Annex N

Transmission Line and Equipment Outage Data

Part I

An IEEE Survey of U.S. and Canadian Overhead Transmission Outages at 230 kV and Above

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Part 2

Frequency of Transmission Line Outages in Canada

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Part 3

Transmission Equipment Reliability Data from Canadian Electrical Association

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AN IEEE SURVEY OF U.S. AND CANADIAN OVERHEAD TRANSMISSION OUTAGES AT 230 KV AND ABOVE

Data Analysis Task Force, Working Group on Statistics of Line Outages,
General Systems Subcommittee, Transmission & Distribution Committee

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Abstract - The Working Group on Statistics of Line Outages was formed in 1981 to develop, implement and summarize the results of a survey of design characteristics of and outage experience with overhead transmission at voltages 230kV and above. The survey, distributed in July, 1985, requested the voluntary submission of specific data on overhead lines in service within the period, 1965-1985. The purposes of the effort were twofold: to update earlier surveys (1949 and 1965), and to address a growing need for line outage data to support evolving probabilistic system models for planning and operation. Data were submitted by utilities from all nine NERC/USA reliability regions and by the Canadian Electric Association representing all of Canada. The outage data were pooled and analyzed to produce average statistics which are summarized in this paper.

Keywords - Overhead Transmission, Outage Statistics, Performance Data, Reliability Analysis.

INTRODUCTION

Since the early 1970's, there has been a growing need for transmission line outage rates and restoration times to support probabilistic models for system planning and operation. Prompted by an EPRI study of transmission outage data requirements [1], the Working Group on Statistics of Line Outages was created in 1981 to develop and implement a survey to update two earlier surveys of overhead transmission in which the IEEE took a leading role [2,3]. Reference [4] provides a description of the background and development of the new survey and of the method for its distribution to potential respondents. Work on a Transmission Outage Data Submission Guide to support the survey progressed in parallel with work on standard definitions for reporting outages of transmission facilities [5]. To the degree possible, the standard definitions were employed in the guide.

Similar to its precedents, the new survey, distributed in 1985, was intended to serve two broad objectives: to provide a snapshot of the design characteristics of overhead transmission facilities operating at 230kV and higher, and to quantify the performance of the various classes of lines on which data were submitted. The background and results in meeting the first objective are reported in [6]. The present paper reports on the second objective.

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Specific goals adopted for the 1985 survey of overhead transmission outage events were:

1. To develop generic estimates of failure rates and restoration times for overhead lines, as functions of operating voltage, circuit length, and number of terminals; and to gain a better grasp of the nature and distribution of outage causes as a function of voltage.
2. To develop statistics on rare events such as three-phase faults at 500kV and 765kV.
3. To develop a better understanding of the nature and cause of related multiple outage events.
4. To correlate circuit availability with circuit design characteristics.
5. To determine how, in general, performance may have changed since the last survey in 1965.
6. To encourage and foster the uniform and consistent collection of transmission line outage data.

The 1985 survey differed from the 1949 and 1965 surveys in that it requested data on (a) related multiple outage events, (b) outage event start and end times, (c) 500kV and 765kV overhead lines, and (d) planned outage events. Outage rates are given on three bases: per 100-miles of circuit, per terminal, and per circuit.

Since the information summarized in this paper represents a second set of 1985 survey results, the numbering of tables and figures continues where [6] left off. That is, the first table of this paper is designated Table 18 and the first figure is Figure 2.

DATA REQUESTED

To use outage experience to estimate outage rates and repair times, two types of information are required: circuit exposure (population) data, and outage-event data. The desired exposure data (summarized in [6]) included basic data on each transmission circuit which could have contributed to the history of outage events. Required data on each circuit consisted of: circuit name (to which was appended the host utility identification number), operating voltage, length, number of terminals, and the specific time period over which the circuit, of a fixed design and configuration, was in service and subject to outage.

The request for outage data presumed that the responding utilities would translate data already collected into the format specified in the Transmission Outage Data Submission Guide (distributed with the request for data). In some cases this translation was performed on data that had already been assembled and pooled on a regional basis. In other cases, the data were assembled and submitted by individual utilities on coding forms.

Figure 2 illustrates the coding form used for the submission of outage event data. (An outage event may have involved a single circuit outage, or two or more related circuit outages.) This form provided a means for identifying the circuit(s) associated with the initiating cause (primary/independent or common-mode outage(s)), and for identifying any other circuit outage(s) required to isolate or remedy the problem (secondary/dependent outage(s)). Secondary outages were of two kinds: direct and indirect. If a secondary outage was a natural consequence of isolating the problem, it was considered a "direct" secondary. If the secondary outage was a result of a second failure, such as a stuck breaker or faulty protective relay, it was considered an "indirect" secondary.

Figure 3 shows the codes available to classify each circuit outage in an event according to: (a) the type of outage, (b) the relation of the particular circuit outage to the initiating cause, (c) whether the circuit was completely or only partially removed from service, (d) whether the initiating problem involved line equipment or terminal equipment, (e) the means by which the circuit was restored to service, (f) the type of fault, (g) the suspected cause of the outage, and (h) the effect of the outage event on the system or its components.

When the outage event involved more than one circuit in a common-mode fashion (because of common tower, common right-of-way, or common terminal), then a "common mode" designation was appropriate. If the initiating cause of an event had directly resulted in the common-mode outage of two or more circuits, then all of these circuits were considered primary outages. For example, if the fault had occurred on a bus, it may have been necessary to remove all circuits connected to that bus to isolate the fault. Each circuit would have been considered part of the same common-terminal, common-mode primary outage. Depending on network configuration, one or more secondary outages may also have been required to isolate the fault.

SURVEY RESPONSE

Seventy-eight utilities volunteered data, representing all nine USA regions of the North American Reliability Council (NERC). The Canadian utilities

X-273 REV. 6-85

TRANSMISSION CIRCUIT OUTAGE REPORTING FORM

PREPARER	DATE	PAGE OF

TRANSMISSION CIRCUIT OUTAGE DATA

TYP (1)	UTILITY I D (2)	EVENT NO (6)	SEQ. NO (11)	TRANSMISSION CIRCUIT IDENTIFICATION (15)	SECT I.D.	START OF OUTAGE MO. DAY YR. HR MIN (32)	END OF OUTAGE MO DAY YR HR MIN (43)	OUTAGE CLASS (54)	REST	FAULT TYPE (62)	OUTAGE CAUSE (65)	EFF (70)

Figure 2. Transmission Circuit Outage Reporting Form.

Outage Classification (OUTAGE CLASS)

OUTAGE TYPE [Col 54]

A - AUTOMATIC
F - FORCED MANUAL
S - PLANNED

MULTIPLE OUTAGES [Col 55-56]

1b̸ - PRIMARY
DD - DIRECT SECONDARY
DI - INDIRECT SECONDARY
CB - COMMMON TERMINAL
CR - COMMON ROW
CT - COMMON TOWER

DEGREE OF OUTAGE [Col 57]

C - COMPLETE
P - PARTIAL

PROBLEM TYPE [Col 58]

L - LINE RELATED
T - TERMINAL RELATED
U - UNKNOWN

Nature of Restoration (REST) [Col 60]

A - AUTOMATIC
M - MANUAL/SUPERVISORY
R - REPAIR/REPLACE
U - UNKNOWN

Fault Type [Col 62-63]

b̸b̸ - NO FAULT OR NO OPEN PHASE
1G - SINGLE PHASE TO GRD
2P - PHASE TO PHASE
2G - DOUBLE PHASE TO GRD.
3P - THREE PHASE
3G - THREE PHASE TO GRD
OP - OPEN PHASE
UF - UNKNOWN

Suspected Cause of Outage (OUTAGE CAUSE) [Col 65-68]

DEFECTIVE POWER EQUIPMENT

1Lb̸b̸ - TRANSMISSION CIRCUIT EQUIP
1LCb̸ - CONDUCTOR
1LTb̸ - TOWER/STRUCTURE
1LSb̸ - SHIELD WIRE
1LIb̸ - INSULATOR/ INSULATION SYS.
1LXb̸ - CABLE

1Sb̸b̸ - TERMINAL/STATION EQUIP.
1SAb̸ - SURGE ARRESTOR
1SBb̸ - CIRCUIT BREAKER
1SCb̸ - SHUNT CAPACITOR BANK
1SPb̸ - PROTECTIVE SYSTEM
1STb̸ - BUS
1SSb̸ - DISCONNECT SWITCH
1TBb̸ - TRANSFORMER
1TRb̸ - SHUNT REACTOR BANK

1Ub̸b̸ - UNKNOWN

HUMAN ELEMENT

2b̸b̸b̸ - HUMAN ELEMENT RELATED
2Ab̸b̸ - IMPROPER RELAY SETTING
2Bb̸b̸ - INCORRECT INSTALLATION
2Cb̸b̸ - IMPROPER DESIGN/ APPLICATION
2Db̸b̸ - MAINTENANCE ACTIVITY
2Eb̸b̸ - CONSTRUCTION ACTIVITY
2Fb̸b̸ - VANDALISM OR SABOTAGE
2Gb̸b̸ - IMPROPER OPERATION

FOREIGN INTERFERENCE

3b̸b̸b̸ - FOREIGN INTERFERENCE
3Ab̸b̸ - ANIMAL
3Bb̸b̸ - BIRD
3Cb̸b̸ - CRANE
3Hb̸b̸ - HUMAN
3Kb̸b̸ - KITE OR OTHER OBJECT
3Pb̸b̸ - AIRCRAFT
3Tb̸b̸ - TREE
3Vb̸b̸ - VEHICLE
3Zb̸b̸ - ANOTHER LINE

POWER SYSTEM CONDITION/ CONFIGURATION

4b̸b̸b̸ - POWER SYS. COND./CONF
4Ab̸b̸ - STABLE OVERLOAD OPERATION
4Bb̸b̸ - STABLE OSCILLATION
4Cb̸b̸ - OUT OF STEP
4Db̸b̸ - OVERVOLTAGE
4Eb̸b̸ - LOSS OF GENERATOR
4Fb̸b̸ - RELAY INCORRECT OPERATION
4Gb̸b̸ - OVERLOAD TRIP
4Hb̸b̸ - UNDERVOLTAGE
4Ib̸b̸ - UNDERFREQUENCY
4Jb̸b̸ - SWITCHING SURGE (VOLTAGE)
4Kb̸b̸ - DYNAMIC OVERVOLTAGE
4Lb̸b̸ - INSTABILITY

OTHER

7Mb̸b̸ - MISCELLANEOUS OR OTHER
7Ub̸b̸ - UNKNOWN

ENVIRONMENTAL

5b̸b̸b̸ - ENVIRONMENT
5Ab̸b̸ - LIGHTNING
5Bb̸b̸ - WEATHER
5BRN - RAIN
5BSN - SNOW
5BSL - SLEET
5BIb̸ - ICE
5BHL - HAIL
5BWH - HIGH WIND
5BHC - HURRICANE
5BTH - THUNDERSTORM
5BTN - TORNADO
5Cb̸b̸ - CONTAMINATION
5CSM - SMOG
5CSb̸ - SALT
5CBD - BIRD DROPPINGS
5CIb̸ - INDUSTRIAL

5CAG - AGRICULTURE

5EMb̸ - EARTH MOVEMENT
5FRb̸ - FIRE
5FLb̸ - FLOOD
5Gb̸b̸ - GALLOPING CONDUCTORS
5Hb̸b̸ - AEOLIAN VIBRATION

SCHEDULED OUTAGE

6b̸b̸b̸ - UNSPECIFIED PLANNED OUTAGE
6Ab̸b̸ - CONSTR., INSTALL., MODIFICATION
6Bb̸b̸ - TRANSMISSION CIRCUIT MAINT.
6Cb̸b̸ - TERMINAL EQUIP. MAINT.
6Db̸b̸ - TEST OR INSPECTION
6Eb̸b̸ - FOREIGN UTILITY REQUEST
6Fb̸b̸ - SYSTEM CONDITION
6Gb̸b̸ - ROUTINE OPERATION

Effects of Outage (EFF) [Col 70]

A - CASCADING
B - LOSS OF GEN
C - LOSS OF TERM BANK
D - LOSS OF LOAD
E - INSTABILITY
F - LOSS OF INTERCONNECTION
G - OVERLOAD
H - LINE DAMAGE
I - EQUIPMENT DAMAGE
J - CONTROLLED LOAD SHED.
K - BLACKOUT
L - LOSS OF OTHER CIRCUITS (< 230kv)
M - NO ADVERSE EFFECT

Note: Under "Suspected Cause of Outage," the symbol "b̸" represents a blank space.

Figure 3. Transmission Circuit Outage Reporting Codes.

were represented in an additional single submission by the Canadian Electrical Association. A total of 38 489 outage records were judged valid and accepted. These consisted of outage types: automatic, forced-manual, and planned, and included primary, secondary, and common-mode outage classes. These outages were derived from 14 120 circuit-years or 583 712 mile-years of circuit exposure. The data submitted were derived from circuits of voltage 230kV and higher in service during various periods within the 1965-1985 time frame. Table 1 (repeated from [6]) provides a snapshot on July 1 of each year of the circuit population contributing to the database. In those NERC regions where the submission was based on regionally pooled data, the number of circuits shown in Table 1 remains roughly constant from year to year over the period that data were submitted. In those regions where submissions were by individual utilities, the number of participating circuits displays a wider year-to-year variation.

Circuit outage event data were submitted with varying levels of care and detail. Some utilities reported single and multiple-line outages as well as forced and scheduled outages, providing start and end times to the minute, carefully conforming to the recommended format, and using the codes defined in the Transmission Outage Data Submission Manual. Other utilities were less careful, and perhaps reported all circuit outages as independent events without identifying related outages. Some gave outage start and end dates, but omitted the time of day (hour and minute). In some cases, important data fields were left blank. The instructions for coding outages were at times misinterpreted.

Some utilities simply submitted their data in their own specific format, leaving the Working Group with the option to convert the data to the desired format. In the latter case, difficulties were often encountered due to a lack of information to guide the required conversion.

Only those outages records which satisfied the minimum data requirements were included in the database. An acceptable outage record was one that provided the minimum required data on an outage event, and documented an event which occurred within the in-service period established by a corresponding valid circuit exposure record.

RESULTS

In the letter requesting circuit outage event data, utilities were assured that all data that were submitted would be pooled and the results presented in summary form only. In an effort to publish survey results without further delay, only basic data analysis has been performed. More detailed analysis, such as the correlation of circuit design characteristics and circuit availability, may yet be performed, depending on the level of interest revealed in the discussion of this paper.

Data Summaries

Table 18 summarizes the nature of the primary forced outages. A primary outage is the circuit that experiences the initiating event. Although two or more circuits involved in a common-mode outage event may also experience an initiating event, the decision was made to exclude these multiple related outage events in Table 18. As the title of Table 18 implies, secondary circuit outages are also not included. Table 18 classifies 15 525 primary forced outages by cause, voltage, problem type (line-related, terminal-related or unknown), and general duration ("momentary" for restoration times less than or equal to one minute, and "sustained" for restoration times equal to or greater than two minutes). The causes of the primary outages are classified into the same categories used in the Outage Reporting Form (see Figure 3). If the problem type was not specified, and it could not be deduced from information on the outage cause (refer to section entitled Data Enhancement), it was classified as "Unknown."

Outage rates are expressed per 100-mile-year for line-related outages, per terminal-year for terminal-related outages, and per circuit-year for all outages combined (terminal-related, line-related, and unknown). In calculating terminal-years exposure, if the number of terminals of any circuit was not specified, it was assumed to have two.

The exposure to outage is summarized at the bottom of Table 18. This represents the mile-years (in hundreds), terminal-years, or circuit-years that were exposed to failure. The total number of line-related primary outages for each voltage is normalized by line

Table 1. Reported Line Population (Number of Circuits) *.

	BY REGION										BY VOLTAGE LEVEL			
	CEA	NPCC	MAPP	SPP	SERC	MAAC	MAIN	ECAR	ERCOT	WSCC	230	345	500	765
1965	0	0	0	6	12	0	0	0	0	0	18	0	0	0
1966	0	0	0	6	14	0	0	0	0	1	21	0	0	0
1967	0	0	0	6	17	0	0	0	0	1	24	0	0	0
1968	0	0	0	10	21	0	0	0	0	1	28	4	0	0
1969	0	0	0	10	22	0	0	0	0	2	29	5	0	0
1970	0	0	0	11	26	0	0	0	0	2	34	5	0	0
1971	0	0	1	19	28	0	0	0	0	2	43	7	0	0
1972	0	0	1	25	34	0	0	0	0	21	55	7	19	0
1973	0	0	1	30	38	0	0	0	0	21	62	9	19	0
1974	0	0	1	37	41	0	0	0	1	28	69	14	25	0
1975	0	0	2	38	46	0	94	103	3	28	91	197	25	1
1976	0	22	2	42	54	0	104	238	11	28	108	334	44	15
1977	0	22	111	49	58	0	113	254	15	29	163	422	45	21
1978	0	22	120	55	64	0	115	263	19	32	178	446	45	21
1979	0	24	134	64	99	376	124	269	20	30	566	479	74	21
1980	502	24	149	66	215	381	123	283	28	31	1021	595	125	61
1981	511	49	161	69	217	389	125	290	38	33	1045	640	130	67
1982	526	49	174	71	218	393	132	302	42	34	1062	664	143	72
1983	550	23	177	75	262	393	123	315	46	36	1071	660	184	85
1984	532	23	0	77	266	397	93	323	49	36	932	567	204	93
1985	0	23	0	63	268	402	0	0	46	37	603	104	130	2

* As of July 1 for the years shown. (Table 1 is repeated from [6].)

Table 18. Primary Automatic and Forced Manual Outages (1) by Cause, Voltage, Problem Type, and Duration Class (2), and Estimated Forced Outage Rates.

