Characterization of Icing Events Based on Statistical Analysis of Field Data

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Abstract – **During the last decade considerable efforts have been made by engineers and researchers in the development, improvement, and validation of models for atmospheric-icing. At CIGELE, the artificial neural-network technique and the statistical (probabilistic) approach are used to develop icing models for forecasting or estimating in real-time precipitation- and in-cloud-icing accumulation on energized transmission line conductors. The models aim at establishing correlation between hourly ice-accumulation rates observed and simultaneously recorded values of the number of Icing Rate Meter signals, ambient temperature, wind speed and direction, and precipitation rate.**

The purpose of this paper is the analysis and characterization of field data for ice events observed in Quebec. The reliability of the available time series, functioning and possibilities of break-downs of the principal instrumentation, establishing limits and criteria for the different phases of icing, are also considered. The results obtained allowed for improving the modeling of ice events over their entire duration, including ice shedding.

I. INTRODUCTION

ATMOSPHERIC icing and its impact on transmission-line equipment is a very complex random phenomenon whose reliable forecasting can be made only by statistical approach and probabilistic modeling, as recommended by the IEC [1]. The creation, training, and validation of models such as artificial neural networks or multiple-variable regression require assessing correlations between atmospheric-icing accumulation and natural-site measurements of pertinent meteorological variables.

In Quebec, an ice-monitoring system, comprising several test sites in the St. Lawrence valley and other areas exposed to icing, has been implemented and instrumented with Icing Rate Meters (IRM). In some stations, such as the Mont Bélair icing-test site, load cells are installed for direct evaluation in real time of the weight of ice accumulated on conductors ([5] and [6]). The calibration, functioning, and interpretation of readings of the principal measurement instruments, IRM and load cell, were the subject of a considerable research work and numerous publications, a few of which are listed below ([2], [5]-[7]).

Recently, a promising application of an artificial neural-network technique has been used for modeling the accumulation phase of in-cloud-icing events [3], or the complete icing process – accumulation, persistence, and ice shedding for precipitation-icing events [5]. The total ice-accumulation, and entire duration between the beginning and complete disappearance of the ice build-up, are used as criteria to evaluate the accuracy of the simulations. Functioning, training, and validating these models necessitate the processing of a considerable quantity of field statistical data. Presently, in Quebec, such data is available from the Hydro-Quebec monitoring and warning system, SYGIVRE. In particular, at the Mont Bélair icing test site, load-cell readings are used for estimating the hourly icing accumulation rate on the phase conductors of a 315 kV transmission line.

Unfortunately, the needed correlations are difficult to establish and have a small statistical significance due, in general, to the following reasons:

- Relatively short period of observation of ice (5 – 15 years) as compared with wind or temperature (50 – 100 years);
- Rarity of icing-event occurrence.
- Great variance of the hourly icing rate, quantity, type, and density of the ice build-up observed. This point may be illustrated with Fig. 1, where in the interval $-3°C < T \le 0°C$, the hourly icing rate observed varies between 0.180 kg/m/h (accumulation) and –0.190 kg/m/h (shedding). There are also some small, positive (accumulation) rates during positive temperatures between 0 and 5°C. A considerable number of small, ice-shedding rates at negative temperatures are also observed. The random variability of the icing rate is so large that the smoothed curve in Fig. 1 have only illustrative purpose, and cannot be used for estimation;
- Strong (random) dependence on several meteorological factors, such as temperature (Fig. 1), wind speed and direction, precipitation rate, relative humidity of air, distribution of droplet size, and quantity of water contained in the surrounding air layer;
- Malfunctioning or breakdowns of the measuring instruments, especially in severe winter conditions with intensive freezing precipitation. Calibration of the IRM shows that its lowest limit of sensibility may deteriorate significantly in heavy precipitation conditions, as a function of the size of the supercooled water droplets and their angle of incidence, and ambient temperature slightly below the freezing point. Moreover, IRM breakdowns, attributable to complete blockage by a dense cover of glaze, may occur in heavy precipitation conditions [2].

