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Reliability Model for a Distribution System Incorporating Snowfall as a Severe Weather Event

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Abstract—Distribution system reliability assessment is essential to ensure reliable power supply to customers by predicting the availability of power supply and taking regulatory actions that the situation demands. Reliability assessment demands thorough study of failure rate nature. In the past, studies have been made on climate based failures due to wind and lightning, but snowfall event which is the growing reason behind power failures today, remains untouched. This paper analyses distribution system's reliability degradation due to snowfall event. A model is derived to find the failure rate due to heavy snowfall and then due to some major severe weather events considered together. A mathematical relation between the power failure rate and the snowfall rate is analytically estimated confirming to measured data. The reliability assessment of an existing power system has been done on a seasonal basis.

Keywords—failure rate; reliability assessment; snowfall event; weather modelling.

I. INTRODUCTION

The reliability assessment of an electrical distribution system is important because the reliability indices give a measure of its performance. The failure rates of transmission and distribution lines are highly enhanced in severe weather conditions. Adverse weather conditions such as snow, lightning, high wind, gales, frost, icing etc. can significantly increase the likelihood of multiple overlapping outages, known as failure bunching [1-5]. The most important factor for determining reliability is the study of number of power interruptions or outages. More than 3/4 of the outages are either equipment failure or weather-related failure. The outages caused by equipment failure tend to be shorter, while weather-related ones tend to be longer [6].

Weather caused failures are not uniformly distributed over the year due to unpredictable nature of severe weather conditions. Hence, the failure rate is considered time-variant [7]. The study is focused on distribution system because, majority of reliability problems arise from distribution systems [8]. Historical data indicate that most power outages are caused by external contact faults, which mainly occur in overhead lines [9-11], due to permanent exposure to environmental factors. Heavy ice-loading due to prolonged snowfall adversely affects power supply consistency.

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II. RELIABILITY MODEL FORMULATION

There are two major weather phenomena responsible for power failure:

1. Snowstorm (wind and snowfall)
2. Thunderstorm (wind and lightning)

A line is subject to failure due to mechanical breakage if the pressure on the line due to snow loading exceeds the critical weight of snow that the line can withstand.

A. Modelling of Time-varying Failure rate during snowfall event

Let time $t = 0$, be defined as the time when the snow load on the overhead transmission line is zero. Let us denote the contributing factors as:

- $f(t)$ - Snowfall rate
- $w_i(t)$ - Snow load on overhead line
- w_{cr} - Critical snow load on overhead transmission line
- $\lambda_{snow}(t)$ - Failure rate during snowfall at any instant t
- λ_{f0} - Failure rate during snowfall at instant $t=0$ i.e. when $w_i(t) = 0$
- λ_{f1} - Failure rate during snowfall at instant $t=t_1$ such that $0 < w_i(t_1) < w_{cr}$, i.e. $(\lambda_{f1} = \lambda_{snow}(t_1))$
- λ_s - A constant failure rate such that $\lambda_s > \lambda_{f1} > \lambda_{f0}$

We get the failure rate due to snowfall event as:

$$\lambda_{snow}(t) = \lambda_{snow}(w_i(t), f(t))$$

$$= \begin{cases} 0, & w_i(t) = 0, f(t) = 0 \\ \lambda_{f0}, & w_i(t) = 0, f(t) > 0 \\ 0, & 0 < w_i(t) < w_{cr}, f(t) = 0 \\ \lambda_{f1}, & 0 < w_i(t) < w_{cr}, f(t) > 0 \\ \lambda_s, & w_i(t) > w_{cr}, f(t) = 0 \\ \lambda_s, & w_i(t) > w_{cr}, f(t) > 0 \end{cases} \quad (1)$$