CAUSE	230 KV						345 KV						500 KV						765 KV					
	LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN	
	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.
DEFECTIVE POWER EQUIPMENT																								
TRANSMISSION CIRCUIT EQUIP	6	55	0	1	0	0	12	70	0	0	0	0	6	6	0	0	0	0	0	4	0	0	0	0
CONDUCTOR	2	59	0	1	0	1	0	6	0	0	0	0	0	4	0	0	0	0	0	8	0	0	0	0
TOWER/STRUCTURE	2	37	0	1	0	3	2	11	0	0	0	0	0	3	0	0	0	0	0	5	0	0	0	0
SHIELD WIRE	7	100	0	0	0	0	7	21	0	1	0	0	1	1	0	0	0	0	4	15	0	0	0	0
INSULATOR/INSULATION SYSTEM	9	45	2	6	0	1	18	37	2	0	0	1	3	12	0	0	0	0	0	13	0	0	0	0
CABLE	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TERMINAL/STATION EQUIPMENT	6	15	6	47	0	0	2	2	156	543	0	0	0	2	4	44	0	0	0	0	29	91	0	0
SURGE ARRESTOR	2	3	1	7	0	0	0	3	1	5	0	0	0	1	0	1	0	0	0	0	0	0	0	0
CIRCUIT BREAKER	0	3	7	59	0	0	2	4	1	11	0	1	0	0	0	28	0	0	0	0	0	0	0	0
SHUNT CAPACITOR BANK	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
PROTECTIVE SYSTEM	2	4	32	185	0	0	0	0	96	194	1	1	2	15	14	28	0	0	0	0	2	4	0	0
BUS	0	0	0	4	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
DISCONNECT SWITCH	0	0	1	10	0	0	0	0	0	4	0	0	1	1	0	5	0	0	0	0	0	0	0	0
TRANSFORMER	2	2	22	36	0	0	0	1	2	6	0	0	1	0	1	3	0	0	0	0	0	1	0	0
SHUNT REACTOR BANK	0	0	0	1	0	0	0	1	0	2	0	0	0	0	0	1	0	0	0	0	0	2	0	0
UNKNOWN	10	16	0	0	2	5	9	42	4	5	18	11	0	1	2	2	0	0	0	0	0	0	0	0
SUB-TOTAL (DEFECTIVE POWER EQUIPMENT)	50	339	73	359	2	10	50	200	262	772	19	14	15	47	22	113	0	0	4	45	31	96	0	0
HUMAN ELEMENT																								
HUMAN ELEMENT RELATED	75	184	31	56	0	0	0	46	118	228	0	0	16	24	4	14	0	0	5	43	14	17	0	0
IMPROPER RELAY SETTING	0	0	3	14	0	0	0	1	1	1	0	0	0	0	1	2	0	0	0	0	0	0	0	0
INCORRECT INSTALLATION	0	1	0	4	0	0	0	0	1	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IMPROPER DESIGN/APPLICATION	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
MAINTENANCE ACTIVITY	1	14	1	3	0	1	3	5	12	18	0	2	0	0	2	7	0	0	0	0	0	0	0	0
CONSTRUCTION ACTIVITY	0	10	2	2	0	0	1	1	1	0	0	0	0	2	0	8	0	0	0	0	0	0	0	0
VANDALISM OR SABOTAGE	2	19	1	1	0	0	0	14	0	1	0	0	1	1	0	0	0	0	0	2	0	0	0	0
IMPROPER OPERATION	0	1	20	30	0	0	3	5	125	124	0	0	3	12	5	13	0	0	0	0	5	5	0	0
SUB-TOTAL (HUMAN ERROR)	78	229	58	112	0	1	7	72	258	377	0	2	20	41	12	45	0	0	5	45	19	22	0	0
FOREIGN INTERFERENCE																								
FOREIGN INTERFERENCE	16	99	0	0	0	0	0	6	0	0	0	0	0	7	0	1	0	0	0	3	0	0	0	0
ANIMAL	0	0	3	1	0	0	3	0	1	1	0	0	0	0	1	0	0	0	4	0	0	0	0	0
BIRD	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
CRANE	2	4	0	0	0	0	4	15	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0
HUMAN	0	0	2	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
KITE OR OTHER OBJECT	3	6	0	1	0	0	1	1	0	0	0	0	1	5	0	0	0	0	0	0	0	0	0	0
AIRCRAFT	1	19	0	1	0	1	4	8	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0
TREE	18	447	1	1	0	1	50	87	1	0	1	2	23	29	0	1	0	0	0	2	0	0	0	0
VEHICLE	3	31	0	0	0	0	3	3	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0
ANOTHER LINE	0	1	1	5	0	0	0	24	0	2	2	1	0	0	1	0	0	0	0	0	0	0	0	0
SUB-TOTAL (FOREIGN INTERFERENCE)	44	608	7	9	0	2	65	145	2	4	3	3	26	60	2	3	0	0	4	5	0	0	0	0
POWER SYSTEM CONDITION/CONFIGURATION																								
POWER SYSTEM. CONDITION/CONF.	9	21	82	82	0	3	0	37	0	59	0	1	7	7	0	2	0	6	1	3	0	0	0	0
STABLE OVERLOAD OPERATION	0	0	0	2	0	0	0	1	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
STABLE OSCILLATION	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OUT OF STEP	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OVERVOLTAGE	0	1	0	20	0	0	0	7	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOSS OF GENERATOR	0	0	0	1	0	0	0	0	0	4	0	1	0	0	0	1	0	0	0	0	0	0	0	0
RELAY INCORRECT OPERATION	2	3	3	0	0	0	1	7	2	9	0	0	1	1	0	12	0	0	0	0	0	4	0	0
OVERLOAD TRIP	0	0	1	40	0	0	0	1	0	15	1	0	0	5	0	7	0	0	0	0	0	3	0	0
UNDERVOLTAGE	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UNDERFREQUENCY	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SWITCHING SURGE (VOLTAGE)	0	0	2	4	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
DYNAMIC OVERVOLTAGE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INSTABILITY	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
SUB-TOTAL (POWER SYSTEM COND./CONF.)	11	33	88	135	0	3	1	53	4	101	2	2	6	13	1	22	0	6	1	4	0	7	0	0

(Continued)

Table 18. (Continued)

CAUSE	230 KV						345 KV					
	LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN	
	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.
ENVIRONMENT												
ENVIRONMENT	221	311	5	14	0	0	126	273	12	8	0	0
LIGHTNING	843	444	4	8	5	1	1 335	268	0	2	11	13
WEATHER	181	226	0	0	0	8	28	82	0	0	72	18
HURRICANE	6	10	0	0	0	0	0	1	0	0	0	0
HAIL	0	0	0	0	0	0	0	0	0	0	0	0
ICE	5	10	0	6	0	5	108	89	0	0	0	8
RAIN	3	3	0	3	0	2	2	0	0	0	0	0
SLEET	0	0	0	0	0	0	0	0	0	0	0	0
SNOW	4	1	0	0	0	0	0	0	0	0	0	0
THUNDERSTORM	35	32	0	0	1	11	9	32	2	0	3	3
TORNADO	1	6	0	0	0	2	1	11	0	0	0	3
HIGH WIND	15	35	3	0	0	1	34	73	0	0	1	1
CONTAMINATION	0	71	0	0	0	0	40	21	2	12	4	3
AGRICULTURE	0	0	0	0	0	0	0	0	0	0	0	0
BIRD DROPPINGS	0	0	0	0	0	0	0	3	0	0	0	0
INDUSTRIAL	0	0	0	0	0	0	0	2	0	0	0	0
SALT	0	0	0	0	0	0	0	4	3	4	0	0
SMOG	0	0	0	0	0	0	9	0	0	0	0	0
EARTH MOVEMENT	0	0	1	0	0	0	0	0	0	0	0	0
FLOOD	0	0	0	0	0	0	0	0	0	0	0	0
FIRE	7	6	0	4	0	1	7	13	0	1	0	0
GALLOPING CONDUCTORS	0	0	0	0	0	0	24	51	0	0	0	0
AEOLIAN VIBRATION	0	0	0	0	0	0	0	0	0	0	0	0
SUB-TOTAL (ENVIRONMENT)	1 321	1 159	13	35	5	31	1 723	905	19	27	91	49
OTHER												
MISCELLANEOUS OR OTHER	4	265	2	0	0	4	112	301	32	127	227	258
UNKNOWN	147	318	24	13	58	127	65	83	2	6	620	471
SUB-TOTAL (OTHER)	151	583	26	13	56	131	177	384	34	133	847	729
SUB-TOTAL (NON-SCHEDULED OUTAGES)	1 655	2 951	265	663	66	176	2 023	1 739	579	1 414	962	799
SCHEDULED OUTAGE (3)												
UNSPECIFIED PLANNED	1	0	2	1	0	0	0	0	0	0	0	0
CONSTR., INSTALL, MODIFICATION	3	0	0	1	0	0	0	3	0	1	0	0
TRANSMISSION CIRCUIT	1	29	0	3	0	0	0	7	0	2	0	0
TERMINAL EQUIP MAINTENANCE	0	0	4	19	0	0	0	0	0	1	0	0
TEST OR INSPECTION	0	1	6	10	0	1	1	0	0	6	0	0
FOREIGN UTILITY REQUEST	0	1	0	3	0	2	0	1	0	0	0	0
SYSTEM CONDITION	0	7	6	15	0	0	0	0	0	6	0	0
ROUTINE OPERATION	0	3	0	4	0	0	0	2	0	0	0	0
SUB-TOTAL (SCHEDULED OUTAGES)	5	41	18	56	0	3	1	13	0	16	0	0
TOTAL NUMBER OF OUTAGES	1 660	2 992	283	719	66	181	2 024	1 752	579	1 430	962	799
EXPOSURE												
MILE-YEARS (HUNDREDS)	2 325		----		----		2 329		----		----	
TERMINAL-YEARS	----		11 681 (4)		----		----		9 490 (4)		----	
CIRCUIT-YEARS	7 265		5 497 (4)		5 497 (4)		5 177		4 726 (4)		4 726 (4)	
OUTAGE RATE												
PER 100 MILE-YEAR	0.714	1.287	----	----	----	----	0.869	0.752	----	----	----	----
PER TERMINAL-YEAR	----	----	0.024	0.062	----	----	----	----	0.061	0.151	----	----
PER CIRCUIT-YEAR	0.226	0.412	0.051	0.131	0.012	0.033	0.391	0.336	0.123	0.303	0.204	0.169

CAUSE	500 KV						765 KV					
	LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN	
	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.
ENVIRONMENT												
ENVIRONMENT	2	3	1	0	0	0	0	8	0	0	0	0
LIGHTNING	261	90	1	0	0	0	132	51	0	0	0	0
WEATHER	192	18	0	0	0	0	13	21	0	0	0	0
HURRICANE	0	0	0	0	0	0	0	0	0	0	0	0
HAIL	0	0	0	0	0	0	0	0	0	0	0	0
ICE	0	4	0	0	0	0	8	8	0	0	0	0
RAIN	2	5	0	0	0	0	0	0	0	0	0	0
SLEET	0	0	0	0	0	0	0	0	0	0	0	0
SNOW	0	0	0	0	0	0	0	0	0	0	0	0
THUNDERSTORM	0	1	0	1	0	2	0	0	0	0	0	0
TORNADO	0	2	0	0	0	0	0	0	0	0	0	0
HIGH WIND	1	9	0	0	0	0	18	5	0	0	0	0
CONTAMINATION	25	6	0	0	0	0	0	2	0	0	0	0
AGRICULTURE	1	0	0	0	0	0	0	0	0	0	0	0
BIRD DROPPINGS	15	8	0	0	0	0	0	0	0	0	0	0
INDUSTRIAL	0	0	0	0	0	0	0	0	0	0	0	0
SALT	0	0	0	0	0	0	0	0	0	0	0	0
SMOG	0	0	0	0	0	0	0	0	0	0	0	0
EARTH MOVEMENT	0	0	0	0	0	0	0	0	0	0	0	0
FLOOD	0	0	0	0	0	0	0	0	0	0	0	0
FIRE	26	30	1	1	0	0	0	0	0	0	0	0
GALLOPING CONDUCTORS	0	0	0	0	0	0	0	0	0	0	0	0
AEOLIAN VIBRATION	0	0	0	0	0	0	0	0	0	0	0	0
SUB-TOTAL (ENVIRONMENT)	545	174	3	2	0	2	171	95	0	0	0	0
OTHER												
MISCELLANEOUS OR OTHER	5	19	0	0	9	13	0	3	1	0	29	31
UNKNOWN	50	47	4	2	15	13	3	17	0	4	33	14
SUB-TOTAL (OTHER)	55	66	4	2	24	26	3	20	1	4	62	45
SUB-TOTAL (NON-SCHEDULED OUTAGES)	669	401	44	187	24	34	188	214	51	131	62	45
SCHEDULED OUTAGE (3)												
UNSPECIFIED PLANNED	0	0	0	2	0	0	0	0	0	0	0	0
CONSTR., INSTALL, MODIFICATION	0	0	0	0	0	0	0	0	0	0	0	0
TRANSMISSION CIRCUIT	0	8	0	1	0	0	0	0	0	0	0	0
TERMINAL EQUIP MAINTENANCE	0	0	0	0	0	0	0	0	0	0	0	0
TEST OR INSPECTION	0	0	0	5	0	0	0	0	0	0	0	0
FOREIGN UTILITY REQUEST	0	0	0	0	0	0	0	0	0	0	0	0
SYSTEM CONDITION	0	0	0	8	0	0	0	0	0	0	0	0
ROUTINE OPERATION	0	4	0	0	0	0	0	0	0	0	0	0
SUB-TOTAL (SCHEDULED OUTAGES)	0	12	0	16	0	0	0	0	0	0	0	0
TOTAL NUMBER OF OUTAGES	669	413	44	203	24	34	188	214	51	131	62	45
EXPOSURE												
MILE-YEARS (HUNDREDS)	764		----		----		399		----		----	
TERMINAL-YEARS	----		2 089 (4)		----		----		433 (4)		----	
CIRCUIT-YEARS	1 221		1 037 (4)		1 037 (4)		456		216 (4)		216 (4)	
OUTAGE RATE												
PER 100 MILE-YEAR	0.853	0.527	----	----	----	----	0.471	0.536	----	----	----	----
PER TERMINAL-YEAR	----	----	0.021	0.097	----	----	----	----	0.118	0.302	----	----
PER CIRCUIT-YEAR	0.548	0.388	0.042	0.196	0.023	0.033	0.412	0.469	0.236	0.606	0.287	0.208

NOTES:

1. EXCLUDES COMMON MODE OUTAGES.
2. EXCLUDES ALL OUTAGES REPORTED WITH INCOMPLETE DURATION DATA.
3. REPORTED AS 'AUTOMATIC' OR 'FORCED MANUAL' OUTAGES.
4. EXCLUDES CIRCUITS WHOSE OUTAGES WERE REPORTED WITH INCOMPLETE DURATION DATA.

exposure (in 100-mile-years) to obtain a line outage rate per 100-miles per year. In a similar fashion, the total number of terminal-related primary outages is normalized by the terminal exposure (in terminal-years) to estimate a line outage rate per terminal per year. The total number of outages for each voltage level (line-related, terminal-related, and unknown) is normalized by the number of circuit-years to develop a general outage rate per circuit per year.

As an example of the use of the outage rates given at the bottom of Table 18, consider the calculation of the rate of occurrence of sustained outages on a particular 230kV circuit, ORS(230), as a function of circuit length and number of circuit terminals. The following equation would be used.

$$ORS(230) = ORSL(230) * \frac{\text{Circuit Length in Miles}}{100} + ORST(230) * (\text{No. of Circuit Terminals}) + ORSU(230)$$

where ORS(230) is the rate of occurrence (per year) of sustained outages for a particular 230kV circuit,
ORSL(230) is the sustained outage rate per 100 miles for 230kV circuits,
ORST(230) is the sustained outage rate per terminal for 230kV circuits, and
ORSU(230) is the sustained outage rate for the average 230kV circuit reflecting those cases where the origin of the problem is either unknown or not specified.

Thus, for a three-terminal, 50-mile, 230kV circuit,

$$ORS = 1.287 * \frac{50}{100} + 0.062 * 3 + 0.033$$
$$= 0.8625 \text{ sustained forced outages per year.}$$

To calculate the rate of occurrence of sustained outages of the average 230kV circuit, ORSA(230), the following equation would be used.

$$ORSA(230) = ORSLA(230) + ORSTA(230) + ORSU(230)$$

where ORSA(230) is the sustained outage rate (per year) for the average 230kV circuit,
ORSLA(230) is the sustained outage rate for the average 230kV circuit due specifically to line-related outages,
ORSTA(230) is the sustained outage rate for the average 230kV circuit due specifically to terminal-related outages,
ORSU(230) is defined above.

Thus, for the average 230kV line,

$$ORSA(230) = 0.412 + 0.131 + 0.033$$
$$= 0.576 \text{ sustained forced outages per year.}$$

The reader is cautioned not to draw conclusions about the ratio of line-related to terminal-related outages reported in Table 18, since a significant number of terminal-related outage records were removed from the database due to an irreconcilable data deficiency.

Table 19 summarizes the distribution of causes, by voltage, of the circuit outages designated as "Planned." Of the 78 responding utilities, 63 reported planned outages. After reviewing the ratio of reported planned outages to the total number of reported outages for each utility, it was observed that some utilities seemed to report planned outages only on an occasional basis. To adjust for this inconsistency in the calculation of planned outage rates, only the planned outages and circuit exposures of those utilities whose ratio of reported planned outages to total reported outages exceeded 15% were used. As a result, Table 19 represents the planned outages and circuit-years exposure of 58 utilities. The number of planned outage records used drops by a mere 0.03% (from 21,321 to 21,259). The ratios for the remaining 58 utilities ranged from 25% to 98% (with an average of 65%).

Table 19 includes 129 of the 181 "Automatic" or "Forced Manual" outages with "Scheduled" outage cause, listed in Table 18. These belong to the 58 utilities assumed to have reported all planned outages.