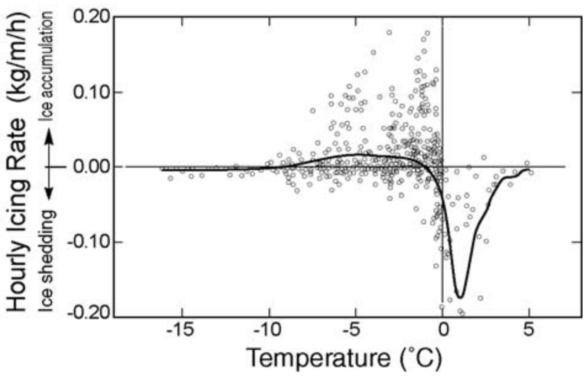

Fig. 1. Hourly icing rate A, as a function of the ambient temperature T.

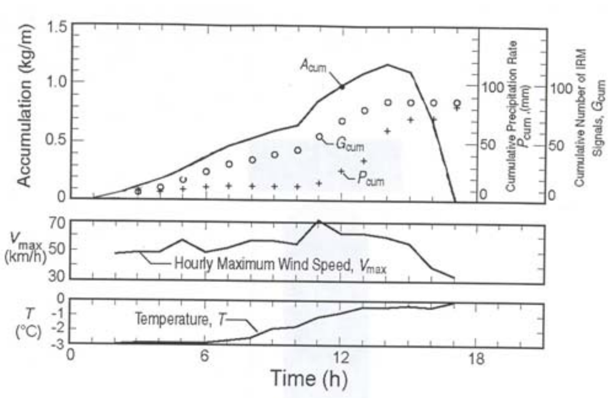

Fig. 2. Evolution in time of the March 9, 1998, precipitation-icing event at Mont Bélair.

- As shown in [6], the distribution of ice-accumulation rate is not normal; it is greatly asymmetric and nearly 90% of observations are in the interval of 0.001 to 0.01 kg/m/h.

All of the enumerated inconveniences, inherent in the available data base, contribute for deteriorating the quality of the modeling and the research of correlations between icing rate and accompanying meteorological variables [4] and [5]. Thus, it is imperative, for the needs of the modeling, to subdivide the data into distinct, homogeneous classes for obtaining statistically significant correlations.

This paper deals with analysis of data for ice events observed at natural icing-test sites in Quebec. The principal purpose of the analysis is the characterization and classification of the available icing-data records in order to facilitate and improve the modeling of icing events by the means of artificial neural-networks or multiple regression techniques [5].

II. THEORETICAL ANALYSIS

In this paper, *icing event* refers to each atmospheric-icing accumulation observed on overhead-line conductors or ground wires. The data records used in the present analysis are furnished by the Mont-Bélair icing-test station from measurements during 57 consecutive icing events (1739 h), in the 1998-2000 winter seasons. These contain the following one-hour-period input data [5]-[7]:

C = Load Cell readings (V)
A = Hourly icing rate (kg/m/h), calculated from C by computer-performed algorithm
A_{cum} = Cumulative ice accumulation (kg/m)
T = Ambient temperature (°C)
G_{cum} = Cumulative number of IRM signals
G = Hourly number of IRM signals
P = Precipitation rate (mm/h)
P_{cum} = Cumulative precipitation (mm)
V_{av} = Mean wind speed (km/h)
V_{max} = Maximum wind speed (km/h)
Z = Wind direction (degrees)

Evolution in time of the ice build-up accumulation weight, A_{cum}, of a typical icing event, which occurred on March 9, 1998, at Mont Bélair, is illustrated in Fig. 2. The accompanying simultaneous variations of wind speed, temperature, cumulative number of IRM signals, and cumulative precipitation are also shown.