The probability of occurrence of failure,
P (failure occurrence)

$$= \begin{cases} 0, & w_i(t) = 0, f(t) = 0; \text{ or } \\ & 0 < w_i(t) < w_{cr}, f(t) = 0 \\ 1, & w_i(t) > w_{cr}, f(t) = 0; \text{ or } \\ & w_i(t) > w_{cr}, f(t) > 0 \\ k, & w_i(t) = 0, f(t) > 0 \\ m, & 0 < w_i(t) < w_{cr}, f(t) > 0 \\ & 0 < k, m < 1 \end{cases} \quad (2)$$

Here, w_{cr} is independent of time, but varies from conductor to conductor used in the overhead transmission line. A line with

conductor of greater mechanical strength will have a higher value of w_{cr} and vice-versa. Thus w_{cr} is a characteristic parameter of a certain conductor, with a constant value.

B. Modelling of Time-varying failure rate during multiple weather events

If we consider lightning, wind, snow load and snowfall events, then we get an estimate stochastic model as follows: Let the events A, B, C, D, F, G be defined as:

Lightning	A: $N_g(t) > 0$
High wind	B: $w(t) \geq w_{crit}$
Heavy snowfall	C: $w_i(t) \geq w_{cr}$
No thunderstorm	G: $(N_g(t) = 0) \cap (w(t) < w_{crit})$
No snowstorm	F: $(w(t) < w_{crit}) \cap (w_i(t) < w_{cr})$
Normal weather	D: $(w(t) < w_{crit}) \cap (w_i(t) < w_{cr}) \cap (N_g(t) = 0)$

where,

$N_g(t)$	-ground flash density
$w(t)$	-wind speed
w_{crit}	-critical wind speed

With zero lightning flash and wind with speed less than the critical, G implies the absence of thunderstorm. In a snowstorm, heavy snowfall is accompanied by high winds; hence F denotes its absence. A normal weather is defined by zero lightning flash, with the wind speed and snowfall rate below their respective critical; hence the event D. $\bar{G}$ and $\bar{F}$ denote thunderstorm and snowstorm respectively.

$$\begin{aligned} \text{Let, } E(\lambda_{lightning}(N_g(t))) &= a \\ E(\lambda_{wind}(w(t))) &= b \\ E(\lambda_{snow}(w_i(t), f(t))) &= c \\ E(\lambda_{norm}) &= \lambda_{norm} = d \\ E(G) &= g \\ E(F) &= f \end{aligned}$$

where, λ_{norm} = Failure rate under normal weather conditions

Then the expected value of failure rate considering effects of wind and snow is modeled as

$$\begin{aligned} E(\lambda(w(t), w_i(t))) &= P(B \cap C^*).b + P(B \cap C).(b + c) + \\ &\quad P(B^* \cap C^*).f + P(B^* \cap C).c \\ &= P(B).b + P(C).c + P(F).f \end{aligned} \quad (3)$$

The result obtained in (3) implies that all the factors-high wind, heavy snowfall, and normal weather conditions can be considered separately. In other words, the failure rate due to multiple factors can be taken as the summation of the failure rates due to each of the individual factors including the constant failure rate during which all the factors are absent. The result (3) is similar to that found in [7]. Therefore, we have,

$$\lambda(w(t), w_i(t)) = \lambda_{wind}(w(t)) + \lambda_{snow}(w_i(t), f(t)) + \lambda_{norm}, \quad (4)$$

which gives the failure rate during a snowstorm event. In (4), it is assumed that λ_{norm} is equal to the failure rate in absence of snowstorm, that is, the absence of snowstorm is considered normal weather condition, irrespective of the presence of lightning. Similarly, the expected value of failure rate considering wind and lightning events is modeled as

$$\begin{aligned} E(\lambda(w(t), N_g(t))) &= P(A \cap B^*).a + P(A^* \cap B).b + \\ &\quad P(A \cap B).(a + b) + P(A^* \cap B^*).g \\ &= P(A).a + P(B).b + P(G).g \end{aligned} \quad (5)$$

$$\lambda(w(t), N_g(t)) = \lambda_{wind}(w(t)) + \lambda_{lightning}(N_g(t)) + \lambda_{norm} \quad (6)$$

The expression (6) gives the failure rate during a thunderstorm. The expressions for failure rates $\lambda_{wind}(w(t))$ and $\lambda_{lightning}(N_g(t))$ are given in [7].