Table 20 classifies the various combinations of one or more circuit outages that comprise the database of outage events. Since the data from several NERC regions consisted only of single-circuit outage events, circuit outages with identical initiation times (to the minute) within the same utility were identified. There is a high probability that these simultaneous circuit outages were, indeed, related events. These are summarized in Table 20 as "Independent Simultaneous" outages. (Note that the independent simultaneous multiple-outage events may easily be recast as independent events. For example, an independent simultaneous event involving three circuit outages in Table 20 may alternatively be considered as three independent events, each involving one circuit.)

Excluded from Table 20 are the data from those submissions consisting entirely of independent primary outages where the duration of the outage was given, rather than the specific outage start and end times (a result of a required data conversion). In this case, it was impossible to identify simultaneous start times.

When an outage event involved a number of circuits, each with a different "Multiple Outage" code, the question arises: What multiple-outage classification should be assigned to this outage? The Working Group's response was arbitrary, but rational. The seven different multiple-outage types were subjectively ranked in order of decreasing probability of occurrence:

- Independent
- Independent Simultaneous
- Direct Secondary
- Common-Terminal Common Mode
- Indirect Secondary
- Common-Tower Common Mode
- Common-Right-of-Way Common Mode

In Table 20, an event is classified according to the least probable multiple-outage type recorded for one or more circuits within the event, and by the voltage of the circuit(s) on which this least probable outage type occurred. For example, using the above ordering for decreasing probability, if an event had involved three circuit outages of types: primary, direct secondary, and indirect secondary, the three-circuit event would have been classified "indirect secondary"--the least probable outage type in the event. The event would have been classified under the voltage level of the circuit whose outage was a specific consequence of the indirect secondary occurrence. As another example, consider an event that had included a common-tower common-mode outage of two lines and, because of a stuck breaker, also had included an indirect secondary outage. This

CAUSE	230KV	345KV	500KV	765KV
UNSPECIFIED PLANNED	29.68%	57.19%	40.87%	84.69%
CONSTRUCTION, INSTALLATION, MODIFICATION	11.51%	10.55%	4.89%	1.26%
TRANSMISSION CIRCUIT MAINTENANCE	18.86%	11.22%	8.66%	1.83%
TERMINAL EQUIPMENT MAINTENANCE	13.28%	12.12%	8.40%	3.67%
TEST OR INSPECTION	11.45%	6.32%	11.84%	1.61%
FOREIGN UTILITY REQUEST	1.83%	0.36%	1.19%	0.00%
SYSTEM CONDITION	0.52%	1.83%	21.36%	6.94%
ROUTINE OPERATION	8.55%	0.22%	1.79%	0.00%
OTHER THAN SCHEDULED (2)	4.33%	0.20%	0.99%	0.00%
TOTAL PERCENT	100%	100%	100%	100%
TOTAL NUMBER OF OUTAGES (3) (4)	5 031	12 972	1 512	1 744
SCHEDULED OUTAGES FROM TABLE 18 (5)	78	28	23	0
TOTAL SCHEDULED OUTAGES	5 109	13 000	1 535	1 744
TOTAL NUMBER OF CIRCUIT-YEARS (3)	2 415	4 112	411	207
PLANNED OUTAGE RATE (PER CIRCUIT-YEAR)	2.12	3.16	3.73	8.41

Notes: (1) Excludes outages classified as secondary or common mode.
(2) Outage Type listed as "Planned" but Outage Cause was other than "Scheduled."
(3) Includes circuits from only those utilities whose reported "Planned" outages comprise at least 15% of their total reported outages.
(4) Total excludes the 181 outages in Table 18 with "Scheduled" Outage Cause.
(5) 129 "Scheduled" outages from Table 18 from those utilities whose reported "Planned" outages comprise at least 15% of their total reported outages.

Table 20. Classification of Multiple Outage Events by Outage Type and Voltage.

VOLTAGE (KV)	TOTAL CIRCUITS INVOLVED IN OUTAGE EVENT	INDEPENDENT SINGLE AND SIMULTANEOUS	INVOLVING DIRECT SECONDARY OUTAGES	INVOLVING COMMON-TERMINAL COMMON-MODE OUTAGES	INVOLVING INDIRECT SECONDARY OUTAGES	INVOLVING COMMON-TOWER COMMON-MODE OUTAGES	INVOLVING COMMON-R.O.W. COMMON-MODE OUTAGES
230	1	3 320	41	11	6	2	0
	2	303	46	26	26	1	0
	3	39	4	2	6	0	0
	4	18	0	1	3	1	0
	5	7	1	0	0	1	0
	6	0	0	0	0	0	0
	7	3	0	0	0	0	0
	8	2	0	0	0	0	0
	Total 230KV	3 692	92	40	41	5	0
345	1	5 807	20	9	9	3	4
	2	577	52	61	14	18	4
	3	99	8	13	2	5	1
	4	16	0	2	0	1	0
	5	1	1	0	0	0	0
	6	1	0	2	1	0	0
	7	1	0	0	0	0	0
	Total 345KV	6 502	81	87	26	27	9
500	1	721	10	5	1	0	0
	2	35	58	4	4	0	0
	3	3	19	0	1	0	0
	4	0	2	0	0	0	0
	5	0	1	0	0	0	0
	Total 500KV	759	90	9	6	0	0
765	1	295	1	0	0	0	0
	2	36	12	4	0	0	0
	3	2	4	1	1	0	0
	4	2	0	0	0	0	0
	5	0	0	0	0	0	0
	6	1	0	0	0	0	0
	Total 765KV	336	17	5	1	0	0
Grand Total		11 289	280	141	74	32	9

event would have been classified "common-tower common mode." The voltage level under which the event would have been classified was that of the common tower line. The above ordering of multiple outage types is somewhat validated by the decreasing magnitude of the Grand Totals in Table 20, as one moves from left to right, corresponding to moving from top to bottom of the above list of multiple outage types.

The first row of entries in Table 20 lists multiple-line outages that appear to involve only a single circuit. These entries arise where the multiple outage involved one or more circuits operating at a voltage lower than 230kV or when the initiating event was a planned outage. Neither lower voltage nor planned circuit outages would appear in the forced outage database on which Table 20 is based.

Table 21 summarizes the incidence of each of the various types of fault that initiated primary outages. These are classified by voltage, by problem type (line-related, terminal-related, or unknown), and whether the resulting outage was momentary or sustained. A high percentage of the fault types were designated as "Unknown" or were not classified at all. Table 21 includes the 181 automatic and forced-manual outage events with "Scheduled" outage causes presented in Table 18.

Table 22 summarizes the distribution of the restoration times of automatic and forced-manual outage events. The first portion of the table reports an analysis of the outage durations that excludes all forced outages of unusually long duration (arbitrarily defined here as outages lasting more than 1000 hours). Inclusion of even one such outage event would significantly increase average duration. The rationale for this action was that, even though such an outage may have, in fact, begun as a forced outage, it was eventually transformed to "scheduled" outage as the power system was adjusted to reestablish a secure and economic operating state. The extracted outages are summarized in the second portion of Table 22.

If the outage duration were exponentially distributed, the ratio of the average to the median would be .632/.500 or 1.264. In Table 22 the ratio ranges between 9.1 and 64.1. It is reasonable to conclude that the urgency of repair (e.g., working overtime, not working overtime, etc.) varies from outage to outage as do the requirements for restoration (switching, repair, replacement, etc.).

Table 23 summarizes by voltage level, first, the incidence of the different outage types. Of a total of 36 846 primary outage records, 15 525 were "Automatic" or "Forced-Manual" outages, the remaining 21 321 were "Planned." At 345kV and above, there is a high ratio of "Forced-Manual, Sustained" outages to "Automatic, Sustained" outages relative to the same ratio at 230kV. This raises a question about postponable outages and the variations among utilities in the distinction between a deferred forced-manual outage and a scheduled outage. (Reference [5] provides a definition for Scheduled Outage: "An intentional manual outage that could have been deferred without increasing risk to human life, risk to property, or damage to equipment.") Unfortunately, information on this arbitrary distinction was not requested in the survey.

The second portion of Table 23 summarizes the degrees of sustained primary forced outage. Since most circuits have only two terminals and no sectionalizing breakers, a fault on the circuit usually resulted in completely de-energizing the circuit. A terminal fault may or may not have de-energized the circuit.

The third portion of Table 23 shows the variation in the effect of sustained primary forced outages. Nearly 30% of all sustained outages had no adverse effect; the effect of 62% were not classified.

Table 24 summarizes the data reported on the nature of restoration following forced (automatic, forced-manual, and not-specified) and planned primary outages. As expected, most planned outages are sustained in nature and are returned to service through manual or supervisory-controlled switching. Most sustained forced outages are similarly restored. Most momentary forced outages are returned through automatic switching. In this table, planned outage events with missing end times were assumed to be momentary.

DATA ENHANCEMENT

Often outage records were found to be incomplete. Depending on which fields happened to have been left blank, the use of an outage record may range from limited application to none at all. Certain inferences, however, were made based on information provided elsewhere in the same outage record (that is, the start and end times of the outage, and outage cause). This information provided a basis for filling certain blank fields with codes other than an "NC" for "Not Classified." The bases for assigning a meaningful code to particular fields are as follows. (Any addition to a data record was identified in a new field of what became an augmented data record; the original record was not altered.)

Outage Type An outage may be classified as automatic, forced-manual, or planned based on how it was initiated. When the Outage Type field was left blank, the outage was classified as "Automatic" if the outage cause was one that would precipitate a phase-to-ground fault. Referring to the Cause Codes given in Figure 3, this was considered the case for outage causes: Contamination (5C), and Foreign Interference (cause codes with prefix "3") except for Human (3H) and Tree (3T). An outage was also classified "Automatic" if the outage cause was identified as a Defective Protective System (1SP), Improper Relay Setting (2A), or Power System Condition: Out of Step (4C), Relay Incorrect Operation (4F), Overload Trip (4G), Switching Surge (4J), Dynamic Overvoltage (4K), or Instability (4L). If the outage type was left blank and the outage cause was any scheduled outage (cause code with prefix "6"), the outage type was classified "Planned."

Multiple Outages In cases where a utility had left the Multiple Outage field blank, the circuit outage was assumed to be "Primary/Independent" (I). If, however, it had the same start-time (to the minute) as one or more other circuit outages reported by the same utility, it was, in addition, recognized as "Simultaneous" (IS). If a utility was observed to report all circuit outages as primary/independent, and it was also observed that some of that utility's circuit outages had identical start-times, an "S" was added to the existing "I" to yield the independent and simultaneous code (IS). In either case, the "IS" indicates that the circuit outages in the same utility with simultaneous start times may have been related and part of a single event.

Fault Type The Transmission Outage Data Submission Guide stated that a blank entry in the "Fault Type" data field is intended to mean "No Fault." This, however, led to some confusion in the interpretation of the data submitted. That is, when the data submitter made no attempt to enter fault-type information, care was required not to confuse this with a series of outages each of which had "No Fault." An "NC" was

Table 21. Primary Automatic and Forced Manual Outages * by Fault Type, Problem Type, and Duration Class.

FAULT TYPE	230 KV						345 KV					
	LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN	
	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM	SUST.	MOM.	SUST.	MOM.	SUST.
NO FAULT OR NO OPEN	21.14%	18.01%	89.75%	74.97%	16.67%	12.71%	2.27%	11.02%	15.54%	27.48%	2.29%	3.25%
SINGLE PHASE TO GROUND	52.89%	24.57%	4.95%	6.54%	34.85%	11.60%	17.29%	38.41%	5.70%	3.36%	14.97%	11.39%
PHASE TO PHASE	5.36%	6.99%	0.35%	1.95%	3.03%	0.55%	0.64%	2.23%	0.17%	0.56%	0.83%	0.13%
DOUBLE PHASE TO GROUND	3.61%	2.51%	0.00%	0.83%	0.00%	2.21%	0.20%	0.74%	0.17%	0.35%	0.21%	0.38%
THREE PHASE	1.14%	1.27%	0.00%	0.00%	0.00%	0.00%	0.30%	0.17%	0.00%	0.14%	0.00%	0.00%
THREE PHASE TO GROUND	0.00%	0.97%	0.00%	0.83%	0.00%	0.00%	0.15%	1.60%	0.17%	0.00%	0.00%	0.25%
OPEN PHASE	0.06%	0.30%	0.00%	0.14%	0.00%	0.00%	0.00%	0.06%	0.00%	0.00%	0.00%	0.00%
UNKNOWN	15.18%	45.09%	3.18%	13.91%	45.45%	72.38%	1.93%	5.02%	3.80%	3.15%	6.86%	18.02%
NOT CLASSIFIED	0.60%	0.30%	1.77%	0.83%	0.00%	0.55%	77.22%	40.75%	74.44%	64.97%	74.84%	66.58%
TOTAL PERCENT	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
TOTAL NO OF FAULTS	1 660	2 992	283	719	66	181	2 024	1 752	579	1 430	962	799

FAULT TYPE	500 KV						765 KV					
	LINE		TERMINAL		UNKNOWN		LINE		TERMINAL		UNKNOWN	
	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.
NO FAULT OR NO OPEN	5.23%	27.12%	68.18%	67.49%	0.00%	32.35%	1.60%	29.44%	0.00%	11.45%	0.00%	0.00%
SINGLE PHASE TO GROUND	74.59%	50.36%	4.55%	6.87%	0.00%	0.00%	39.36%	43.46%	0.00%	0.00%	0.00%	0.00%
PHASE TO PHASE	3.44%	5.08%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
DOUBLE PHASE TO GROUND	4.19%	5.33%	0.00%	0.49%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
THREE PHASE	0.60%	1.21%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
THREE PHASE TO GROUND	0.15%	1.21%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
OPEN PHASE	0.00%	1.21%	0.00%	0.49%	0.00%	0.00%	1.06%	3.27%	0.00%	0.00%	0.00%	0.00%
UNKNOWN	1.20%	1.69%	2.27%	2.46%	0.00%	11.76%	0.53%	1.87%	0.00%	0.76%	0.00%	2.22%
NOT CLASSIFIED	10.61%	6.78%	25.00%	20.20%	100.00%	55.88%	57.45%	21.96%	100.00%	87.79%	100.00%	97.78%
TOTAL PERCENT	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
TOTAL NO OF FAULTS	669	413	44	203	24	34	188	214	51	131	62	45

* NOTE: EXCLUDES COMMON MODE OUTAGES

Table 22. Statistics of the Outage Durations (in Hours) of Sustained Primary Automatic and Forced Manual Outages (1, 2, 3) by Voltage and Problem Type.

	230KV			345KV			500KV			765KV		
	LINE RELATED OUTAGES	TERMINAL RELATED OUTAGES	ALL (4) FORCED OUTAGES	LINE RELATED OUTAGES	TERMINAL RELATED OUTAGES	ALL (4) FORCED OUTAGES	LINE RELATED OUTAGES	TERMINAL RELATED OUTAGES	ALL (4) FORCED OUTAGES	LINE RELATED OUTAGES	TERMINAL RELATED OUTAGES	ALL (4) FORCED OUTAGES
AVERAGE	7.94	9.85	8.44	16.65	10.68	14.29	17.94	10.82	15.32	14.2	13.91	12.87
5 PERCENTILE	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.12	0.03
10 PERCENTILE	0.02	0.03	0.02	0.02	0.05	0.03	0.03	0.05	0.03	0.05	0.28	0.1
25 PERCENTILE	0.03	0.13	0.03	0.05	0.17	0.08	0.08	0.17	0.1	0.2	0.5	0.37
MEDIAN VALUE	0.22	0.9	0.3	0.57	0.85	0.72	0.28	1.18	0.45	1.38	1.4	1.4
75 PERCENTILE	2.2	3.65	2.37	6.02	3.85	4.53	3.18	6.28	4.68	8.4	7.07	7.32
90 PERCENTILE	10.3	12.72	10.9	24.7	17.23	22.25	21.43	22.45	22.45	30.8	29.27	28.7
95 PERCENTILE	23.2	24.27	24.1	59.88	41.72	51.45	77.2	63.27	74.37	53.92	59.2	52.25
MAXIMUM VALUE	845.27	823.18	845.27	976.85	854.02	976.85	893.08	180.53	893.08	294.55	272	294.55
TOTAL HOURS (DURATION)	23 693	7 032	32 726	29 095	15 252	56 656	7 411	2 176	9 911	3 039	1 822	5 018
TOTAL NUMBER OF OUTAGES	2 985	714	3 879	1 747	1 428	3 966	413	201	647	214	131	390

NOTES:

(1) EXCLUDES COMMON MODE OUTAGES

(2) ANY OUTAGES OF DURATION LONGER THAN 1,000 HOURS WERE EXCLUDED IN COMPILING DURATION STATISTICS (SEE BELOW)

(3) "SCHEDULED OUTAGES" SHOWN IN TABLE 18 ARE INCLUDED IN THIS TABLE

(4) THIS COLUMN IS THE SUM OF "LINE-RELATED", "TERMINAL-RELATED" AND "UNKNOWN" PROBLEM-TYPE OUTAGES

	OUTAGES LONGER THAN 1,000 HOURS											
TOTAL HOURS (DURATION)	55 581	17 339	74 916	44 345	11 852	130 743	0	4 517	22 038	0	0	0
TOTAL NUMBER OF OUTAGES	7	5	13	5	2	15	0	2	3	0	0	0

Table 23. Distribution of Primary Outages with Respect to Outage Type, Degree of Outage, and Effect of Outage, by Voltage.