Three distinct phases characterize the evolution in time of the ice build-up during an icing event, as follows:

- Accumulation. Hourly icing rate $A \geq 0.001$ kg/m/h. Normally, except in the cases of IRM malfunctioning or breakdowns discussed earlier, this phase is indicated by the emission of IRM signals ($G \geq 1$ signal/h);
- Persistence. $-0.001 < A < 0.001$ kg/m/h, without IRM signals ($G = 0$). The limits of $\pm$ 0.001 kg/m/h are chosen arbitrarily as the smallest absolute values discernible by the load cell. The optimal width of these limits is reconsidered in the next section.
- Shedding (disappearance of the ice build-up). Negative values of icing rate, $A \leq -0.001$ kg/m/h, without IRM signals ($G = 0$). For $T < -1$°C, ice shedding is mainly due to sublimation, and for $T > -1$°C – to melting or breaking.

In this paper, relating a one-hour-period ice accumulation to precipitation or in-cloud icing, is made only on the presence or absence of precipitation ($P > 0$ or $P = 0$ mm/h). Following the above classification, the icing data from Mont Bélair may be resumed as shown in TABLE I.

TABLE I
CLASSIFICATION OF 1739 h ICING DATA RECORDED AT THE MONT-BELAIR TEST SITE. THE CHOSEN LIMIT BETWEEN THE ACCUMULATION AND PERSISTENCE PHASES IS 0.001 kg/m/h.

		Precipitation Icing (P >0)	In-cloud icing (P =0)	Total:
Accumulation	Normal ($G > 0$)	188 h	229 h	417 h
	Abnormal ($G = 0$)	83 h	249 h	332 h
Persistence	Normal ($G = 0$)	26	320	346
	Abnormal ($G > 0$)	28	64	92
Shedding	Normal ($G = 0$)	78	437	515
	Abnormal ($G > 0$)	14	23	37
	Total:	417	1322	1739

In Table I, the following groups of the icing data are apparent:

1) Positive accumulation rate – $A > 0$, emission of IRM signals, $G > 0$, $T < 0$. This is the most commonly observed ice accumulation on conductors indicated by the emission of

IRM signals. In Tables I and IV, these data are denoted as *normal accumulation*.

2) Positive, accumulation rates, $A > 0$, emission of IRM signals, $G > 0$, and $T > 0$. These are very rare cases (see the three points in the first quadrant of Fig.1). They can be considered as sublimation on conductor surface colder than the ambient temperature.

3) Positive accumulation rates, $A > 0$, no emission of IRM signals, $G = 0$, and $T < 0$. These accumulations, non-indicated by IRM signals, are denoted as *abnormal* because they are difficultly distinguishable from persistence. These cases, about 31% of the accumulation data during wet conditions and 52% for dry conditions can be related, as explained earlier, to IRM malfunction or breakdowns.

4) Very small icing rates close to zero – persistence, or negative icing rates – ice-shedding, with no emission of IRM signals, $G = 0$. In the existing monitoring system SYGIVRE, a certain number of hours, depending on the type of ice, without IRM signals indicate the end of the current ice event. In Tables I and IV, these cases are denoted as *normal*.

5) Small positive or negative icing rates, indicated by emission of IRM signals, $G > 0$, are frequently observed. These periods represent local ice shedding during a period of ice accumulation [2]. They are due to mechanical breaking of the ice build-up under wind pressure, or other, unknown reasons. In Tables I and IV, these cases are denoted as *abnormal.*

A further subdivision of the ice-shedding phase into two important subgroups may be made: (i) disappearance by sublimation – for temperatures $T < -1^{o}$C, and (ii) shedding by melting or breaking – for $T > -1^{o}$C (Fig. 1). Ice shedding by sublimation has a similar effect as the ice persistence on the line reliability – the ice build-up persists almost unchanged on conductors, and represents a potential danger of large, combined wind-and-ice loadings. Fortunately, the two groups of ice shedding are easily distinguishable from each other by the ambient temperature, as mentioned above.