Practically, the normal weather condition is defined by the intersection of the absence of snowstorm and thunderstorm.

$$\begin{aligned} \text{This is shown as, } D &= F \cap G \\ &= \lambda_{norm} \\ &= (B^* \cap C^*) \cap (A^* \cap B^*) \\ &= (A^* \cap B^* \cap C^*) \end{aligned} \quad (7)$$

The expected value of failure rate considering all three events- wind, lightning and snowfall, is modeled as:

$$\begin{aligned} E(\lambda(w(t), w_i(t), N_g(t))) &= \\ &P(A \cap B^* \cap C^*).a + P(A^* \cap B \cap C^*).b + P(A^* \cap B^* \cap C).c + P(A \cap B \cap C^*).a + P(A \cap B \cap C).b + P(A^* \cap B \cap C).b + P(A^* \cap B \cap C).c + P(A^* \cap B^* \cap C^*).d \\ &= P(A).a + P(B).b + P(C).c + P(D).d \end{aligned} \quad (8)$$

and, the failure rate as:

$$\begin{aligned} \lambda(w(t), w_i(t), N_g(t)) &= \lambda_{wind}(w(t)) + \lambda_{snow}(w_i(t), f(t)) \\ &\quad + \lambda_{lightning}(N_g(t)) + \lambda_{norm} \end{aligned} \quad (9)$$

III. MODEL ESTIMATION THROUGH REAL DATA ANALYSIS

In this section, the failure and weather statistics of the 21 most populated states of USA have been extracted and plotted to find a relationship between failure rate and snowfall rate. Since, we are concerned about failure due to snowfall event alone, we have considered only the winter months with substantial amount of snowfall, as observed in U.S.A.

A. Failure and Weather statistics

Outage and snowfall data for the winter months (January 2007 to April 2009) were extracted for the 21 most populated

cities of U.S.A. with heavy snowfall. The outage graph of U.S.A for the above 16 months was obtained from [12]. Data selected were irrespective of the cause of outage. This graph, of the number of outages versus month, was utilized to calculate the hourly failure rates for each month using the relation:

$$\text{Failure rate, } \lambda = \frac{\text{number of outages in the month}}{(\text{number of days in the month} \times 24)} \quad (10)$$

The calculated failure rates are given in Table I. Snowfall rate data were extracted from the National Climatic Data Centre (NCDC), under NOAA (National Oceanic and Atmospheric Administration) Satellite and Information Service [13]. The selection of the 21 most populated towns of USA with heavy snowfall is based on the research results given in [14] and [15].

B. Estimation by Curve-Fitting Method

The response of the failure rates to the increasing snowfall rates has been analyzed by curve-fitting method in MATLAB. The power and linear modeling approaches were estimated and the results are shown in Fig. 1 and Fig. 2 respectively. Estimated power model parameters are given in Table II, and the goodness of fit of the model approaches are given in Table III. The SSE (Sum of Squared Errors), RMSE (Root Mean Square Error) and R-square values are listed in Table III.

On comparing Fig. 1 and Fig. 2, it is seen that Fig.1, i.e., the power model approach gives a better fit to the data than the linear model approach. This is confirmed by the R-square values in Table III, where the power model has a higher R-square value. The lesser the SSE, or the more the R-square value, the better is the fitting of the data to the curve. The failure rate during normal weather conditions was determined by dividing the number of failures occurring during normal weather by the duration of normal weather. The compliance with power model shows that the failure rate increases with increasing snowfall according to the following relation:

$$\lambda_{\text{snow}}(t) = \gamma f(t)^{\beta} \cdot \lambda_{\text{norm}} \quad (11)$$

where, γ and β are model parameters whose estimated values are given in Table II. The data-log in Table I has been plotted against snowfall rate data in Fig.1 and Fig.2 for power model and linear model approach respectively.