OUTAGE TYPE	230 KV	345 KV	500 KV	765 KV
SUSTAINED - AUTOMATIC	31.60%	6.80%	12.47%	7.56%
SUSTAINED - FORCED MANUAL	2.61%	6.72%	9.75%	6.90%
SUSTAINED - NOT SPECIFIED	1.34%	5.85%	0.17%	1.56%
MOMENTARY - AUTOMATIC	17.50%	14.33%	25.33%	11.70%
MOMENTARY - FORCED MANUAL	0.55%	0.34%	0.07%	0.00%
MOMENTARY - NOT SPECIFIED	0.30%	2.67%	0.00%	0.66%
PLANNED	46.09%	63.30%	52.21%	71.62%
TOTAL PERCENT	100%	100%	100%	100%
TOTAL NUMBER OF OUTAGES	10 946	20 563	2 902	2 435

DEGREE OF OUTAGE (SUSTAINED)	230 KV	345 KV	500 KV	765 KV
COMPLETE	95.66%	97.97%	91.23%	100.00%
PARTIAL	0.85%	1.06%	8.77%	0.00%
NOT CLASSIFIED	3.49%	0.98%	0.00%	0.00%
TOTAL PERCENT	100%	100%	100%	100%
TOTAL NUMBER OF OUTAGES	3 892	3 981	650	390

EFFECT OF OUTAGE (SUSTAINED)	230 KV	345 KV	500 KV	765 KV
CASCADING	0.00%	0.00%	0.00%	0.00%
LOSS OF GENERATION	0.62%	0.08%	0.00%	0.00%
LOSS OF TERMINAL BANK	0.00%	0.00%	0.00%	0.00%
LOSS OF LOAD	3.47%	0.08%	1.85%	0.00%
INSTABILITY	0.10%	0.00%	0.00%	0.00%
LOSS OF INTERCONNECTION	2.24%	4.14%	8.92%	0.00%
OVERLOAD	0.00%	0.00%	0.77%	0.00%
LINE DAMAGE	2.80%	0.03%	1.54%	0.00%
EQUIPMENT DAMAGE	0.05%	0.05%	7.54%	0.00%
CONTROLLED LOAD SHED	0.03%	0.00%	0.00%	0.00%
BLACKOUT	0.00%	0.05%	0.00%	0.00%
LOSS OF OTHER CIRCUITS (<230KV)	0.59%	0.38%	0.00%	3.33%
NO ADVERSE EFFECT	40.34%	15.10%	48.46%	43.85%
NOT CLASSIFIED	49.77%	80.11%	30.92%	52.82%
TOTAL PERCENT	100%	100%	100%	100%
TOTAL NUMBER OF OUTAGES	3 892	3 981	650	390

* NOTE: EXCLUDES COMMON MODE OUTAGES

Table 24. Mode of Restoration as a Percent of Total Number of Primary Outages.

	230KV				345KV				500KV				765KV			
	FORCED		PLANNED		FORCED		PLANNED		FORCED		PLANNED		FORCED		PLANNED	
	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.	MOM.	SUST.
AUTOMATIC	31.45%	2 05%	0.10%	0.18%	39.84%	2.00%	1.05%	0.21%	52.42%	11.68%	0.26%	0.00%	41.39%	0.29%	1.26%	0.00%
MANUAL/SUPERVISORY	1.00%	32 25%	2.50%	66.87%	0.42%	35.86%	1.38%	95.59%	0.58%	29.99%	0.53%	82.28%	0.00%	52.24%	0.06%	98.68%
REPAIR/REPLACE	0.17%	5 41%	1.57%	5.57%	0.04%	4.32%	0.01%	0.26%	0.07%	4.04%	0.00%	7.80%	0.00%	0.58%	0.00%	0.00%
UNKNOWN	1.42%	26 25%	0.10%	23.12%	6.94%	10.58%	0.02%	1.49%	0.07%	1.15%	0.00%	9.13%	2.17%	3.33%	0.00%	0.00%
TOTAL # OUTAGES	5 901		5 031		7 546		12 972		1 387		1 512		691		1 744	
TOTAL PERCENT	100%		100%		100%		100%		100%		100%		100%		100%	

* NOTE: EXCLUDES COMMON MODE OUTAGES

inserted in this field to indicate "Not Classified" only when it was obvious that a utility uniformly made no attempt to classify the type of fault. If a utility had occasionally a non-blank code in this field, it was assumed that the data submitter was consistent and that a blank field was intended to mean 'No Fault.'

COMPARISON WITH 1965 SURVEY

The 1949, 1965 and the 1985 surveys had common basic objectives: the pooling of transmission line outage experience to gain a better understanding of outage occurrence rates and causes (especially of rare events), the correlation of line performance with design, and, in general, the promotion of formal collection of circuit outage and exposure history.

Unlike the previous two surveys, the 1985 survey partitioned initiating problems into "Line-Related" and "Terminal-Related" in an attempt to develop outage rates that were functions of circuit length and number of circuit terminals, respectively. Whereas the 1949 and 1965 surveys classified outages only as "Temporary" or "Permanent," the 1985 survey requested outage start and end times to provide a basis for estimating average outage duration. The 1985 survey also collected data on planned outages.

Table 25 provides sample comparisons of the results of the 1965 and 1985 surveys. (A similar table could be developed using 1949 survey results.) The first column provides direct comparisons of the response to the survey, the fraction of the forced outages that were "Sustained" (assumed equivalent to

"Permanent" in the 1965 survey), and the fraction of forced outages that were caused by lightning. (Lightning continued to be the prevalent cause of outage.)

The comparisons in the second column of Table 25 required some manipulation of the data collected in the 1965 survey to ensure a common basis. Because the exposure data for the 1965 survey were expressed only in circuit-mile-years, comparison must be confined to primary forced outage rates as a result of line-related problems. This requires that outages initiated by terminal-related problems be removed from the 1965 results.

In the calculation of the lightning outage rates in Table 24, it was assumed that the outages of "Unknown" problem type collected in the 1985 survey (Table 18) were line-related. These were then combined with

Table 25. Sample Comparisons of the Results of the 1985 and 1965 Surveys.

	1985 Survey	1965 Survey
Time Period Surveyed (1)	21 Years	15 Years
No. of Circuits Involved		
At 230kV	1 071	325
At 287kV	0	10
At 345kV	664	51
At 500kV	204	0
At 765kV	93	0
Total	2 032	386
Circuit Exposure (Mile-Years)		
At 230kV	232 454	145 645
At 287kV	0	10 678
At 345kV	232 949	14 743
At 500kV	78 364	0
At 765kV	39 945	0
Total	583 712	171 066
No. of Primary Forced Outages (2) (Events)		
At 230kV	5 901	1 659
At 287kV	0	213
At 345kV	7 546	896
At 500kV	1 387	0
At 765kV	691	0
Total	15 525	2 568
No. of Primary Planned Outages (Events)		
Total	21 259	0
Fraction of Primary Forced Outages That were "Sustained" (3)		
At 230kV	66%	34%
At 287kV	--	24%
At 345kV	53%	19%
At 500kV	47%	--
At 765kV	56%	--
Overall	57%	29%
Fraction of Primary Forced Outages Caused by Lightning		
At 230kV	22%	36%
At 287kV	--	13%
At 345kV	22%	64%
At 500kV	27%	--
At 765kV	24%	--
Overall	22%	42%

	1985 Survey	1965 Survey
Lightning Outage Rate (4) (Per 100-Mile-Year)		
At 230kV	0.556	0.409
At 287kV	--	0.262
At 345kV	0.698	3.039
At 500kV	0.473	--
At 765kV	0.458	--
Overall	0.596	0.627
Forced Outage Rate (5) (Per 100-Mile-Year)		
At 230kV		
Momentary	0.714	0.648
Sustained	1.287	0.301
Total (6)	2.000	0.971
At 287kV		
Momentary	--	1.461
Sustained	--	0.468
Total (6)	--	1.939
At 345kV		
Momentary	0.869	3.276
Sustained	0.752	0.692
Total (6)	1.621	3.988
At 500kV		
Momentary	0.853	--
Sustained	0.527	--
Total	1.380	--
At 765kV		
Momentary	0.471	--
Sustained	0.536	--
Total	1.008	--
Phase-to-Ground Fault Rate (5) (Per 100-Mile-Year)		
At 230kV	0.713	0.548
At 287kV	--	0.365
At 345kV	0.510	3.147
At 500kV	0.902	--
At 765kV	0.418	--
3-Phase & 3-Phase-to-Ground Fault Rate (5) (Per 100-Mile-Year)		
At 230kV	0.037	0.010
At 287kV	--	0.009
At 345kV	0.018	0.163
At 500kV	0.019	--
At 765kV	0.000	--

Notes:

(1) Time Period Surveyed: 1985 Survey, 1/65-12/85; 1965 Survey, 1/50-12/64.

(2) The event count for the 1985 survey excludes common-mode outages.

(3) Assumes that all outages of duration class "Not Reported" in the 1965 survey were sustained in nature.

(4) Assumes that all lightning outages in the 1965 survey were line-related. Includes "Line-Related" and "Unknown" and excludes "Terminal-Related" lightning problem types assembled in the 1985 survey.

(5) To approximate outage rates due to line-related problems, 1965 outage rates are adjusted to exclude terminal-related outages by removing those caused by "Terminal Equipment", "Undesired Relay Operation" and "Personnel Error". The 1985 outage rates exclude "Terminal-Related" and "Unknown" problem types.

(6) Includes those events for which Outage Type (Momentary/Sustained) was "Not Reported" in the 1965 survey.

those known to be "Line-Related" to calculate the line-related rate. In the results of the 1965 survey, all lightning outages were assumed to have been line-related in the calculation of a comparable rate.

To calculate forced outage and fault rates as functions of circuit length, the following assumptions were made. On the 1985 side, only the line-related outages were considered. (If the outages of "Unknown" problem type were also assumed to be line-related, the outage rate would increase--especially for 345kV.) On the 1965 side, the assumption was made that outages caused by "Terminal Equipment Failure," "Undesired Relay Operation" and "Personnel Error" were terminal-related, and that all other outages were line-related. These were subtracted from the total outage count before calculating the forced outage rate as a function of circuit length.

The sample comparison of the results of the two surveys, as presented in Table 25, suggests the following shifts in outage characteristics. In more recent years, the fraction of primary forced outages that were sustained has increased, while the fraction of primary forced outages that was caused by lightning has decreased. Lightning outage rates, however, appear to have increased in the 1985 survey (recognizing that the 345kV sample in the 1965 survey was small). The line-related primary forced outage rates also appear generally to have increased (an increase that would be even more pronounced if some fraction of the outages of "Unknown" problem-type in Table 18 were assumed to be line-related).

CONCLUSIONS AND RECOMMENDATIONS

On Meeting Survey Goals

In the Introduction, six goals adopted by the Working Group are listed. The first three goals relate to estimating failure rates and restoration times and gaining a better understanding of causes and effects. The results reported in this paper address all three goals with the exception of summarizing the causes of the related multiple outage events. Because of the multiplicity of outage combinations, an event-by-event study is required to adequately generalize the nature of the causes. Further effort in this area will be guided by the interests and concerns of the readers as expressed in the discussion of this paper.

To expedite the publication of the basic survey data, the fourth goal of exploring the correlation of circuit design characteristics with circuit outage rate has been left to a future effort. The nature and depth of this effort will again depend on the level of interest displayed by the readers.

The degree of success in meeting the fifth goal of updating results and determining how performance has changed since the last survey is difficult to assess. The comparison attempted in Table 25 is based on surveys of two different populations. Although the goals were similar, the circuits and their environments were not. The general manner of collecting and recording outage data may have also been different.

With regard to the sixth goal of fostering the uniform and consistent collection of transmission line outage and exposure data, the 1985 survey process was a success. The Transmission Outage Data Submission Guide, along with its companion Circuit Characteristic Data Submission Guide, developed by the Working Group, served as a model and starting point for a number of utilities that had not previously formally collected the data.

The Next Survey

As more utilities institute transmission data collection systems, and as the data are standardized and pooled on a regional basis, the justification for and value of pooling data over a broad and diverse geographic area such as North America falls into question. It is likely that, by the year 2000, most of the utilities that responded to the 1985 survey will be contributing transmission data to regional databases. Because of the increasingly evident inadequacies of deterministic approaches to ensuring the adequacy of transmission systems, many other utilities will have likely implemented data collection systems. Because of these tendencies, the task of updating this survey will be less formidable, and more likely to succeed in satisfying goals similar to those of the 1985 effort. If, however, by the year 2000, many utilities remain uncommitted to the systematic collection of transmission data, then the new survey will collect data that would not otherwise have been assembled, and, as in the past, utility participation in data collection will have been encouraged and advanced.

Whether the effort be focused on the development of a regional database, or on a survey of North America, there should be an effort to better capture and characterize the nature of related multiple outage events. An unfortunate aspect of the 1985 survey was that large blocks of outage data were reported totally as single-circuit independent events.

Time taken in careful preparation of a future survey will pay a significant dividend when the time arrives to analyze the data. Spend time investigating the nature of available data, so that the request for data will not require a heroic effort in response. Care should be taken to clearly define terms and provide codes for all possible situations. Never use an blank field as a response option. Finally, avoid, if possible, undertaking the conversion of a contributing entity's data to the desired format. This task is best done by someone with an intimate and working knowledge of the original data collection system.

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DISCUSSION

RONALD O. GUNDERSON, Nebraska Public Power District, Hastings, Nebraska: The authors are to be commended for the effort in this immense task. The authors state that a significant number of terminal related outage records have been removed from the outage database because of irreconcilable data deficiencies. Not including these outages in the calculation of outage rates will lead to outage rates which are significantly lower than the actual outage rates of the lines. Would the authors indicate how many outage records were excluded and some examples of the type of irreconcilable data deficiencies which occurred.

Historically, outage rates for terminal related outages have been expressed in terms of outages per terminal year. The assumption is made that the number of terminal related outages is directly proportional to the number of terminals. It would be interesting to know if the data supports this assumption. Is the outage rate per terminal year for two terminal lines essentially the same as that for three terminal lines or four terminal lines? Or are the outage rates for multiple terminal lines greater because of the increased complexity of the associated protection systems and the possibility of incorrect operations? Similar questions can be asked of the bus configuration at each terminal. Reference [1] concludes that outage rates and durations for terminal related outages are different for different bus configurations. Can the task force give estimated outage rates for different bus configurations? Future collection efforts should collect data on the type of bus configuration at each terminal.

The goal of correlating circuit design characteristics with circuit outage rates is a worthwhile goal. Utilities need to know how the different design characteristics such as single circuit line vs. double circuit line and different types of construction material and configuration affect the performance of transmission lines. This information becomes more important as the transmission system becomes more heavily loaded and outages become more critical.

The industry needs to better understand what factors influence transmission line performance. By collecting data over a large area with the same format, analyses can be performed which may improve this understanding. For example, do relatively short lines in urban areas have the same performance characteristics as relatively long lines in rural areas? What is the effect of different climates on outage performance? Reference [2] describes an outage data collection format which was developed by two NERC regions and is being utilized by them. This format collects characteristic data on different types of basic construction, terminal configuration, and common exposure. Information is collected for related outage events also.

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M. Oprisan (Canadian Electrical Association, Montreal, Quebec, Canada): I wish to compliment the authors, members of the Working Group on Statistics of Line Outages, on the excellent and comprehensive analysis provided in their paper. From personal experience I know what a formidable task it is to compile such a vast amount of information, ensure the consistency of data and try to derive meaningful statistics which could be of use to the contributors.

The Canadian Electrical Association has collected transmission equipment outage data since 1978 and I have included below, for comparison, a portion of the report covering the 5-year period 1986-1990 for 230 kV transmission lines, both momentary and sustained outages.

Summary of Transmission Line Statistics for Line-Related Sustained Forced Outages

Voltage Classi-fication	Kilometre Years (km.a)	Number of Outages	Total Time (h)	Frequency (Per 100 km.a)	Mean Duration (h)	Unavail-ability (%)
200-299 kV	171,104	929	11,502	0.5429	12.4	0.077

Summary of Transmission Line Statistics for Line-Related Momentary Forced Outages

Voltage Classi-fication	Kilometre Years (km.a)	Number of Outages	Frequency (per 100 km.a)
200–299 kV	171,104	1,008	0.5891

Summary of Transmission Line Statistics for Terminal-Related Sustained Forced Outages

Voltage Classi-fication	Terminal Years (a)	Number of Outages	Total Time (h)	Frequency (Per a)	Mean Duration (h)	Unavail-ability (%)
200-299 kV	4,870	658	3,070	0.1351	4.7	0.007

With regard to momentary and sustained outages, I noticed on page 3 of your paper under Data Summaries that a momentary outage is defined as having a restoration time of less than or equal to one minute. However, a sustained outage is defined as having a restoration time equal to or greater than two minutes. The CEA system defines a sustained outage as having a restoration time greater than one minute. Was the restoration time between one and two minutes purposefully excluded from your definitions?

On Table 18, page 4, among Defective Equipment Primary Causes you list Circuit Breakers, Transformers, Shunt Reactor Banks, etc. I was wondering if these should be actually lumped together with the transmission lines and if by doing so one does not get a somewhat distorted image of transmission line performance. In the CEA system these pieces of power equipment are analyzed separately as components of the transmission system.

I should also note that all Canadian utilities have agreed, from the beginning, to submit the transmission component inventory and outages in full and in a consistent format which resulted in meaningful and useful statistics based on a large database. This can be partly attributed to the fact that the number of utilities involved is rather small even if some of them are large in size. This comment applies to the last paragraph of the "On Meeting Survey Goals" on page 12 and I should add that as far as the Canadian utilities are concerned the interest has been and I believe will always be there for collecting this type of information. I suspect that the same will be true for the U.S. utilities.

In concluding, I would like to know how you see the usefulness of such a survey conducted every 15–20 years. Surveys were conducted in 1949, 1965, 1985 and you seem to be talking about the next one in 2000. You will certainly appreciate the reason for this question since, as I mentioned before, CEA has produced such surveys annually since 1978.

Manuscript received January 26, 1993.

MAIN Transmission Outage Task Force: G. A. Johnson, chairman (Central Illinois Public Service Co.); **E. C. Pfeiffer** (Union Electric Co.); **P. B. Burke** (Commonwealth Edison Co.); **D. L. Smith** (Wisconsin Public Service Corp.); **A. W. Schneider, Jr.** (MAIN Coordination Center): The Mid-America Interconnected Network (MAIN) Transmission Outage Task Force was among the participants in the survey leading to this paper; thus we appreciate first hand the difficulty of providing certain requested data items which were not in our computer file of EHV transmission outages. The Data Analysis Task Force has succeeded beyond our expectations in providing "typical" performance measures which can help the industry to prioritize development of analytical tools. In addition, this survey has stimulated revisions to MAIN data collection procedures so that relevant characteristics of EHV outages are recorded permanently in an easily retrievable form.