In general, the physical aspect of the ice build-up during an event presents a mixture of glaze, rime, or wet snow. On the other hand, as will be discussed in the next section, the icing events of *precipitation-* or *in-cloud*-icing type show some very different characteristics. For this reason, selecting homogeneous data, for training the neural-networks, or for multiple regression analysis, must be related to the type of icing event considered. In the present paper, this characterization is based on the presumption that the physical characteristics of ice are determined in the accumulation phase, and influence greatly the behavior of the ice build-up during the persistence or shedding periods. Following the prescriptions of the IEC [1], two types of icing events are considered: of precipitation- and in-cloud-icing type. *Wet snow* is not considered here for: (i) there are not data for wet snow in the time series studied because the IRM, in its present variant, does not react to precipitation of snow, and (ii) this kind of accumulation rarely affects the reliability of the overhead transmission lines.

- Icing event of *precipitation-icing* type, determined by freezing precipitation ($P > 0$) during 100-50% of hours in the accumulation phase;
- Icing event of *in-cloud-icing* type, determined by the absence of precipitation ($P = 0$) during 100-50% of hours in the accumulation phase.

The characterization of the 57 icing events observed at Mont-Bélair is made in Table II, for precipitation icing, and Table III, for in-cloud icing. The following notation is employed in these tables:

NIE = Chronological number of the ice event
A_t Total ice accumulation in kg/m
N_t Total duration of the ice event in hours
N_{ac} Duration of the accumulation phase in hours
$N_{w.ac}$ Number of hours with precipitation during the accumulation phase
$N_{dr.ac}$ Number of hours without precipitation during the accumulation phase

$$R_{w.ac} = \frac{N_{w.ac}}{N_{ac}} \times 100\% \text{ and } R_{dr.ac} = \frac{N_{dr.ac}}{N_{ac}} \times 100\%$$

The data in Tables II and III are arranged in descending order with respect to $R_{w.ac}$ or $R_{dr.ac}$. Icing event 50 (the last line in Table II) is arbitrarily classified as precipitation-icing event. It can be as well classified as in-cloud icing event, because the percentage $R_{w.ac} = R_{dr.ac} = 50\%$.

TABLE II
ICING EVENTS CLASSIFIED AS OF PRECIPITATION ICING TYPE

NIE	Date	A_t Kg/m	N_t h	N_{ac} h	$N_{w.ac}$ h	$R_{w.ac}$ %
1	12.02.98	0.103	8	4	4	100
8	26.03.98	0.017	4	1	1	100
22	21.12.98	0.185	14	4	4	100
25	18.01.99	0.396	12	7	7	100
26	23.01.99	0.538	17	11	11	100
28	02.02.99	0.142	15	3	3	100
32	28.02.99	0.382	15	8	8	100
35	22.03.99	0.021	7	1	1	100
43	19.12.99	0.360	13	7	7	100
54	09.04.00	0.080	5	3	3	100
57	24.04.00	0.147	12	8	8	100
39	26.11.99	0.468	15	10	9	90.0
53	08.04.00	0.286	18	10	9	90.0
4	24.02.98	0.049	27	13	10	76.9
7	09.03.98	1.178	16	13	10	76.9
48	09.03.00	0.085	18	4	3	75.0
13	19.11.98	0.396	15	11	8	72.7
11	10.11.98	0.632	16	9	6	66.7
12	14.11.98	0.211	31	12	8	66.7
16	30.11.98	0.768	16	10	6	60.0
19	06.12.98	0.693	21	15	9	60.0
44	02.01.00	1.239	61	25	15	60.0
33	01.03.99	0.663	61	27	16	59.3
9	31.03.98	2.083	93	39	23	59.0
15	26.11.98	0.267	85	29	17	58.6
45	11.01.00	0.047	28	11	6	54.5
50	16.03.00	0.087	17	6	3	50.0

III. RESULTS AND DISCUSSION

As shown in Table I, abnormal-accumulation data represent an important percentage, especially for in-cloud icing events – 52.1%. These abnormal data decrease considerably the quality and precision of the neural-network modeling or the fitting by multiple-regression technique. As shown in Figs 3 and 4, if the persistence limits are increased from ± 0.001 kg/m/h in such a manner that small accumulation rates are considered as persistence, the number of abnormal positive rates will decrease considerably. These cases will be considered as normal persistence. The percentage of abnormal data can be minimized if the persistence limits are chosen ±0.013 kg/m/h (Fig. 3 and 4).

