period, T.   The higher the failure rate, the lower the line cost. Figure 3 presents a typical plot for the initial cost versus line failure rates.
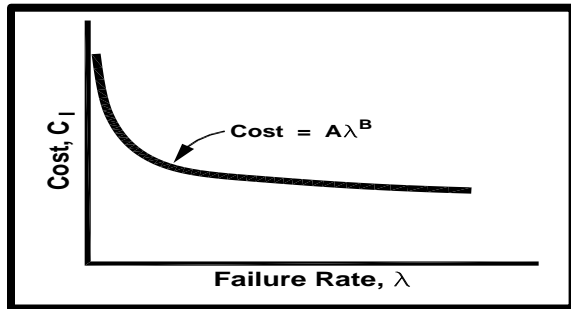

Figure 3: Initial line cost versus failure rate

The above relationship can be expressed in terms of a power law

$$C_I = A\, \lambda^B \tag{2}$$

where A and B are the two constants obtained from a regression analysis and λ is the failure rate (occurrences per year),

ECOST Model

The present value of the future failure cost in equation [1] has two components; (1) the expected replacement cost of the line (**ERC**) and (2) the expected cost of energy not supplied after a failure (**ECOST**).

Future failure cost = ERC+ ECOST $\tag{3}$

where

$$\text{ERC}, C_f\ = P_f\, C_R, \tag{4}$$

C_f= expected failure cost of the line which primarily includes the replacement cost of the line section, C_R that failed during

an extreme icing event. This cost can be estimated reasonably based on the past failure data. P_f = annual probability of failure

$$\text{ECOST} = \text{EENS} * \text{CCDF} \tag{5}$$

Primarily, this ECOST can vary widely depending on the consequence of the failure on the system, customer distributions and hence, the composite customer damage function (CCDF) normally expressed in \$/kWh (Billinton and Allan, 1996). EENS will also be dependent on the system peak load as well as the system state during a failure event.

Figure 4 depicts a one component repairable system. For this system, it has two states. The availability and the unavailability are computed as
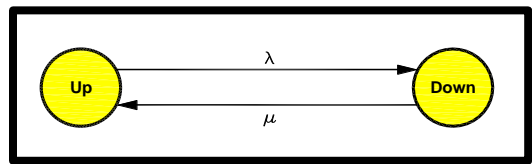

Figure 4: A Simple Two State Markov Diagram

$$\text{Availability} = \frac{\mu}{\lambda + \mu} \tag{6}$$

$$\text{Unavailability} = \frac{\lambda}{\lambda + \mu} \tag{7}$$

where μ= repair rate (repair occurrences per year)

For a two components repairable system such as a parallel configuration, the system unavailability for both components down is obtained in equation (8)
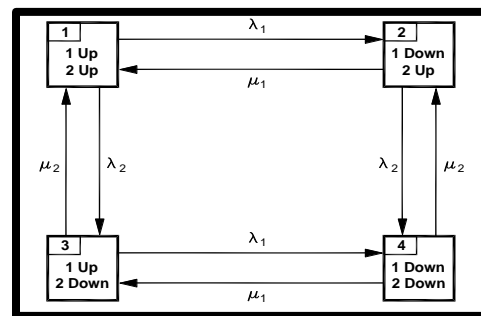

Figure 5: Markov Diagram for a Parallel Configuration (Billinton amd Allan, 1996)

$$\text{Unavailability} \ = \frac{\lambda_1 \lambda_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{8}$$

λ_1= failure rate of line 1

λ_2= failure rate of line 2

μ_1= repair rate of line 1

μ_2= repair rate of line 2

The above state probabilities are calculated based on a "Markov Model". The model can be applied to a system of two parallel lines transporting power from a generating plant to the load center (Figure 6).
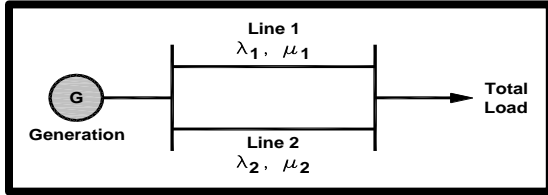

Figure 6: Two parallel line configuration

Assuming that the system components have identical failure and repair rates, the system up state and the down state are given

$$\text{Up State} = \frac{\mu}{(\lambda+\mu)^2} \qquad [9]$$

$$\text{Down State} = \frac{2\lambda\mu+\lambda^2}{(\lambda+\mu)^2} \qquad [10]$$

The expected energy not supplied (EENS) is computed based on an annual peak load of P (MW) with a load factor of α

$$\text{EENS} = [\frac{\lambda\mu+\lambda^2}{(\lambda+\mu)^2}] \, (\alpha \, P) \, 8760 \quad (MWhr) \qquad [11]$$

Therefore, the cost of unsupplied energy is

$$\text{ECOST} = \text{EENS} * \text{CCDF}$$
$$= [\frac{\lambda\mu+\lambda^2}{(\lambda+\mu)^2}] \, (\alpha \, P) \, 8760 \quad MWhr \quad CCDF \, (\frac{\$}{KWhr}) \qquad [12]$$

The present value of the sum of the two failure costs presented in equation [4] and in equation [12] can be estimated over a service life of n years with a discount rate of r, For a fixed discount rate and a service life, a constant factor can be used for the present value term and the failure cost can be multiplied by this factor to estimate the present value of the future failure cost. This failure cost should be added to the initial line cost to obtain the total cost in equation (1) and shown in Figure 1. C_T in equation (1) is a function of the line failure rate, λ, the repair rate, μ, the direct cost of failure, C_f, the unit cost of energy not supplied (CCDF) and the expected energy not supplied (EENS).The optimum failure rate, λ is determined by setting the derivative of $\frac{dC_T}{d\lambda}$ =0 in equation (1) for fixed values of μ, CCDF, present value factor and C_f.