From time to time suggestions are made to establish an ongoing collection of EHV transmission outage data covering all of North America. This would be similar to the GADS collection of generating unit outage data. This would be of questionable value because indices computed from such data would probably be poor predictors of the performance of any particular line. There are at least two reasons for this. First, overhead lines operate in very diverse environments, compensated to some extent by the line design. Second, the "vintage" of a transmission line is much more difficult to establish than that of a generating unit, as old lines are cut and extended to new terminals to meet new system requirements.

However, periodic efforts such as this paper stimulate the trend toward complete data collection on outages which is essential to make rigorous estimates of future performance, as in comparing the reliability of alternative designs.

The Data Analysis Task Force has presented forceful conclusions which should be carefully considered in creating or revising regional data collection schemes. The resulting data will be greatly enhanced, and future pooling of data will require much less effort and fewer interpretations and assumptions.

Indices computed using the methods of this paper will be less adequate for lines of more complex topology, such as the 115 kV through 161 kV transmission lines used to supply distribution substations and industrial customers from EHV points of supply. These lines may have greater impact on the reliability of supply to customers, because there is often a lower level of redundancy. They are also subject to frequent sectionalizing and switching. Does the Task Force plan to recommend data collection methods to develop useful performance indices for such lines?

Manuscript received February 16, 1993.

J. Endrenyi and L. Wang (Ontario Hydro, Toronto, Canada): One of the purposes of this survey is to address the need for line outage data in probabilistic modelling for planning and operation. The survey results reported in this paper involves the pooling of line outage data submitted by utilities in the U.S. and Canada. A pertinent question to ask is: can the pooling process be carried out without considering such factors as homogeneity in line design and operating environment? Similar questions have been asked in the pooling of generating unit data, and these questions are now being addressed by the Task Force on Generating Unit Data Pooling of the Application of Probability Methods Subcommittee. Unconstrained pooling may reduce the usefulness of the information.

We noticed that in Table 18 the weather-related outages are separately identified. This is, however, not sufficient information to calculate separate good- and severe-weather outage rates required in some reliability models. To obtain these rates, the average duration of severe weather periods would also be needed. Yet, this information is dependent on the region and probably cannot be pooled. Is any extension of the work foreseen to address this problem?

Finally, we would like to congratulate the members of the Data Analysis Task Force for their effort and valuable contributions in compiling and analyzing a tremendous amount of line outage data.

Manuscript received February 22, 1993.

HELENANN VOLPE AND BRIAN SILVERSTEIN (Bonneville Power Administration, Portland, OR). We commend the Data Analysis Task Force for the excellent job that they did in gathering and analyzing the large volume of outage data that was collected. The results are good indicators of large scale trends in outage rates for transmission lines operating at or above 230-kV.

Would the authors please expand on the "irreconcilable data deficiency" that leads to the caution not to draw conclusions about the ratio of line-related to terminal-related outages.

Reference was made, both in the paper and at the presentation, to the large amount of unanalyzed design related material in the data base [6] and the question arose as to what should be done with it. Perhaps some exploratory multi-variate analysis will point to those design parameters which warrant further investigation, either by this group or by others.

One possibility for future work is to join with the Working Group on Performance Records under the Application of Probability Methods Subcommittee, who have an ongoing effort on Data Pooling for Generators. With contributor permission, and removing utility identification, the data could also be made available to researchers in computer readable form.

Through the efforts of the Task Force, the authors now have a comprehensive understanding of the strengths and weaknesses of the data collection format that was used in this project. Some suggestions are made for

improvement in the section on The Next Survey. If data subsequent to 1985 can be collected in a materially similar form, it may be possible to observe trends in outage rates. This common basis for comparison will make the analysis more valuable.

Manuscript received February 22, 1993.

R. J. Ringlee (Power Technologies, Inc., Schenectady, NY): Appreciation and compliments are due the Data Analysis Task Force for its success in presenting results much more comprehensive than preceding surveys, results that represent a significant contribution to the overhead line performance data base and which should be of value in improving estimates of outage rate and restoration for overhead lines. Collection of data on multiple outage events is a significant addition to the data base. Data on the likelihood of these events are essential for bulk power system reliability prediction and knowledge of their likelihood is a necessary input to rational formation of reliability criteria for design of lines and stations. For exampie, Table 20 indicates that a significant fraction of the multiple outages were identified as arising from common-terminal common mode. Table 18 indicates that nearly one third of the sustained outages for 500 and 765 kV circuits were identified as terminal related. Data in both Tables prompt the question of root cause for the high numbers of terminal-related outages and raise the opportunity to explore the reliability benefit/cost of improved station equipment performance and alternative station designs.

The step of exploring the correlation of circuit outage rate with line design characteristics is of fundamental importance; may the Task Force receive the encouragement it seeks to continue its efforts in this direction.

The authors have indicated that trend analysis should not be attempted by comparison of the data between successive surveys owing to the differing data sets involved. The discussor agrees if the comparison were to be made between statistics representing the aggregate performance of all circuits of a given voltage. There's an alternative that might be considered if the information on specific circuits were available in successive surveys: paired comparisons. Circuits that appear in both surveys would be candidates for making estimates of trends. In like manner, paired comparisons could be made with the circuit data in the latest survey to compare the effect of design by pairing circuits of dissimilar design but located in similar geographical areas and using the data that span the same period.

Manuscript received February 24, 1993.

T. E. McDermott (Power Technologies, Inc., Pittsburgh, PA): The task force has effectively presented a large amount of data on transmission outages, and this information should be valuable to the industry. Other investigators may wish to pursue goal 4 of the survey, by correlating outages with certain design parameters. Would it be possible to maintain the raw data presented in this paper and in [6], in electronic format, under the auspices of the General Systems Subcommittee?

Many of the reported outages were caused by lightning. The IEEE Working Group on Estimating the Lightning Performances of Transmission Lines has a public-domain computer program (FLASH) to predict the lightning performance of overhead lines. With the outage data in this paper and the design data in [6], it may be possible to validate or improve the models in FLASH. The Electric Power Research Institute also has a program (MULTIFLASH) that offers a prediction of multi-phase and/or multi-circuit outages. The data collected by this task force would be very useful in analyzing the results of both programs, if the data were kept accessible in an electronic format.

Manuscript received March 1, 1993.

V. S. Rashkes (former Chief of EHV Field Tests Division of Electric Power Research Institute, Moscow, Russia; now with General Electric at the EPRI High Voltage Transmission Research Center, Lenox, MA): Statistical data on the service performance of HV/EHV transmission lines were collected and analyzed also in the USSR during many tens of years. The high interest of power engineers in each new publication on this subject demonstrates that they recognize very clearly how important and beneficial it is to use service experience for future improvements in transmission reliability.

For American power engineers it would be of interest to compare their own service experience published in the discussed paper with the Soviet one which is summarized in recent publications [1–3].

General characteristic of Soviet transmission network. The territory of the former USSR is much larger than that of the US (22.4 and 9.4 million sq. km respectively), its population exceeds the US population only by 10% (284 and 245 million people in 1988), so the medium density of population was much lower than in the USA. Electric energy production was significantly less than that of the USA and in 1990 reached 1.8 million GW.hours. As a result, main power flows were less than in the USA, and the HV transmission network was not so dense and multicircuit transmission was rare. Nevertheless the total length of HV transmission lines was very large and increased fast (in thousands km):

in 1960- about 150, in 1970- 450, in 1980- 780, in 1990- 1100.

Total length of EHV lines—345 kV and above—was (in thousands km):

in 1960- about 5, in 1970- 28, in 1980- 55, in 1990- 98.

The voltage level of 400–500 kV in Soviet transmissions was reached in 1956–62, 750 kV- in 1966, 1150 kV- in 1985, and in 1990 there were in operation (in thousands km):

330 kV- about 32, 500 kV- 55, 750 kV- 10, 1150 kV- 1.

All Soviet 750 and 1150 kV lines, as well as the absolute majority of 500 kV lines are single circuit. Reserves in network transmitting capacity and in generating capacity are small, so for the Soviet power utilities is very important to reach high service reliability, especially for EHV lines. Progress in line design, proper choice of insulation and overvoltage protection, wide application of high-speed autoreclosing, especially single-pole, efforts to maintain necessary level of service and repair works permitted to reach this goal. Service experience in the USSR was analyzed on a regular base (annually). This helped considerably in improving reliability.

Service experience data. For analysis in [1] author used data of 1981–1985 with total volume about 2.6 million km.year. These data were compared with earlier published [4–7], which covered about 0.3 million km.years during 1959–1980 but were for different regions of the USSR.

The specific number of Soviet line outages for each rated line voltage were (per 100 km.years):

For lines	110 kV	150 kV	220 kV	330 kV	500 kV	750 kV
In 1981–1985	3.0	1.8	1.5	1.5	0.6	0.2
In [4–7]	1.5–3.5	–	0.5–2.0	1.5–3.2	0.58	

The spread in the data of [4–7] is caused by regional differences in insulation contamination, lightning protection etc., so the averaged figures from the more recent survey based on a bigger observation volume are more reliable. For 1150 kV lines, their total length and observation period are too small for dependable evaluation, but preliminary results show that the specific number of outages is about 0.1 per 100 km.year. It is of interest to characterize the reasons of outages for EHV lines. According to [8, 9] the causes of outages of Soviet 500 and 750 kV lines are (in % of total number of outages):

	500 kV	750 kV
Defects of manufacturing and maintenance	17.9	13.7
Ice, snow, conductor galloping, etc.	11.6	3.8
Wind	9.3	20.6
Lightning	12.7	20.0
Flashover of contaminated insulation	4.2	8.6
Fire, mechanical damages by outgoing people and transport	16.6	13.8
Unknown reasons	27.7	17.5

Specific number of outages in the Soviet network is in satisfactory agreement with previously published American and Canadian data including [10].

One of the goals for the analysis performed was to check the effectiveness of high-speed autoreclosing as a very inexpensive measure to improve line reliability. The percentage of arcing faults which could be potentially cleared by high-speed reclosing could be assessed only approximately because faulty phase voltage was not always of sufficient size to determine from the oscillograms of the failure if short circuit was through arc. So probability of arc faults was evaluated as:

110–220 kV- 0.6–0.9, 330 kV- 0.7–0.85, 500–750 kV- 0.65–0.75

(higher values are applicable to lines with higher specific number of outages due to lightning storms or polluted insulation flashovers). Arc faults may be created also by wind, conductor galloping, fire, outgoing vehicles' movement etc., so the incidence of arc faults is in good agreement with the above mentioned statistical reasons of trippings. Possibly, the percentage of arc faults is even higher because special analysis showed that unsuccessful high-speed reclosings originally supposed to be metal or tree short-circuits were associated with too small dead times or with multiple flashovers of contaminated insulation in unfavorable weather conditions.

The proportion of single-phase faults in the total number of line trippings increases with rated voltage and, correspondingly, with growing tower dimensions:

220 kV-0.6, 330 kV-0.8, 500 kV-0.92, 750 kV-0.98.

This means that for EHV lines single-pole high-speed reclosing becomes the main mode of reclosing. Really, although composite single- and three-phase reclosing devices are in common use in the USSR, the single-phase mode of their operation is predominant in the 330-500 kV network and is practically the only one for 750 kV lines. For 750 kV lines three-phase high-speed autoreclosing works only at mistaken trippings of the line.

Success of high-speed reclosing slightly decreases with EHV rated voltage and is somewhat less than in the USA:

	110 kV	220 kV	330 kV	500 kV	750 kV
Single-phase in the USSR	0.58	0.73	0.72	0.62	0.52
Single- and 3-phase total in the USSR	0.75	0.76	0.75	0.62	0.52
Single- and 3-phase total in USA [11]	0.62	0.70	0.85	0.77	0.67.

This primarily occurs because fault rate sharply falls with rise of rated voltage and therefore various defects that autoreclosing cannot correct become more pronounced.

It could be seen that such a simple measure as single-phase high-speed autoreclosing provides continuity of power supply through EHV lines in a half or three quarters of the outages.

Dead time for the Soviet EHV lines usually equals, in dependence of secondary arc current, 0.6–2.5 sec. Automatic devices for high-speed reclosing worked properly in 99.8% of cases. Information about reliability of other kinds of relay protection and automatic devices is given in [3].

A small specific rate of outages in 750 kV lines together with high enough efficiency of high-speed reclosure led to the situation when one tripping of such line due to its failure is statistically as frequent as one tripping due to the failure of substation equipment and 0.5–1 tripping due to malfunctioning of relay protection devices or mistakes of service personnel. The same situation was found in Canada [10]. Such data show the practical necessity of paying attention to equipment reliability, transmission schemes and personnel training.

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Manuscript received March 1, 1993.

R. B. ADLER, C. R. HEISING, T. S. WHITE, M. G. LAUBY, S. L. DANIEL JR., R. P. LUDORF: We hasten to thank the discussers for their expressions of appreciation for the efforts of the Working Group on Statistics of Line Outages. We thank them also for their thoughtful and provocative comments and questions. Their discussion has motivated us to explore further the correlations and implications of the line outage and design history entrusted to us.

Several discussers raised questions on the nature of the data deficiencies that prompted the Data Analysis Task Force (DATF) to discard data. This by and large arose when we had to convert data from one form to another. In these cases, the data were submitted in a format different from the requested format. In several cases, with the help of the data submitter, the DATF developed a conversion program for both the outage and exposure data. In some cases, however, certain essential data was absent. One particularly troublesome type of conversion is from a database developed by a collection system whose primary purpose is to estimate component outage and repair rates. The IEEE format, however, is oriented to the development of outage and repair rates for the transmission circuit as a unit [1].

Concerns about the value of pooled data are ever present. Pooling of non-homogenous data always introduces questions on just what is represented. One of the conclusions of the IEEE Task Force on Generating Unit Data Pooling (of the Application of Probability Methods Subcommittee) is that one must always focus on the planned use of the pooled data in developing the survey forms. The design of the IEEE survey was guided by the goals outlined in the Introduction.

From the members of the MAIN Transmission Outage Task Force, we are pleased to hear that our efforts in developing an effective survey have stimulated review and improvement in data collection procedures. This discusser underscores a important observation: pooling transmission outage data over all of North America provides a poor basis for the predicting the performance of any specific line where weather, terrain and other characteristics are known. Such data pooling over such a broad geographic area does, however, provide initial estimates, which are then tempered in accordance with local conditions. This is especially the case for rare events such as three-phase faults at 500kV and 765kV.

The Data Analysis Task Force agrees that it is desirable to establish a guideline for the collection of outage data on transmission of voltages below 230kV (69, 115, 135 and 161kV). We would recommend that the present questionnaire serve as a starting point for a collection system for outage history at these (sub)transmission voltages.

The DATF agrees with Mr. Ringlee in his observation that a high proportion of outages (both single and multiple) are terminal related. Because of earlier-discussed data deficiencies, many terminal-related outages were not included in the summaries, while line-related outages on the same lines were included. As a result, an even higher proportion of the outages are terminal related. We agree that this observation points to improved station equipment performance as a potentially fruitful area for improving the reliability of the transmission system.

Although it would be desirable to see how the performance of particular lines may have changed from the 1965 to 1985 surveys, the data collected in the 1965 survey are lost. The comparison of circuits of different designs within the 1985 survey, but operating in similar geographic areas, is difficult because of a lack of detailed geographic information requested on the lines. This is a comparison that can, however, be made using the general regional characteristics of the host utility, and will be considered in the next phase of this work.

A clarification on our procedure for removing certain outage data is necessary to address Mr. Gunderson's concern that such omissions may lead to outage rates which are significantly lower than the actual outage rates of the lines. In all cases, the exposure data were adjusted to avoid this consequence. Both line-related and terminal-related outages had to be removed. The largest block of data removed were terminal related outages as noted in Footnote No. 4 to Table 18. The reader is cautioned not to take the ratio of terminal-related to line-related outages, since the terminal-related outages are under represented.

Mr. Gunderson suggests that terminal-related outages on a circuit may not be linearly related to the number of terminals that line has as we have assumed. The reason cited is that the complexity of protection systems increases as the number of terminals increases. Table 18 indicates that a significant portion of the terminal-related outages are due to problems with the protective system at all voltages but 765kV. At 765kV, 100% of the circuits upon which outages were reported have only two-terminals [6]. We will delve more deeply into this observation in the next phase of our work. We cannot, however, do the same for variations in bus configuration, since we did not collect data to characterize this undoubtedly important variable. We agree with Mr. Gunderson that the nature of land development and weather characteristics along the r.o.w. might correlate with outage rate. There is always the balance to be struck, however, between what data might be desirable, what data is readily available, and the possible risk of overwhelming the person assembling and submitting the data.

We agree with Messrs. Endrenyi and Wang in their observation that the weather-related outages reported in Table 18 (under the "Environment" general cause) tell us little about the impact of weather. This is because we did not ask for a characterization of weather exposure in the circuit population data. Table 18 only confirms our suspicion that weather effects are the predominant outage cause within the "Environment" category.

We expect to make better use of the lightning-related outage data in the next phase of the data analysis. Lightning performance will be correlated with isokeraunic level, and with number and angle of shielding wires. We may also find correlation of lightning outages with other design characteristics.

Ms. Volpe and Mr. Silverstein identify the Working Group on Performance Records as a supportive setting for further analysis of the data. The DATF will explore the merits of this suggestion.

It has been the intent of the Working Group on Statistics of Line Outages to document thoroughly the data collection system used in the 1985 survey and to identify its weaknesses [4,6]. The goal is to state the lessons learned and possibly to ease the preparations for the next general survey. In doing so, we would hope also to facilitate the capture and observation of trends over time as Ms. Volpe and Mr. Silverstein have suggested.