TABLE III

ICING EVENTS CLASSIFIED AS OF IN-CLOUD ICING TYPE

NIE	Date	A_t Kg/m	N_t h	N_{ac} h	$N_{dr.ac}$ h	$R_{dr.ac}$ %
2	12.02.98	0.033	11	2	2	100
5	28.02.98	0.094	7	5	5	100
6	01.03.98	0.502	88	39	39	100
10	02.11.98	0.357	71	37	37	100
14	20.11.98	0.068	50	23	23	100
17	02.12.98	0.056	19	4	4	100
18	04.12.98	0.259	22	10	10	100
20	13.12.98	0.093	19	7	7	100
27	24.01.99	0.040	12	4	4	100
29	04.02.99	0.103	17	8	8	100
34	12.03.99	0.033	11	6	6	100
36	24.03.99	0.027	15	5	5	100
38	15.11.99	0.050	7	3	3	100
40	28.11.99	0.035	15	5	5	100
46	01.02.00	0.044	21	9	9	100
55	10.04.00	0.071	29	8	8	100
56	23.04.00	0.048	11	3	3	100
31	18.02.99	0.057	71	21	20	95.2
51	29.03.00	0.156	51	21	20	95.2
3	19.02.98	0.113	45	20	18	90.0
30	12.02.99	0.088	25	8	7	87.5
37	13.11.99	0.319	29	23	20	87.0
41	06.12.99	0.398	193	59	58	84.1
21	19.12.98	0.084	14	6	5	83.3
42	14.12.99	0.286	106	39	32	82.1
49	14.03.00	0.057	27	15	12	80.0
52	05.04.00	0.046	25	5	4	80.0
47	02.03.00	0.154	31	15	11	73.3
23	22.12.98	0.054	16	3	2	66.7
24	16.01.99	0.098	21	10	6	60.0

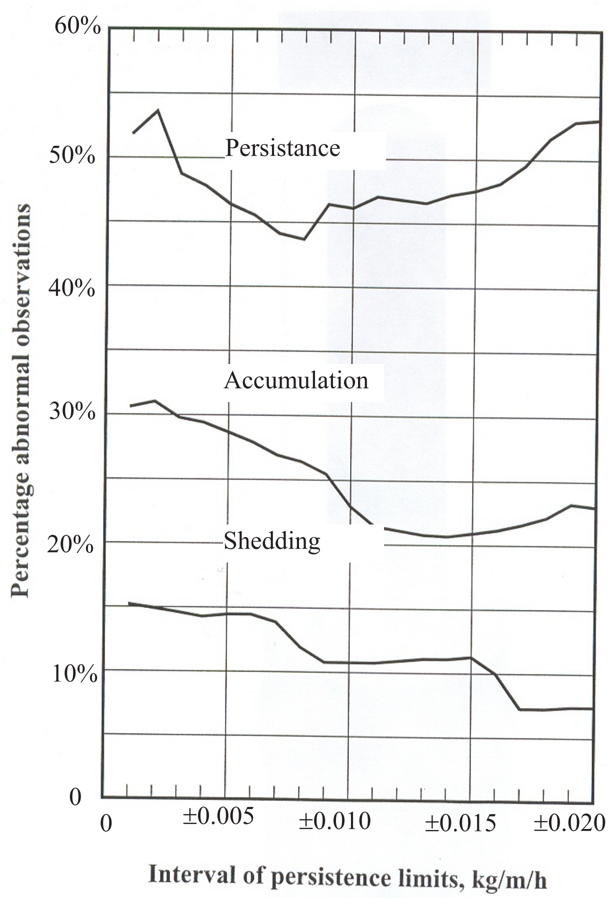

Fig. 3 Percentage of abnormal measures as a function of the chosen persistence limits for precipitation-ice events