IV. DISTRIBUTION SYSTEM RELIABILITY ASSESSMENT

The behavior of reliability indices with respect to seasonal changes is analyzed. The two main seasons- summer and winter, are considered for reliability assessment. For summer, data for May, June, July and August are observed, while for winter, data for January, February, March, April, November and December are used. The indices have been calculated analytically using the IEEE standard expressions [16] below:

$$\text{SAIDI} = \frac{\sum (r_i \times N_i)}{\sum N_i}$$

$$\begin{aligned} \text{ASAI} &= \left[1 - \left\{ \frac{\sum (r_i \times N_i)}{N_t \times T} \right\} \right] \times 100 = 1 - \frac{\text{SAIDI}}{T} \\ \text{ASUI} &= 1 - \text{ASAI} = \frac{\text{SAIDI}}{T} \\ \text{CAIFI} &= \frac{\sum N_0}{\sum N_i} \\ \text{CIII} &= \frac{\sum N_i}{\sum N_0} = \frac{1}{\text{CAIFI}} \end{aligned} \quad (12)$$

where, N_i = Total number of customers interrupted
 r_i = Restoration time
 N_t = Total number of customers served
 T = Time period under study
 N_0 = Number of interruptions

The reliability indices are normally calculated on either monthly or yearly basis; however, it can also be calculated daily, or for any other time period. In this paper, they are calculated season-wise. The chosen place of study here is Central U.S.A. region [17] which includes a total of 20 states. Outage data of summer and winter seasons of 2008 have been used from [12]. Table IV shows the reliability assessment results, which have been obtained analytically using the expressions in (12).

TABLE I
FAILURE RATES (OUTAGES PER HOUR) FOR THE WINTER MONTHS FROM JANUARY 2007 TO APRIL 2009

Month	2007	2008	2009
January	0.4368	0.5241	0.5040
February	0.8270	0.7183	0.6696
March	0.6720	0.7500	0.3965
April	0.5902	0.4444	0.4652
November	0.6000	0.5500	-
December	0.8782	0.7000	-

Fig. 1. Failure rate (outages/ hour) as a function of snowfall rate (inches/hour). Power model fit with real data.

Fig. 2. Failure rate (outages/ hour) as a function of snowfall rate (inches/hour).Linear model fit with real data.

TABLE II

ESTIMATED PARAMETERS FOR THE DISTRIBUTIONS FITTED TO WEATHER INTENSITIES

Parameter	Estimated Value
β	0.3219
γ	4.4438
λ_{norm}	0.057

TABLE III

GOODNESS OF FIT RESULTS

Model	SSE	R-Square	RMSE
Power	0.01436	0.9042	0.03994
Linear	0.02345	0.8436	0.05105

TABLE IV

RELIABILITY INDICES FOR WINTER-SUMMER 2008

Reliability indices	Summer	Winter
SAIDI	1.4546	1.8994
CAIFI	2.466×10^{-3}	1.166×10^{-3}
ASAI	0.9995	0.9996
ASUI	4.97×10^{-4}	4.348×10^{-4}
CIII	405.55	857.36

V. CONCLUSION

Heavy ice-loading due to prolonged snowfall can lead to mechanical failure of overhead lines, eventually leading to power interruption. This paper analyzed the effect of heavy snowfall on the reliability of an electrical distribution system. A probabilistic model of the failure rate in terms of the major weather events as wind, lightning and snowfall is presented. Reliability assessment of an existing power system is done on a seasonal basis to make a comparison between the system performance during winter and summer. Weather and failure statistics have been used to approximate a relation between power failure rate and snowfall rate. It is seen that failure rate increases with increasing snowfall rate. In other words, heavy snowfall degrades system reliability. It is expected that the results will be helpful for the utilities to predict the system reliability from weather forecasts.

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