Mr. Rashkes has provided some provocative observations on the practice and performance of the Russian transmission system operating at voltages similar to those that we have surveyed. Of particular interest to the DATF are the observations on the fraction of single-phase faults that have occurred on the Russian system, and on the benefits of single-pole reclosing. From Table 21 of the paper, we similarly observe that single-phase faults caused by line-related problems are the predominant cause of outage at all voltages. Whereas the Russian experience has indicated that 60% to 98% of the total trippings are from single-phase faults, our data from Table 21 indicate this portion to lie in the range from 18% to 52%. Perhaps, without single-pole switching to help indicate the nature of the fault, there is a less accurate identification of the fault type. Mr. Rashkes summarizes the success of single- and three-phase high-speed reclosing as lying in the range of a half to three-quarters. If we were to assume the "success" rate to be defined as the ratio of momentary line-related outages to the sum of momentary and sustained line-related outages, we observe a success rate in the range from a third to two-thirds. Single-pole reclosing may have a significant and important positive impact on transmission network reliability.

Some interesting comparisons may also be made to Mr. Rashkes' summary of outage causes. Wind and contamination have much less impact in our survey, which may be the result of either differences in design, or differences in operating environment. Lightning, on the other hand, has a greater impact on line outages. This may be due to a basic difference in circuit design, or to a greater incidence of lightning near those circuits on which data were reported?

We observe that the Russian data appears to be normalized only by circuit length, and not by the number of terminals involved. It appears that no distinction was made between terminal- and line-related outages.

The utilities and power pools responded to the IEEE survey of overhead transmission outages with the agreement that the "data will be held in strict confidence and only summaries will be reported..." The Working Group is, therefore, obliged not to release the detailed data for use by others. As an alternative we are willing to work with any other IEEE working group or task force in exploring the implications of the data. This would include Mr. McDermott's suggestion that we discuss possible data analysis that may be of interest to the IEEE Working Group on Estimating the Lightning Performances of Transmission Lines.

The DATF thanks Mr. Oprisan for sharing his insight on the benefits of pooling data. Since he has offered a sampling of the CEA transmission statistics, we will make a few comparisons of the results at 230kV. (The reader will recall that our data includes CEA data.) Referring to our Table 18 and converting miles to kilometers, our data indicates a line-related sustained forced outage frequency of 0.80 per 100 km.a (compared to CEA's 0.54 per 100 km.a), and momentary forced outage frequency of 0.44 per 100 km.a (compared to CEA's 0.58 per 100 km.a). Our Table 22 shows an average duration of the line-related sustained forced outages of 7.9 hours (compared to CEA's 12.4 hours). With regard to terminal-related sustained forced outages, our data indicates a frequency of 0.06 per terminal.a (compared to CEA's 0.14 per terminal.a), and a duration of 9.8 hours (compared to CEA's 4.7 hours).

Mr. Oprisan has identified a point of confusion in our definition of momentary and sustained outages. We define a momentary outage as one whose duration is one minute or less. Since we request outage start and end times only to the nearest minute, the next larger increment in duration is two minutes. Thus any outage with calculated duration of two minutes or more is considered sustained. Depending on how the data submitter may have rounded off the outage start and end times, an outage that was in fact of duration between one and two minutes may be classified momentary or sustained.

Mr. Oprisan observes that the failure of terminal equipment is listed as outage causes of circuits. Our approach treats the a transmission line and its terminal equipment as a unit, and provides statistics on the "transmission unit." An alternate approach is oriented to the development of statistics on the transmission components. The latter approach is favored by CEA. The DATF found that there are some problems with converting data collected under one approach to a form compatible with the other approach.

Again we thank the discussers for their questions, comments and recommendations. These have provided us with the impetus to forge onward with a more detailed analysis of the data collected.

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FREQUENCY OF TRANSMISSION LINE OUTAGES IN CANADA

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Abstract - Frequent transient and sustained forced outages of transmission equipment can significantly affect the performance of industrial and commercial power systems and the processes they control. A knowledge of the primary causes (e.g., adverse weather, defective equipment, etc.) of transmission line sustained and transient forced outages and which physical components of a transmission line (e.g., line conductors, structure, hardware, etc.) are affected is essential for designing and maintaining reliable transmission systems. Historical transmission reliability data provides the ability to predict [1] the performance of various transmission line configurations and assess the impact of forced outages on industrial and commercial power systems. When no historical voltage sag data is available, historical transmission line reliability statistics can be used to predict the voltage sag activities at a particular site. The prediction methodology will appear in the next edition of IEEE Std. 493 (i.e., IEEE Gold Book). This paper will present a summary of the Canadian Electrical Association's Equipment Reliability Information System statistics on the forced outage performance characteristics of transmission equipment for Canadian utilities for the period 1988 - 1992. The paper will reveal the structure of the data base and present relevant summary data necessary for the application of these reliability methodologies[1].

I. INTRODUCTION

"In 1975 the Canadian Electrical Association (CEA) adopted a proposal to create a facility for centralized collection, processing and reporting of reliability and outage statistics for electrical generation, transmission and distribution equipment. To coordinate the development of this Equipment Reliability Information System CEA constituted the Consultative Committee on Outage Statistics. In 1978, the transmission stage of the information system was implemented when Canadian utilities began supplying data on transmission equipment in accordance with the Instruction Manual for Reporting Component Forced Outages of Transmission Equipment" [2].

The performance of transmission lines can be viewed from many different perspectives. To understand the variance in these perspectives, it is necessary to define the data base structure of transmission line performance data. The structure for the CEA transmission equipment forced outage data base is shown in Figure 1.

The major classifications of transmission lines are according to their operating voltage level and their supporting structure (e.g., double pole wood construction). The forced outage data is divided into two categories; namely, sustained and transient forced outages. The sustained forced outages are further divided into "line-related" and "terminal related" forced outages while transient forced outages are only defined in terms of "line-related" forced outages. The "line-related" and "terminal related" forced outages are further subdivided into primary causes and subcomponent categories.

The identified ***primary causes*** of transmission line forced outages are:

- defective component
- adverse weather
- adverse environment
- system condition
- human element
- foreign interference
- unknown

The identified ***subcomponents*** affected by transmission line forced outages are:

- structural
- joints & deadends
- conductor
- insulation system
- ground wire
- hardware
- other

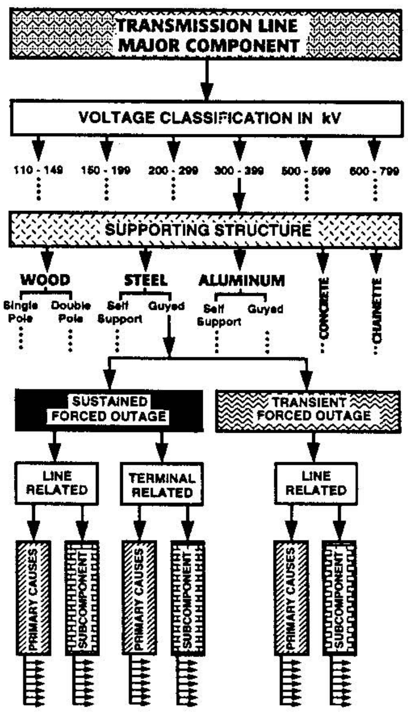

Fig. 1 Canadian Electrical Association transmission line data base structure

Historical transmission line forced outage statistics provide key answers to often posed questions:

1. What are the prime causes of transmission line forced outages?
2. Does the frequency of transmission line forced outages vary significantly with the supporting structure (e.g., wood, steel, etc.) and the operating voltage of a transmission line?
3. How long are transmission line sustained forced outages?
4. What is the weakest link of a transmission line? Is it the line conductors, line hardware, insulators, ground wires, its structure?

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Table I below is a summary of the inventory at December 31, 1992 by voltage classification based on the data supplied by all utility contributors.

TABLE I
INVENTORY OF TRANSMISSION LINES
AS OF DECEMBER 31, 1992

STATISTIC	VOLTAGE CLASS 110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
Length (km.)	41,456	12,255	37,096	9,857	9,061	10,191
Terminals	2,057	167	1,125	271	221	331

II TRANSMISSION LINE "LINE-RELATED" SUSTAINED FORCED OUTAGES

"A **sustained forced outage** refers to a transmission line-related forced outage, the duration of which is one minute or more. It does, therefore, not include automatic reclosing events" [2]. The percentage of transmission line "line-related' sustained forced outages stratified according to the primary cause of forced outages and voltage classification is shown in Figure 2. A summary of transmission line statistics for line-related sustained forced outages is shown in Table II.

The identification of the primary cause as adverse weather (i.e., lightning, rain, freezing rain, ice, snow, wind, high ambient temperature, low ambient temperature, freezing fog or frost, tornadoes) versus defective equipment requires some clarification[3]. "If it is known that equipment has failed as a consequence of adverse weather and that the weather conditions were within the design parameters of the failed equipment then the PRIMARY CAUSE CODE must be DEFECTIVE EQUIPMENT. And conversely, if the weather conditions were outside of the design parameters of the failed equipment (e.g., tornado) the PRIMARY CAUSE CODE must be ADVERSE WEATHER.

TABLE II
SUMMARY OF TRANSMISSION LINE STATISTICS FOR
LINE-RELATED SUSTAINED FORCED OUTAGES

STATISTIC	VOLTAGE CLASS 110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
Kilometer Years (km.a)	215,547	10,867	180,449	46,169	42,431	50,998
Number of Outages	2,849	73	992	133	263	91
Total Time (h)	22,231	619	12,171	2,799	6,291	557
Frequency per 100 km.a	1.3218	0.6718	0.5497	0.2881	0.6198	0.1784
Mean Duration (h)	7.8	8.5	12.3	21.0	23.9	6.1

For all voltage classes of transmission lines, **adverse weather** accounts for approximately 70% of sustained forced outages with the exception of the 600-799 kV voltage class. For the 600-799 kV voltage class, **adverse environment** accounts for a significant percentage of sustained transmission line outages (e.g., 32.96%).

Defective equipment and foreign interference account for another approximately 20 percent of the sustained forced outages while the remaining primary cause categories account for approximately 10% of the sustained forced outages. Adverse environment includes the following conditions: salt spray, industrial pollution, humidity, corrosion, vibration, fire and flooding. [3]

The frequency of transmission line "line-related" sustained forced outages classified by voltage class and supporting structure expressed in "outages per 100 km per year" is listed in Table III.

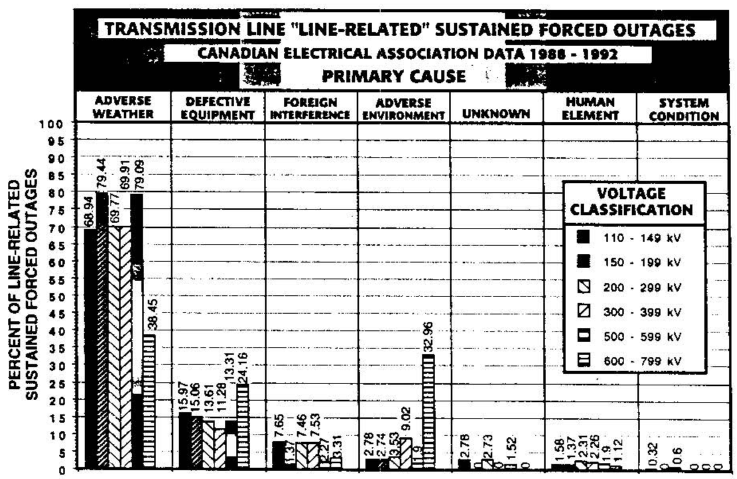

Fig. 2 Percent of transmission line "line-related" sustained forced outages stratified by primary cause and voltage class

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TABLE III
FREQUENCY OF LINE-RELATED SUSTAINED FORCED OUTAGES CLASSIFIED BY
VOLTAGE CLASS AND SUPPORTING STRUCTURE
EXPRESSED IN "outages per 100 km per year"

SUPPORTING STRUCTURE	VOLTAGE CLASS 110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
WOOD SINGLE POLE	0.9725	-	-	-	-	-
WOOD DOUBLE POLE	1.0543	0.8589	0.6147	0.0974	-	-
STEEL SELF-SUPPORTING	1.8976	0.3515	0.4565	0.3114	0.5765	0.2442
STEEL GUYED	1.8722	-	1.6193	0.2243	0.8399	0.0822
ALUMINUM SELF-SUPPORTING	1.3793	-	0.9205	-	0.5253	-
ALUMINUM GUYED	-	-	0.3727	-	-	-
CHAINETTE	-	-	-	-	-	0.1998
ALL SUPPORTING STRUCTURES	1.3218	0.6718	0.5497	0.2881	0.6198	0.1794

The frequency of transmission line outages is the number of outages divided by kilometer years which are in turn divided by 100. It is interesting to note the variance in the frequency of sustained forced outages with increasing voltage classes for a given support structure. The primary causes of sustained forced outages for each supporting structure tend to follow the distinctive statistical pattern shown in Figure 2. Detailed information on individual structures is presented in Reference 2.

The percentage of sustained transmission line line-related forced outages stratified according to the subcomponent which caused a forced outage is shown in Figure 3. The highest percentage of line-related sustained forced outages for all voltage classes is the "insulation system" subcomponent of a transmission line. It is important to note: the "insulation system (of a transmission line) includes the insulation by the atmosphere and/or by the insulators. Hardware is intended to comprise accessories associated with the line conductors but not with the ground wires" [3].

III DURATION OF TRANSMISSION LINE LINE-RELATED SUSTAINED FORCED OUTAGES BY VOLTAGE CLASSIFICATION AND SUPPORTING STRUCTURE

The mean and median duration of line-related sustained transmission line forced outages classified by supporting structure and voltage class are listed in Table IV. Note the significant differences in the mean duration of sustained forced outages for a given supporting structure and for a given voltage class. The important point to not from Table IV is the significant variance between the mean and median line-related sustained forced outage duration levels. The mean value is particularly sensitive to lengthy forced outages which results in the mean value being significantly greater than the median value.

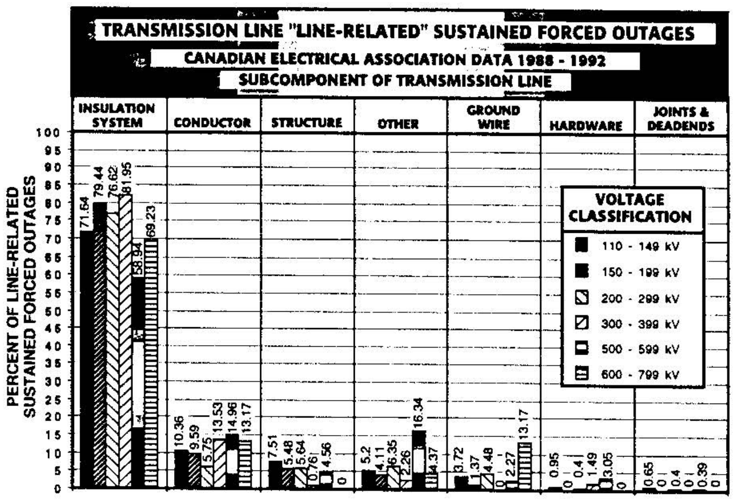

Fig. 3 Percent of transmission line "line-related" sustained forced outages stratified by subcomponent and voltage class

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TABLE IV
THE MEAN AND MEDIAN DURATION OF
LINE-RELATED SUSTAINED FORCED OUTAGES
CLASSIFIED BY VOLTAGE CLASS AND SUPPORTING
STRUCTURE EXPRESSED IN HOURS

SUPPORTING STRUCTURE	VOLTAGE CLASS 110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
WOOD SINGLE POLE	10.8 (0.31)	-	-	-	-	-
WOOD DOUBLE POLE	9.4 (0.10)	4.0 (0.22)	9.8 (0.12)	-	-	-
STEEL SELF-SUPPORTING	6.1 (0.08)	27.2 (0.16)	11.7 (0.15)	22.4 (0.21)	14.5 (0.10)	6.3 (0.05)
STEEL GUYED	1.1 (0.05)	-	19.1 (0.17)	1.1 (0.21)	42.4 (0.22)	1.9 (0.15)
ALUMINUM SELF-SUPPORTING	8.7 (2.26)	-	43.7 (0.05)	-	64.9 (0.79)	-
ALUMINUM GUYED	-	-	7.4 (1.13)	-	-	-
CHAINETTE	-	-	-	-	-	9.0 (0.24)
ALL SUPPORTING STRUCTURES	7.8 (0.10)	8.5 (0.22)	1 2.3 (0.15)	21.0 (0.20)	23.9 (0.15)	6.1 (0.08)

NOTE: Values not enclosed in brackets represent the average value while those values enclosed in brackets represent the median duration of sustained forced outages.

IV TRANSMISSION LINE "LINE-RELATED" TRANSIENT FORCED OUTAGES

A "transient forced outage refers to a transmission line forced outage the duration of which is less than one minute and is, therefore, recorded as zero. It covers only automatic recloser events". The actual duration of transmission line transient forced outages can be estimated from power line monitors but the process is prohibitively expensive and problematic since the duration of the transient forced outage is dependent upon the location of the power line monitor with respect to the origins of the transient forced outage. The percentage of transmission line line-related transient forced outages stratified according to the primary cause of forced outages and voltage classification is shown in Figure 4. A summary of transmission line statistics for line-related transient forced outages is shown in Table V.

TABLE V
SUMMARY OF TRANSMISSION LINE STATISTICS FOR
LINE-RELATED TRANSIENT FORCED OUTAGES

STATISTIC	VOLTAGE CLASS 110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
Kilometer Years (km.a)	215,547	10,867	180,449	46,169	42,431	50,998
Number of Outages	2,493	12	1,031	31	904	35
Frequency per 100 km.a	1.1566	0.1104	0.5714	0.0671	2.1305	0.0686

The percentage of transmission line "line-related" transient forced outages stratified by subcomponent and voltage class is shown in Figure 5. Similar to sustained forced outages, the insulation system of a transmission line accounts for approximately 90% of all transient forced outages for all transmission line voltage classes. Transmission line conductor and ground wire subcomponents represent a very small percent of the sustained forced outages.