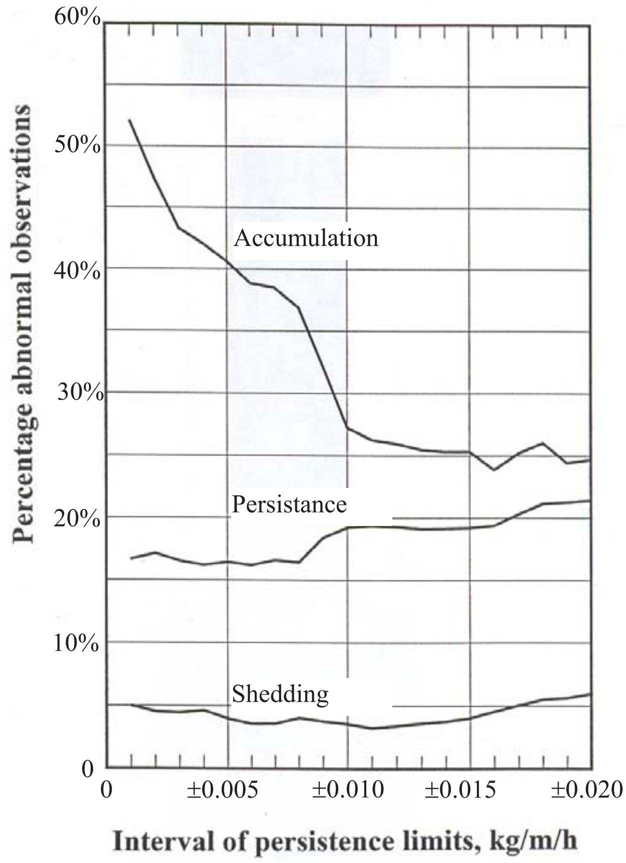

Fig. 4 Percentage of abnormal measures as a function of the chosen persistence limits for in-cloud-ice events

As shown in Fig. 1, the interval of ±0.013 kg/m/h covers also the majority of data for shedding by sublimation. As described in [5], decrease of percentage of abnormal accumulation-rate data has a positive effect on the quality of the modeling and fitting by regression. Persistence limits of ± 0.013 kg/m/h were adopted for the purposes of this work. It is of interest noting that these limits are pertinent for both precipitation- and in-cloud ice events. Further widening of the chosen limits is not effective, because it considerably decreases the quantity of data in the accumulation group (Table IV).

TABLE IV

CLASSIFICATION OF 1739 h ICING DATA. THE PERSISTENCE LIMITS ARE OF ±0.013 kg/m/h.

		Precipitation Icing (P >0)	In-cloud icing (P =0)	Total:
Accumulation	Normal ($G > 0$)	141 h	114 h	255 h
	Abnormal ($G = 0$)	37 h	39 h	76 h
Persistence	Normal ($G = 0$)	94	833	927
	Abnormal ($G > 0$)	82	197	279
Shedding	Normal ($G = 0$)	56	134	190
	Abnormal ($G > 0$)	7	5	12
	Total:	417	1322	1739

Characterization of ice events as of precipitation- and in-cloud ice type, allows to also bring out some important differences between the two classes. These concern the distributions of:

- Total ice accumulation, A_t
- Total duration of the ice events, N_t
- Percentage of accumulation period with respect to N_t