The solution of the optimum failure rate, λ at a minimum total cost is done in two steps. In the first step, the total cost,

initial cost and the present value of the future failure cost in equation (1) are plotted for various failure rates for fixed values of μ, CCDF, present value factor and C_f. The approximate zone for the optimum failure rate, λ is determined from this graph where the total cost is at near minimum. In the next step, the optimization of the equation (1) is done numerically using a Newton-Raphson technique where an iterative scheme is used to determine the more precise solution. Finally, a check is made with the graphical solution to ensure that the final result is meaningful.

Effect of Repair Rate (μ) and its linkage to failure severity

The advantage of using this system concept is that one can model the frequency and severity of the line failure through two parameters only, λ and μ respectively. For example, if the tower has a simple bridge failure due to ice overloading (Figure 7), it is reasonable to assume that the line can be repaired quickly (say less than a day). This could be classified as low level failure severity and μ will reflect this condition. On the other hand, if there is a moderate to severe cascade failure where several towers are lost, then the number of days required to repair the line could be significant (say 3-5 days) and μ could be adjusted accordingly to assess the impact of the failure severity (hence the line security) on the system. A 3 day repair time implies a repair rate, λ would be 122.0 occurrences per year

Figure 7: Bridge Failure at the top of Hawke Hill (Haldar, 2007)

Typical line design only considers a fixed design return period. To the best of author's knowledge, this is the first time a system model is developed for line design to integrate the simultaneous effects of the line failure rate (return period for reliability) and repair rate (outage duration for security) explicitly. The model is used to study the effects of these parameters on the total line cost and availability.

VI. EXAMPLE PROBLEM

Let us assume that we want to connect a generating plant with two parallel transmission lines to a substation (Figure 6) and the peak load demand is P (MW) with a load factor of α. It is also assumed that these lines will be designed to have identical failure and repair rates under extreme icing events. The problem is to determine the optimum return period to which the line should be designed considering explicitly the reliability and security of the lines. The baseline parameters

are μ =365 occurrences per year (1 day repair duration) and CCDF =$20/kWhr. Figure 8 presents the cost versus failure rate plot for the baseline parameters.
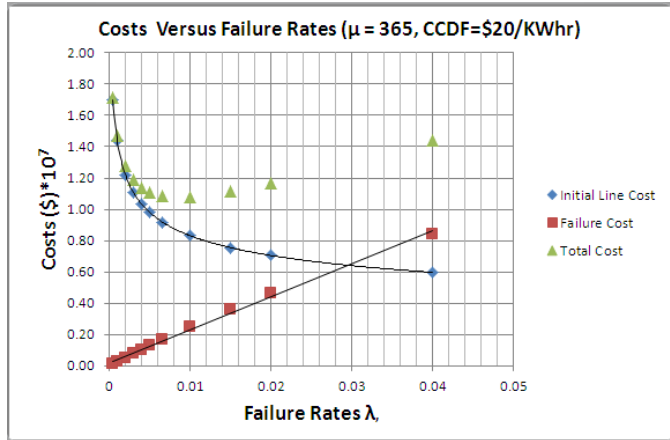

Figure 8: Costs versus Failure Rates (Base line Case)

In the next step, the optimization of the equation (1) is done numerically where an iterative approach is used to determine the more precise solution for the minimum total cost and the associated failure rate, λ. For the baseline case, the optimum failure rate is 0.00113 occurrences per year. Therefore the lines should be designed for a return period of 88 year. A sensitivity analysis is carried out using the data for the two parameters (1) repair rate, μ and (2) CCDF

Table 1: Sensitivity of optimum failure rate with repair Rate

μ (occurrences per year)	λ (occurrences per year)	Return Period (year)
730	0.0199	50
365	**0.0113**	**88**
122	0.0047	212
52	0.0024	416

Table 2: Sensitivity of optimum failure rate with CCDF

CCDF ($/kWhr)	λ (occurrences per year)	Return Period (year)
10	0.02	50
20	**0.0113**	**88**
30	0.0082	122
40	0.0065	153

Table 1 presents the variations of optimum failure rate with respect to the line repair rate. CCDF is kept constant. The line should be designed for higher return periods if the repair rate has a lower value implying that the line will be out of service longer. Table 2 presents the optimum failure rate with respect to unit cost of CCDF. In this case, μ is kept constant. As the unit cost increases, the failure rate decreases indicating that the line to be designed for a higher return period.

VII. SUMMARY

The paper provided a basis for computing the optimum return period of an overhead line considering the initial line cost and the cost of losses due to line failures. The failure cost consists of two components; (1) expected cost of the line replacement and (2) the cost of expected energy not supplied. A mathematical model is developed for a parallel line configuration and it is shown clearly that the optimum design return period is significantly influenced by the duration of the line repair once it has failed. For an expected long duration of line repair (lower line security), the line should be designed for a higher return period to ensure that the total cost is minimized.

Duration of a repair can be directly related to the extent of the failure zone and therefore, can be linked to the number of tower failures. A good numerical model can provide the estimated cascade zone under various load conditions and this can be linked to the possible repair rates using the information form a utility's historical database. The sensitivity analysis shows that optimum failure rate is less sensitive to the unit cost of energy compared to the repair rate.

VIII. REFERENCES

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