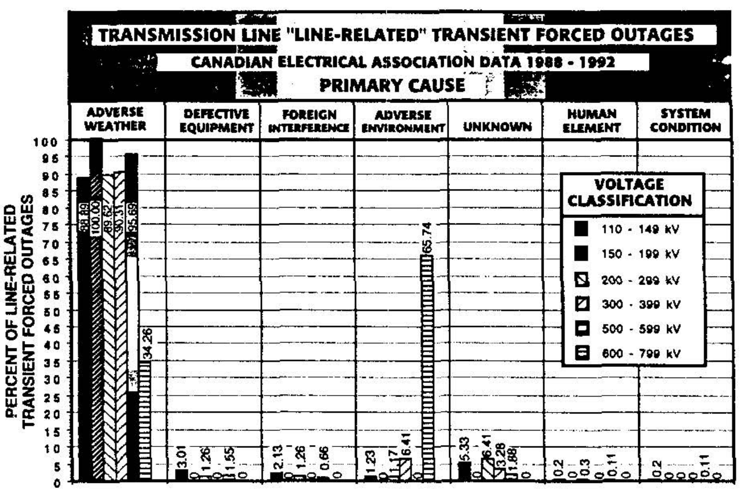

Fig. 4 Percent of transmission line "line-related" transient forced outages stratified by primary cause and voltage class

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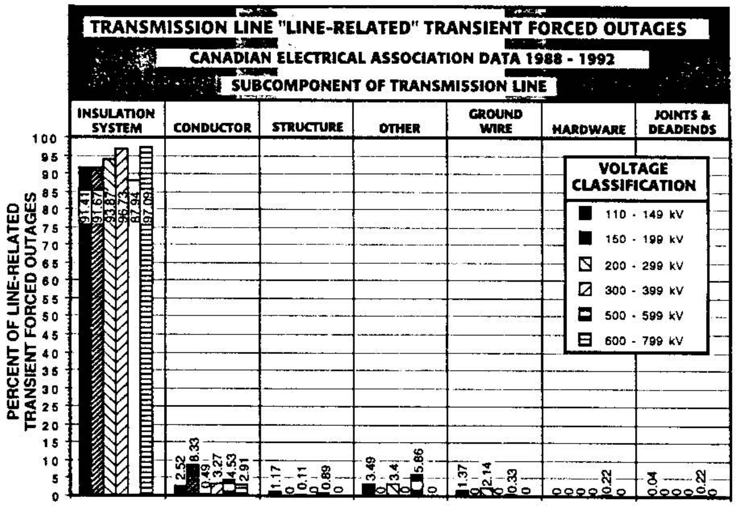

Fig. 5 Percent of transmission line "line-related" transient forced outages stratified by subcomponent and voltage class

The major primary cause of transient forced outages is "adverse weather which accounts for approximately 90 percent of all transient forced outages for all voltage classes except the 600-799 kV class where adverse weather is the dominant cause. The statistical pattern of primary causes of transient forced outages and sustained forced outages is similar.

The frequency of transmission line transient "line-related" forced outages classified by voltage class and supporting structure expressed in "outages per 100 km per year" is listed in Table VI. The frequency of transient forced outages varies significantly for a given supporting structure and for a given voltage class similar to Table III for sustained forced outages. Figure 6 reveals the frequency of transient and sustained forced outages for various voltage classes.

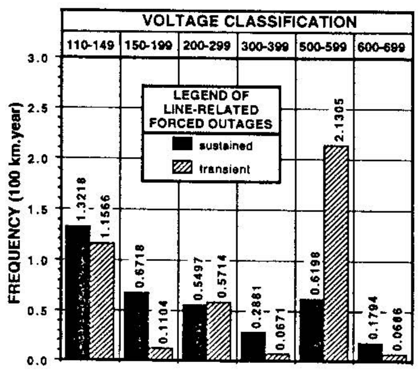

Fig. 6 Frequency of line-related sustained and transient forced outages of transmission lines by voltage classification

TABLE VI
FREQUENCY OF LINE-RELATED TRANSIENT FORCED OUTAGES CLASSIFIED BY VOLTAGE CLASS AND SUPPORTING STRUCTURE EXPRESSED IN "outages per 100 km per year"

SUPPORTING STRUCTURE	VOLTAGE CLASS 110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
WOOD SINGLE POLE	1.2619	-	-	-	-	-
WOOD DOUBLE POLE	1.0495	0.1456	0.7073	0.0	-	-
STEEL SELF-SUPPORTING	1.2743	0.0502	0.5259	0.0764	2.0363	0.1390
STEEL GUYED	0.4309	-	0.2816	0.0408	2.8263	0.0110
ALUMINUM SELF-SUPPORTING	-	-	0.8368	-	1.3133	-
ALUMINUM GUYED	4.2912	-	-	-	-	-
CONCRETE	4.6875	-	-	-	-	-
ALL SUPPORTING STRUCTURES	1.1566	0.1104	0.5714	0.0671	2.1305	0.0686

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V TRANSMISSION LINE "TERMINAL-RELATED" FORCED OUTAGES

A summary of transmission line statistics for terminal-related sustained forced outages is shown in Table VII. It is important to note in Table VII the significant difference between the mean and median duration of terminal-related sustained force outages revealing the impact of lengthy outage duration levels on the mean value.

TABLE VII
SUMMARY OF TRANSMISSION LINE STATISTICS FOR TERMINAL-RELATED SUSTAINED FORCED OUTAGES

	VOLTAGE CLASS					
STATISTIC	110 -149	150 -199	200 -299	300 -399	500 -599	600 - 799
Kilometer Years (km.a)	9,583	627	5,263	1,147	606	539
Number of Outages	1,574	82	991	150	186	153
Total Time (h)	16,352	619	8,618	3,889	8,887	3,949
Frequency per 100 km.a	0.1642	0.1307	0.1883	0.1307	0.3069	0.2394
Mean Duration (h)	10.4	7.0	8.7	25.9	47.8	25.8
Median Duration (h)	0.05	0.30	0.22	0.37	0.64	1.70

The percent of transmission line "terminal-related" forced outages classified by their primary cause and voltage level is shown in Figure 7. Note that the statistical outage patterns of the primary causes of "terminal-related" forced outages is significantly different than "line-related" sustained and transient forced outages. Defective equipment for all voltage classes is the dominant cause of "terminal-related" forced outages. Damage equipment includes some of the following categories [2]:

- deterioration due to age
- incorrect manufacturing design
- incorrect manufacturing materials
- incorrect manufacturing assembly
- lack of maintenance

Research is required to investigate why defective equipment is the dominant cause for transmission terminal-related forced outages for all voltage categories and can the impact of equipment failures be reduced economically. Some of the following questions could be posed:

(1) Are the equipment reliability design levels too low and what are these levels set by the manufacture and utilities?

(2) Is the equipment subjected to rigorous compliance testing during commissioning prior to being accepted?

(3) Is the equipment maintained adequately?

(4) Is the equipment installed correctly in the field?

The "human element" is the second most dominant causes of forced outages while adverse weather is significantly less for all voltage classes with the exception of the 150-199 kV voltage class. The category "human element" includes some of the following issues[2]:

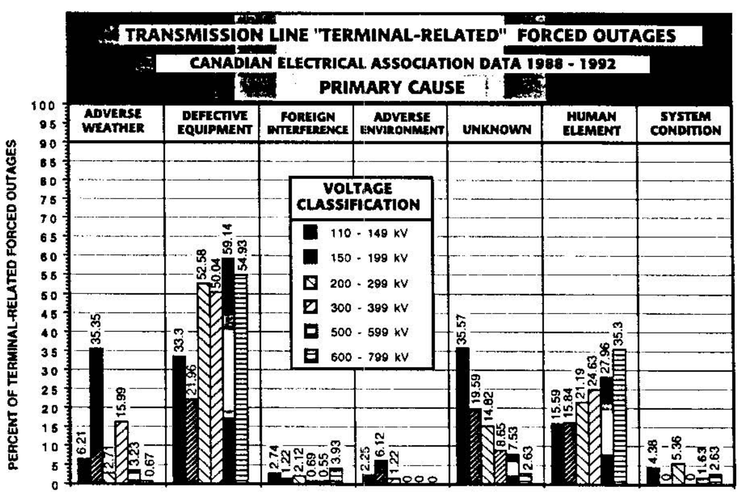

Fig. 7 Percent of transmission line "terminal-related" sustained forced outages stratified by primary cause and voltage class

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- incorrect system records or diagrams
- incorrect use of equipment
- incorrect construction, installation or maintenance
- incorrect protection setting
- switching error
- testing
- incorrect circuit labelling
- deliberate or accidental damage by employees or utility contractors

Research is required to define why the human element is a significant primary cause. Questions concerning the adequacy of training and adaptation to new technologies can be posed.

The percent of transmission line "terminal-related" forced outages classified by their voltage class and subcomponents is shown in Figure 8. With reference to Figure 8, "control and protection equipment" account for the largest percent of known sustained forced outages for all voltage classes. Several questions can be posed on the dominance of "control and protection equipment" causing termnal-related forced outages. They are:

(1) Is the "new" technology a problem"?

(2) Are the setting too complex resulting in conflicting protection control decisions and subsequent failures?

(3) Is the control and protection equipment rigorously tested prior to installation and maintained adequately during its service life?

The "unknown" category was the largest factor for the lower voltage categories and significantly less at the upper voltage levels. For the 600-699 kV voltage class, the disconnect subcomponent was a significant factor. The disconnect and potential device subcomponents accounted for approximately 10 to 30 percent of terminal-related forced outages.

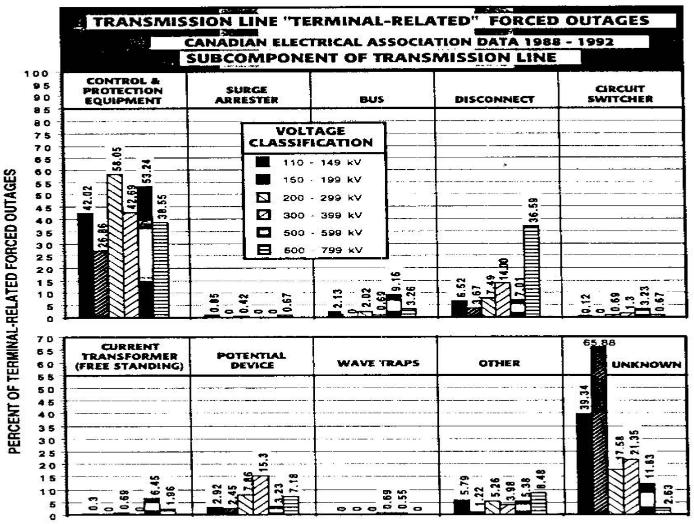

Fig. 8 Percent of transmission line "terminal-related" sustained forced outages stratified by subcomponent and voltage class

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VI CONCLUSIONS

This paper has present a summary of the Canadian Electrical Association's transmission equipment statistics in graphical form to reveal the line-related and terminal-related forced outage performance characteristics of transmission lines. Detailed statistics on other major component of the transmission equipment (i.e., cable, transformer bank, circuit breaker, synchronous compensator, static compensator, shunt reactor bank, shunt capacitor bank and series capacitor bank) are beyond the scope of this paper but are contained in Reference 3.

The frequency and duration of transmission line forced outages classified by their supporting structures was presented to reveal the variance in the performance of different supporting structures (e.g., wood, steel, etc.) for various voltage levels and the possible variance in using a single index for a specific voltage class. The paper revealed the significant difference between the mean duration of transmission line forced outages and the median revealing the impact of lengthy transmission line outages on the mean value. For all voltage classifications, fifty percent of the time the duration of sustained forced outages was less than 15 minutes.

The primary cause of transmission line sustained forced outages was "adverse weather" and accounted for approximately 70% of the sustained forced outages. The insulation system subcomponent accounted for the largest percentage of sustained forced outages. These results provide the research base necessary to improve transmission line design characteristics. The primary cause and major subcomponent that resulted in transient forced outages were similar to the sustained forced outage characteristics (i.e., approximately 90% of the transient forced outages were caused by "adverse weather" and were attributed to the "insulation system".

The primary cause of transmission line "terminal-related" forced outages was "defective equipment" followed by "human element". The "control and protection equipment" accounted for the highest percentage of terminal-related forced outages.

These findings provide a knowledge base which is essential to analyse and evaluate the performance of transmission line with the objective of maximizing their reliability performance. For example, as transmission lines age how will these statistics change and at what point in time and at what level of performance degradation will it be necessary to replace these facilities?

A question often posed is: ' how good are those old transmission line surveys? Answer: they are pretty good, don't throw them away, they are required for trending analysis. The 1988-92 survey results were compared with the 1978-83 survey results for line-related and terminal-related forced outages. The same forced outage patterns were dominate in both surveys. A simple comparison is shown in Table VIII where it is clear that the variance is small for terminal-related forced outages while line-related forced outages the variance is significantly larger (i.e., note lower levels in the latest survey).

TABLE VIII
SUMMARY OF 1988-92 AND 1978-83 FREQUENCY OF LINE-RELATED AND TERMINAL RELATED FORCED OUTAGES

STATISTIC	VOLTAGE CLASS 110-149	150-199	200-299	300-399	500-599	600-799
Frequency of line-related forced outages (per 100 km year)						
(1998-92)	1.3218	0.6718	0.5497	0.2881	0.6198	0.1784
(1978-83)	2.4942	NA	0.9096	0.4444	1.0036	0.3551
Frequency of terminal-related forced outages (per 100 km year)						
(1998-92)	0.1642	0.1307	0.1883	0.1307	0.3069	0.2394
(1978-83)	0.1715	NA	0.2274	0.1596	0.2275	0.4895

VII ACKNOWLEDGEMENTS

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Transmission Equipment Reliability Data from Canadian Electrical Association

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Abstract—Frequent forced outages of transmission equipment can significantly affect the performance of industrial and commercial power systems and the processes they control. Historical transmission reliability data provides the ability to predict the performance of various transmission line configurations and assess the economic impact of forced outages on industrial and commercial power systems. The prediction methodologies are presented in IEEE Std. 493 (i.e., IEEE Gold Book) [1]. This paper will present a summary of the Canadian Electrical Association's Equipment Reliability Information System [2], [3] statistics on the forced outage performance characteristics of transmission equipment (i.e., transformers, circuit breakers, cables, etc.) for Canadian utilities for the period 1988-1992. The paper will reveal the structure of the data base and present relevant summary data (i.e., the frequency and duration of forced outages) necessary for the application of these reliability methodologies. A knowledge of the primary causes of the major equipment forced outages as to whether the outages are primarily due to the subcomponents of the major equipment or to its terminal equipment is essential for designing, operating and maintaining a reliable transmission system. This paper will discuss and identify for each major equipment the primary subcomponent (e.g., transformer windings) and the terminal equipment (e.g., auxiliary equipment) which dominated the forced outage statistics of the major equipment for the five year period.

Index Terms—Transmission, equipment, reliability, CEA, failure.

I. Introduction

"In 1975, the Canadian Electrical Association (CEA) adopted a proposal to create a facility for centralized collection, processing and reporting of reliability and outage statistics for electrical generation, transmission and distribution equipment. To coordinate the development of this Equipment Reliability Information System CEA constituted the Consultative Committee on Outage Statistics. In 1978, the transmission stage of the information system was implemented when Canadian utilities began supplying data on transmission equipment in accordance with the Instruction Manual for Reporting Component Forced Outages of Transmission Equipment" [2].

The performance of transmission lines can be viewed from many different perspectives. To understand the variance in these perspectives, it is necessary to define the data base structure of transmission line performance data. The structure for the CEA transmission equipment forced outage data base is illustrated in Fig. 1.

With reference to Fig. 1, the frequency and duration of major equipment forced outages for each major component presented in this paper will be stratified by voltage classification which will further be divided into two categories, namely;

1) All integral subcomponents of the major equipment
2) All terminal equipment of the major equipment.

For each major component, the dominant subcomponent(s) (e.g., on-load tap changer) and dominant major equipment terminal failures (e.g., control and protection equipment) will be presented. A presentation of all the other subcomponent and terminal equipment failure statistics is beyond the scope of this paper but can be obtain in [3]. Two reliability indices are presented for the duration of equipment forced outages, namely, the mean and mediam. For the majority of transmission system equipment forced outages, there is a significant difference between the mean and the mediam indicating the skewness of the underlying distributions and the sensitivity of the mean to lengthy outages. Given the frequency and duration of forced transmission equipment outage statistics, the reliability methodologies presented in IEEE Std. 493 (i.e., IEEE Gold Book) can be used to predict the performance of transmission system operating configurations and assess their impact on industrial and commercial facilities.

Historical transmission system equipment forced outage statistics provide key answers to often posed questions:

1) What are the prime causes of transmission system equipment forced outages?
2) Does the frequency of transmission system equipment forced outages vary significantly between its internal subcomponent and its associated terminal equipment?
3) How long are transmission system equipment forced outages?
4) What are the dominant subcomponent and terminal equipment outages which significantly degrade the performance of a major piece of transmission system equipment?

II. Transformer Banks

In the Canadian Electrical Association's (CEA) "Equipment Reliability Information System," two types of transformer banks are considered, namely "one three phase element" and "three single-phase elements." The subcomponents of these transformer bank is divided into the following components:

1) Bushing (Including CT's).

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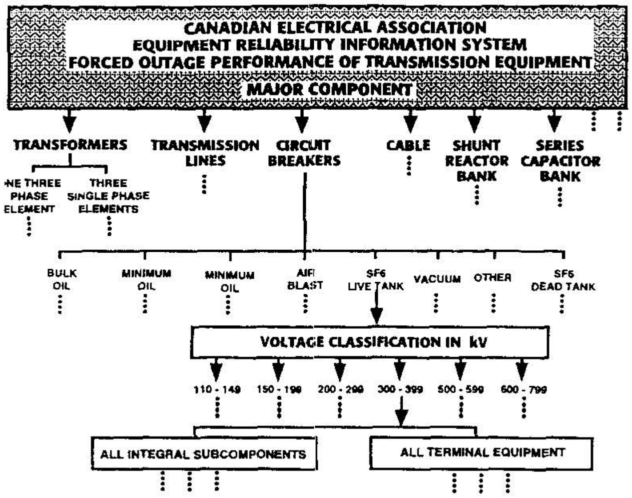

Fig. 1. Canadian Electrical Association transmission equipment data base structure.