A. Distribution of Total Ice Accumulation, A_t

In a previous work [6], the authors showed that the total ice accumulation, for all 57 icing events, has an exponential distribution. As shown in Figs 5 and 6, the same is true for the icing events of precipitation- and in-cloud-icing type taken separately. This is confirmed also from the equality of the both statistics: mean and standard deviation (Table V), which is characteristic for the exponential distribution. The great difference between the means: $\overline{A}_t = 0.43 \pm 0.09$ kg/m for precipitation-icing events, and 0.127 ± 0.023 kg/m for in-cloud-icing events, is confirmed by the 2-tailed, Wilcoxon non-parametric test at 0.001- significance level. This result shows that A_t during the precipitation-icing events is, in average, 3.4 times greater than for in-cloud-icing events.

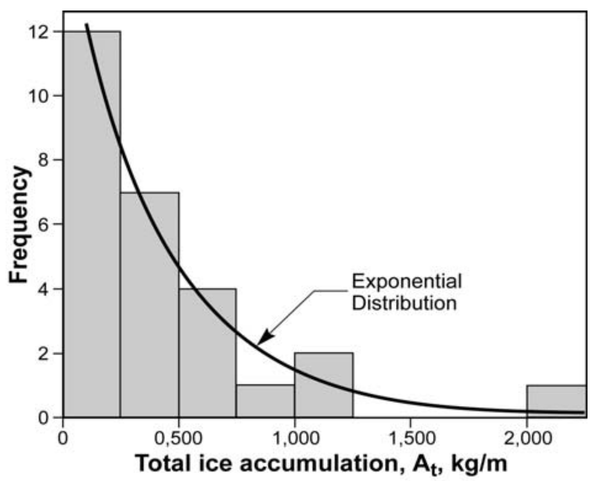

Fig. 5 Distribution of total ice accumulation, A_t, for precipitation-ice events

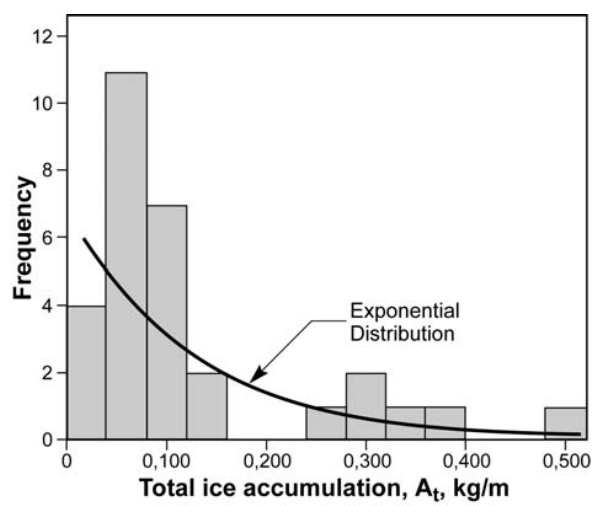

Fig. 6 Distribution of the total ice accumulation, A_t, for in-cloud-ice events

TABLE V
STATISTICAL PARAMETERS OF THE DISTRIBUTION OF TOTAL ICE ACCUMULATION, A_t

Statistic	Precipitation Icing	In-cloud Icing
Mean	0.43 ± 0.09 kg/m	0.127 ± 0.023 kg/m
Standard deviation	0.47 kg/m	0.125 kg/m
Median	0.29 kg/m	0.078 kg/m
Minimum	0.017 kg/m	0.027 kg/m
Maximum	2.08 kg/m	0.50 kg/m
Skewness	2.1	1.70
Kurtosis	5.3	2.05

B. Distribution of Total Duration of Ice Events, N_t,

Statistical parameters of the distribution of total duration of icing events, N_t, resumed in Table VI, show that in-cloud-icing events last in average longer ($\overline{N}_t = 36$ h) than precipitation-icing events ($\overline{N}_t = 24.4$ h). However, statistical tests show that the hypothesis of equality of the means cannot be rejected (significance level 0.121), and further increasing the sample size is needed.

TABLE VI
STATISTICAL PARAMETERS OF THE DISTRIBUTION OF TOTAL DURATION OF THE ICE EVENTS, N_t,

Statistic	Precipitation Icing	In-cloud Icing
Mean	24.4 ± 4.4 h	36.0 ± 7.0
Standard deviation	23 h	38
Median	16 h	21.5
Minimum	4 h	7
Maximum	93 h	193
Skewness	2.1	2.8
Kurtosis	3.5	9.1

C. Distribution of Percentage of Accumulation Period With Respect to N_t

Another distinctive characteristic of icing events is the percentage of accumulation period with respect to the total event duration. Analysis of data from Tables II and III shows that this percentage is 47.7 ± 3.4 % for precipitation-icing events, and 39.4 ± 2.6 % for in-cloud-icing events. Statistical tests show that the hypothesis of equality may be rejected at 0.06-level of significance. However, larger sample size is needed for increasing the statistical significance of the tests used.

IV. CONCLUSIONS

In this paper, characterization of atmospheric-icing events was made for the needs of models for studying and forecasting ice loading on overhead transmission-line conductors. The icing data, recorded at the Mont Bélair icing-test site in Quebec, are processed at CIGELE, and cover 57 icing events (1739 h) in three consecutive winter seasons.

The main purposes of this study are (i) analysis and classification of icing data for a statistic-based modeling by the artificial-neuron-network or multiple-regression techniques, (ii) validation of the theoretical and empirical models, and (iii) a better understanding of the icing and ice shedding processes.

The main characterization of the icing events studied refers the event as precipitation type, if 100-50% of its accumulation phase is in wet (freezing precipitation, $P > 0$) conditions. Similarly, an icing event is referred to as in-cloud-icing type, if 100-50% of its accumulation phase is in dry, $P = 0$, conditions. This classification allows bringing out some similarities of the distributions, and some important differences between their statistical parameters:

- Total ice accumulation, A_{cum}, of the both types has an exponential distribution. Results from the analysis show that, on average, icing accumulation rates during periods with precipitation, $P > 0$, are significantly greater than those during periods with dry conditions, $P = 0$. The great difference between the means: $\overline{A}_{\mathrm{t}} = 0.43 \pm 0.09$ kg/m for precipitation-ice events, and 0.127 ± 0.023 kg/m for in-cloud-ice events, is confirmed by statistical tests at high level of significance.

- In-cloud-icing events last in average longer ($\overline{N}_{\mathrm{t}} = 36$ h), than precipitation-icing type ($\overline{N}_{\mathrm{t}} = 24.4$ h). However, further increasing the sample size is needed for a statistically reliable estimation.
- Percentage of the accumulation phase with respect to the whole duration of the event. This percentage is 47.7 ± 3.4 % for precipitation-icing events, and 39.4 ± 2.6 % for in-cloud-icing events.

Analysis of one-hour-period data, as a function of the readings of the principal measurement instruments, shows a great percentage of abnormal accumulation rates, non-indicated by IRM signals, $G = 0$. If the persistence limits are increased from $\pm$ 0.001 to $\pm$0.013 kg/m/h, in such a manner that small accumulation rates are considered as persistence, this percentage can be minimized. Decrease of percentage of abnormal accumulation rate data has a positive effect on the quality of the modeling by artificial neural-networks or on the fitting by multiple regression. Persistence limits of $\pm$ 0.013 kg/m/h were adopted for both precipitation- and in-cloud icing events. Further widening of the chosen limits is not effective, because it decreases considerably the quantity of data in the accumulation group. The chosen interval also covers the majority of data for shedding by sublimation.

Future research is planed at CIGELE, covering the field of artificial neural-networks, multiple-variable-regression, and probabilistic (statistics based) modeling of atmospheric icing on overhead transmission lines. For the successful accomplishment of this research, continuous input with increased volume of improved and diversified data is needed for studying of both precipitation and in-cloud icing.

V. ACKNOWLEDGMENTS

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