2) Windings.
3) Core.
4) Leads.
5) Cooling Equipment.
6) Auxiliary Equipment.
7) Other.

The identified terminal equipment categories for transformers are:

1) Control and Protection Equipment.
2) Surge Arrester.
3) Bus.
4) Disconnect.
5) Circuit Switcher.
6) Current Transformer (Free Standing).
7) Potential Devices.
8) Motor-Operated Ground Switch.
9) Other.
10) Unknown.

The frequency and duration of all integral subcomponents and all terminal equipment forced outages for **one three phase element transformer banks** are listed in Table I.

The dominant known cause(s) of **subcomponent** forced outages for *single three phase transformer banks* for each voltage class and their percentage of the total frequency of subcomponent forced outages are:

110–149 kV	On-load Tap Changer	28.33%
150–199 kV	Auxiliary Equipment	44.40%
200–299 kV	On-load Tap Changer	33.13%
300–399 kV	On-load Tap Changer	25.00%

110–149 kV	On-load Tap Changer	21.10%
150–199 kV	Auxiliary Equipment	39.33%
200–299 kV	Cooling Equipment	15.91%
300–399 kV	On-load Tap Changer	26.32%
500–599 kV	Cooling Equipment	22.22%
600–799 kV	Windings	26.67%
	Bushings (including C.T.,'s)	20.00%
	Cooling Equipment	20.00%
110–149 kV	On-load Tap Changer	28.33%
500–599 kV	On-load Tap Changer	33.33%
	Windings	25.00%
600–799 kV	Cooling Equipment	26.51%

The dominant known cause(s) of {**terminal equipment** forced outages for *single three phase transformer banks* for each voltage class and their percentage of the total frequency of terminal equipment forced outages are:

110–149 kV	Control & Protection Equipment	42.06%
150–199 kV	Control & Protection Equipment	75.00%
200–299 kV	Control & Protection Equipment	42.37%
300–399 kV	Control & Protection Equipment	55.55%
500–599 kV	Control & Protection Equipment	37.04%
600–799 kV	Control & Protection Equipment	50.00%

The frequency and duration of all integral subcomponents and all terminal equipment forced outages for **three single—phase element transformer banks** are listed in Table II.

The dominant known cause(s) of subcomponent forced outages for *three single-phase transformer banks* for each voltage class and their percentage of the total frequency of subcomponent forced outages are:

TABLE I
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES TRANSFORMER BANK ONE THREE PHASE ELEMENT (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
110 - 149 kV	0.0330	509.4	13.88	0.0936	28.0	3.85
150 - 199 kV	0.0510	1.3	0.72	0.0227	52.3	19.49
200 - 299 kV	0.0389	311.1	18.81	0.1136	35.7	5.98
300 - 399 kV	0.0291	745.6	15.13	0.0491	27.2	8.03
500 - 599 kV	0.0587	2,204.3	80.84	0.1320	11.0	4.47
600 - 799 kV	0.1058	1,458.7	8.42	0.0772	76.2	9.10

TABLE II
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES TRANSFORMER BANK THREE SINGLE PHASE ELEMENTS (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
110 - 149 kV	0.0372	173.2	13.72	0.0512	50.9	7.08
150 - 199 kV	0.1632	91.6	3.12	0.0715	47.5	1.67
200 - 299 kV	0.0422	62.2	5.43	0.0498	36.9	1.72
300 - 399 kV	0.0886	426.8	7.07	0.0466	46.9	2.60
500 - 599 kV	0.0327	146.4	15.48	0.0738	18.0	1.92
600 - 799 kV	0.0560	1,550.0	37.07	0.0485	1,157.1	8.05

TABLE III
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS110-149 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPT-ING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
BULK OIL	0.0311	165.8	14.87	0.0522	20.5	2.27
MINIMUM OIL	0.0216	466.0	24.94	0.0339	31.9	0.17
AIR BLAST	0.0402	171.7	21.38	0.0476	116.4	0.13
SF6 LIVE TANK	0.0251	93.0	4.94	0.0474	121.0	0.28
VACUUM	-	-	-	-	-	-
OTHER	-	-	-	-	-	-
SF6 DEAD TANK	0.2366	84.2	24.50	0.2340	72.7	8.69

The dominant known cause(s) of **terminal equipment** forced outages for *three single-phase transformer banks* for each voltage class and their percentage of the total frequency of terminal equipment forced outages are:

110–149 kV	Control & Protection Equipment	31.33%
150–199 kV	Control & Protection Equipment	41.16%
200–299 kV	Control & Protection Equipment	61.54%
300–399 kV	Control & Protection Equipment	60.00%
500–599 kV	Control & Protection Equipment	55.74%
600–799 kV	Control & Protection Equipment	46.15%

III. CIRCUIT BREAKERS

In the Canadian Electrical Association's (CEA) "Equipment Reliability Information System," the following types of circuit breakers are considered:

1) Bulk Oil.
2) Minimum Oil.
3) Air Blast.
4) SF6-Live Tank.
5) Vacuum.
6) Other.
7) SF6-Dead Tank.

TABLE IV

FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS 150-199 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPTING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
BULK OIL	0.0760	41.8	1.38	0.0760	5.6	0.67
MINIMUM OIL	0.0295	107.9	9.90	0.0349	7.3	0.69
AIR BLAST	0.0284	83.5	13.82	0.0481	307.9	3.10
SF6 LIVE TANK	-	-	-	-	-	-
SF6 DEAD TANK	0.0289	45.2	50.71	0.0289	15.0	14.6

TABLE V

FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS 200-299 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPTING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
BULK OIL	0.0561	228.2	5.53	0.1121	25.2	2.41
MINIMUM OIL	0.0582	265.8	8.00	0.0678	62.3	0.96
AIR BLAST	0.1056	99.2	6.95	0.1300	94.5	4.13
SF6 LIVE TANK	0.0172	42.5	4.50	0.0438	8.3	0.30
VACUUM	-	-	-	-	-	-
OTHER	0.0118	4,490.2	4,490.20	0.0235	10.31	0.27
SF6 DEAD TANK	0.0741	105.5	12.96	0.1209	19.4	4.00

The subcomponents of each type of circuit breaker are divided into the following components:

1) Bushing (Including C.T.'s).
2) Operating Mechanisms.
3) Interrupters.
4) Insulation System (Support Insulators).
5) Resistors or Grading Capacitors.
6) Interrupting Medium.
7) Auxiliary Equipment.
8) Other.

The identified terminal equipment categories for each type of circuit breaker are:

1) Control and Protection Equipment.
2) Surge Arrester.
3) Bus.
4) Disconnect.
5) Circuit Switcher.
6) Current Transformer (Free Standing).
7) Potential Devices.
8) Other.
9) Unknown.

The frequency and duration of all integral subcomponents and all terminal equipment forced outages of each type of circuit breaker for each voltage class are listed in Tables III-IX, respectively.

The dominant known cause(s) of **subcomponent equipment** forced outages for **110-149 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

Operating Mechanisms	42.74%
Auxiliary Equipment	18.45%

The dominant known cause(s) of **terminal equipment** forced outages for **110-149 kV circuit breakers** and the percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	60.59%

The dominant known cause(s) of **subcomponent equipment** forced outages for **{150-199 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

Bushings	20.00%
Auxiliary Equipment	18.45%

The dominant known cause(s) of **terminal equipment** forced outages for **150-199 kV circuit breakers** and the

TABLE VI

FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS 300-399 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPT-ING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
BULK OIL	0.1000	20.4	20.43	-	-	-
MINIMUM OIL	0.0116	429.7	28.25	0.0466	274.6	5.45
AIR BLAST	0.0845	189.3	34.60	0.0513	88.2	0.95
SF6 LIVE TANK	0.0132	119.5	119.48	0.0658	3.7	0.63
SF6 DEAD TANK	0.1141	265.0	21.45	0.0552	22.6	2.74

TABLE VII

FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS 500-599 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPT-ING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
BULK OIL	0.0500	715.9	715.87	-	-	-
MINIMUM OIL	-	-	-	-	-	-
AIR BLAST	0.0849	106.1	15.55	0.1297	65.4	4.81
SF6 LIVE TANK	-	-	-	0.6500	3.8	1.73
OTHER	-	-	-	0.2500	96.3	96.32
SF6 DEAD TANK	0.1002	121.4	3.55	0.2246	218.3	7.27

TABLE VIII

FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS 600-699 kV (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPT-ING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
MINIMUM OIL	-	-	-	-	-	-
AIR BLAST	0.2388	318.9	22.28	0.1202	187.7	6.17
SF6 DEAD TANK	0.3158	38.3	21.32	0.0526	722.3	722.27

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
INTERRUPT-ING MEDIUM	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
MINIMUM OIL	-	-	-	-	-	-
AIR BLAST	0.2388	318.9	22.28	0.1202	187.7	6.17
SF6 DEAD TANK	0.3158	38.3	21.32	0.0526	722.3	722.27

percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	17.65%
Disconnect	20.00%

The dominant known cause(s) of **subcomponent equipment forced outages for 200–299 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

TABLE IX
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CIRCUIT BREAKERS (1988–1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
110 - 149 kV	0.0344	187.4	18.35	0.0513	38.9	1.20
150 - 199 kV	0.0339	79.1	6.17	0.0443	145.2	1.88
200 - 299 kV	0.0738	156.1	7.37	0.1053	60.2	2.70
300 - 399 kV	0.0752	199.5	33.91	0.0595	100.9	0.98
500 - 599 kV	0.0814	116.6	8.20	0.1521	118.6	5.99
600 - 799 kV	0.2354	1315.4	22.28	0.1174	190.0	6.17

Operating Mechanisms	36.50%
Interrupting Medium	23.99%

The dominant known cause(s) of **terminal equipment** forced outages for **200–299 kV circuit breakers** and the percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	67.89%
Bus	13.71%

The dominant known cause(s) of {**subcomponent equipment** forced outages for {**300–399 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

Operating Mechanisms	48.80%
Interrupting Medium	32.20%

The dominant known cause(s) of {**terminal equipment** forced outages for {**300–399 kV circuit breakers** and the percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	62.12%

The dominant known cause(s) of {**subcomponent equipment** forced outages for {**500–599 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

Operating Mechanisms	57.55%

The dominant known cause(s) of **terminal equipment** forced outages for **500–599 kV circuit breakers** and the percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	63.63%
Bus	22.73%

The dominant known cause(s) of {**subcomponent equipment** forced outages for {**600–699 kV circuit breakers** and the percentage of the total frequency of subcomponent forced outages are:

Operating Mechanisms	51.99%
Interrupting Medium	22.73%

The dominant known cause(s) of {**terminal equipment** forced outages for {**600–699 kV circuit breakers** and the percentage of the total frequency of terminal equipment forced outages are:

Control and Protection Equipment	40.34%
Disconnect	28.57%

, IV. CABLES

In the Canadian Electrical Association's (CEA) "Equipment Reliability Information System," the subcomponents of cable related forced outages are divided into the following subcomponents:

1) Pothead.
2) Joints.
3) Conductor.
4) Insulation System.
5) Auxiliary Equipment.
6) Other.

The identified terminal equipment categories for cable related forced outages are:

1) Control and Protection Equipment.
2) Surge Arrester.
3) Bus.
4) Disconnect.
5) Circuit Switcher.
6) Current Transformer (Free Standing).
7) Potential Devices.
8) Other.
9) Unknown.

The terminal equipment categories for cable related forced outages is identical to circuit breakers.

The frequency and duration of cable related forced outages for each voltage class is shown in Table X.

The dominant known cause(s) of {**subcomponent** forced outages for *cable related forced outages* for each voltage class

TABLE X
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES CABLE (1988-1992)

	CABLE-RELATED FORCED OUTAGES			TERMINAL RELATED FORCED OUTAGES		
VOLTAGE CLASS	FREQUENCY per 100 km per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY per 100 km per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
110 - 149 kV	3.1884	39.3	3.28	0.1897	20.3	1.26
150 - 199 kV	0.0	0.0	0.0	0.0	0.0	0.0
200 - 299 kV	0.6803	176.5	8.15	0.0101	0.1	0.06
300 - 399 kV	13.3333	17.5	17.52	0.0	0.0	0.0
500 - 599 kV	0.2632	2.8	2.82	0.2000	22.6	2.00

TABLE XI
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES SHUNT REACTOR BANK (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
Up to 109 kV	2.2128	23.1	2.17	2.9362	5.3	1.43
110 - 149 kV	0.5455	38.0	5.07	2.0000	5.7	2.16
200 - 299 kV	4.0000	6.0	5.67	1.0000	1.4	1.40
600 - 799 kV	4.0000	229.9	7.18	1.0000	26.4	8.05

TABLE XII
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES SHUNT REACTOR BANK (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
Up to 109 KV	0.0344	627.8	5.13	0.1484	46.1	0.33
110 - 149 kV	0.0	0.0	0.0	0.0267	0.1	0.08
150 - 199 kV	0.0	0.0	0.0	0.0	0.0	0.0
200 - 299 kV	0.0800	89.4	12.51	0.2000	42.5	4.90
300 - 399 kV	0.0897	91.4	18.50	0.0717	3.3	0.61
500 - 599 kV	0.0314	29.2	7.80	0.0392	46.9	4.93
600 - 799 kV	0.2375	477.9	5.50	0.1029	65.8	4.17

TABLE XIII
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES SHUNT CAPACITOR BANK (1988-1992)

and their percentage of the total frequency of subcomponent forced outages are:

110-149 kV	Insulation System	58.18%
150-199 kV	No forced outages occurred	0.0%
200-299 kV	Insulation System	40.00%
300-399 kV	Insulation System	50.00%
500-599 kV	Insulation System	100.00%

The dominant known cause(s) of {**terminal equipment** forced outages for *cable related forced outages* for each voltage class and their percentage of the total frequency of terminal equipment forced outages are:

110-149 kV	Control & Protection Equipment	40.00%
	Disconnect	37.14%
150-199 kV	No forced outages occurred	0.0%
200-299 kV	Unknown	50.00%
300-399 kV	No forced outages occurred	0.0%
500-599 kV	Control & Protection Equipment	75.00%

The frequency and duration of forced outages for the following equipment are listed in their respective Tables:

1) Synchronous Compensator Table XI.
2) Shunt Reactor Bank Table XII.
3) Shunt Capacitor Bank Table XIII.
4) Series Capacitor Bank Table XIV.

Details of the subcomponents and terminal equipment

TABLE XIV
FREQUENCY AND DURATION OF ALL INTEGRAL SUBCOMPONENTS AND ALL TERMINAL EQUIPMENT FORCED OUTAGES SERIES CAPACITOR BANK (1988-1992)

	ALL INTEGRAL SUBCOMPONENTS			ALL TERMINAL EQUIPMENT		
VOLTAGE CLASS	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)	FREQUENCY occurrences per year	MEAN DURATION (hours)	MEDIAN DURATION (hours)
Up to 109 KV	0.0067	193.3	193.27	0.0	0.0	0.0
110 - 149 kV	0.6857	57.7	5.60	0.1143	377.1	13.60
200 - 299 kV	0.0	0.0	0.0	0.0	0.0	0.0
500 - 599 kV	4.0222	41.0	12.08	2.6000	42.5	18.92
600 - 799 kV	0.2222	2.9	2.92	0.1111	10.0	10.00

forced outages for the above four equipment categories are not provided in this paper due to the scope of the paper, but these details can be found in [3].

V. CONCLUSIONS

This paper has presented a summary of the Canadian Electrical Association's "Equipment Reliability Information System Forced Outage Performance of Transmission Equipment" of the period 1988–1992. The paper presented the frequency and duration (i.e., mean and median) of forced outages of the following major equipment by voltage class:

1) Transformer Banks.
2) Circuit Breakers.
3) Cables.
4) Static Compensator.
5) Shunt Reactor Banks.
6) Shunt Capacitor Banks.
7) Series Capacitor Banks.

For all the major equipment categories, the forced outage statistics were divided into "all integral subcomponents" and "all terminal equipment" categories to provide a clear distinction between the major causes of transmission system equipment. For each major equipment category, the dominant subcomponent and dominate terminal equipment which contributed the most to the frequency of the major equipment forced outages was identified.

For transmission banks, the subcomponent and terminal equipment frequency of forced outages were of the same order of magnitude for the on-three phase element transformer bank and the three-single-phase element transformer bank. In the majority of cases, for both types of transformer banks, the mean duration was significantly greater than the median for all voltage classes. The dominant transformer bank subcomponent forced outages were "On-load Tap Changer" and the "Auxiliary Equipment" for all voltage classes. The dominant transformer terminal equipment forced outages was the "**Control and Protection Equipment**" for all voltage categories.

For circuit breakers, the higher the voltage class, the higher the frequency of forced outages for subcomponent and terminal equipment forced outages. The mean duration for subcomponent and terminal equipment forced outages was significantly higher than the median for both categories. The dominant circuit breaker subcomponent forced outages were the "Operating Mechanisms" and the "interrupting Medium." The dominant circuit breaker terminal equipment forced outage category was "**Control and Protection Equipment.**"

For cables the terminal related forced outages were significantly less than the cable related forced outages. The dominant cable subcomponent forced outage was the "Insulation System" and the dominant terminal related forced outage was again "**Control and Protection Equipment.**"

The frequency and duration of transmission equipment forced outage statistics presented in this paper provides the basis for analyzing transmission system configurations and assessing the impact of forced outages on industrial and commercial facilities (e.g., voltage sags at a given physical location, the cost of power outages, the optimum operating configuration, etc.). The methodologies for performing these studies are found in IEEE Std. 493 (IEEE Gold Book).

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