Research on Common-Mode and Dependent (CMD) Outage Events in Power Systems– A Review

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Research on Common-Mode and Dependent (CMD) Outage Events in Power Systems– A Review

The RRPA Subcommittee Working Group PACME

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***Abstract*—The purpose of this paper is to present a review of some fundamental concepts and practical applications in the area of common-mode and dependent (CMD) outage events in power systems. The paper is a result of ongoing activity carried out by the Probability Applications for Common and dependent Mode Events (PACME) Working Group (WG) of the Reliability, Risk and Probability Applications (RRPA) Subcommittee. The PACME Working Group was formed in 2010 to review, advance and present the research and practical applications in the area of CMD outage events. The paper presents state-of-the-art in research, modeling and applications of CMD outage events in power system planning and operation. Issues considered include: data monitoring and collection, and probabilistic modeling and evaluation in the planning and operation of power generation and transmission systems. Additionally, some results obtained from outage data statistics corresponding to CMD outage events in systems such as GADS, TADS, and CEA are presented.**

***Index Terms*—** Bulk power systems, CEA, common-mode and dependent outage events, failures, GADS, outage data, TADS, transmission system reliability.

I. INTRODUCTION

Maintaining an adequate level of reliability in the planning and operation of the power system is a fundamental aspect of an electric utility's strategy. The advantages of probabilistic techniques over deterministic approaches (e.g. withstanding a single outage or N-1) in reliability studies have been recognized [1]-[6]. The primary assumption in early probabilistic studies was that component outages were random events occurring independently [1]. This assumption simplified the calculation process, but is unwarranted in many practical cases. Previous studies and studies undertaken by several Institute of Electrical and Electronics Engineers (IEEE) Task Forces and Working Groups (WG) show that common-mode and dependent (CMD) outage events can significantly reduce power system reliability [7]-[13].

Papers published by PACME WG present a review the fundamental concepts in modeling CMD outages [7]-[10]. They indicate that considerable activity has taken place in many parts of the world in creating rigorous reliability models and evaluation techniques that are capable of dealing with CMD failure events. These papers also show that accurate analysis of CMD outage events in reliability evaluation requires proper definition and mathematical modeling of such events. The underlying concepts of these models and techniques reflect the various philosophies, policies, and operational constraints of different utilities. Several mathematical models that rigorously consider CMD outage events are available, but most data collection procedures are inadequate to calculate the performance indices needed to forecast the impact of such events [7].

Reference [11] shows that most of the current methods of calculating a generation system loss of load probability (LOLP) assume generator-forced outages are independent; i.e., the forced outages of a unit are not related to those of other units. Some outages of generating units, however, are not independent events, the proportion depending on issues of plant configuration [11]. In addition, the rate and duration of forced outages are function of generator utilization and maintenance effort.

Modeling protection system failures and misoperations that in most cases result in dependent outage events is an important topic that has been studied in the past [14]-[16]. Advanced control technologies create even more complex modes of failure which may outage multiple units. Integration of variable energy sources into power system presents further difficulties and challenges in data classification and modeling of CMD [17]-[18].

This paper presents the results of ongoing research carried out by the PACME WG of the RRPA Subcommittee. It goes beyond its earlier published conference papers [7], [9]-[10] by assimilating all of the WG's work on the topic, and by calculating the basic common-mode and dependent indices for typical transmission elements using CEA, NERC TADS and WECC TRD outage data systems and for generators using NERC GADS outage data system. In addition, this paper provides a summary of challenges and opportunities for the future work.

The goal of this paper is to provide a review on issues related to CMD outage data monitoring and collection, probabilistic modeling and evaluation, and their application in the planning and operation of electric power systems.

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The paper aims to 1) review and discuss basic definitions of CMD outage events, 2) review major causes of CMD events, 3) review the development of models and methods considering CMD events, 4) calculate representative indices of CMD outage events from the major North American outage databases, and 5) present challenges in modeling and assessing the impact of CMD events on the performance of power systems.

II. DEFINITIONS AND ILLUSTRATIVE EXAMPLES OF CMD EVENTS

Basic terminology and definitions of independent, common-mode and dependent outage events used in this paper are those defined in IEEE Standards [19]-[20] and the North American Electric Reliability Corporation (NERC) Transmission Availability Data System (TADS) [21].

A. Common-Mode Outages

A detailed list of illustrative examples for common-mode outages is provided in previous WG papers [8], [10]. The presence of a single "actor" is the principal distinction from dependent or cascading outage events.

B. Dependent Outages

A dependent outage or outages may result from a number factors, such as failure of equipment, malfunctioning of protective devices, weather conditions, natural disasters, loading conditions, power transfers, maintenance, human error, etc. Usually, an initiating event for a dependent outage propagates via different mechanisms beyond the initial outage to multiple outages, which sometimes result in cascading failures [7], [10]. Assessing the conditional probability of such dependent events has always been a challenge for utility planning and operation departments. Reference [21] lists the following five categories of cause codes that could potentially result in a dependent outage event.

1) *Failed AC Substation Equipment:* Failed alternating current (AC) substation equipment failures, most commonly a stuck circuit breaker often results in dependent outages. The TADS manual defines this category as a failure of substation equipment 'inside the substation fence,' including transformers and circuit breakers but excluding protection system equipment [21].

2) *Failed Protection System Equipment:* Protection system failures and misoperations often result in dependent outages. As the name implies, the TADS manual defines this category as the failure of protection system equipment including any relay and/or control misoperations [21].

3) *Human Error:* Human error can, in some situations, cause dependent outages. The TADS manual defines these as outages caused by any incorrect action traceable to employees and/or contractors operating, maintaining, and/or providing assistance to the transmission owner [21]. An example would be a relay setting error.

4) *Power System Condition:* Power system conditions such as instability, overload trip, out-of-step, abnormal voltage, or abnormal frequency can also cause dependent outages [21].

5) *Weather-Related Outages:* Weather-related outages can cause dependent outage events in a power system. They are defined in TADS manual as outages caused by weather, such as snow, extreme temperature, rain, hail, fog, sleet/ice, wind (including galloping conductor), tornado, microburst, dust storm, and flying debris caused by wind [21].

III. MODELS AND METHODS REVIEW

The creation of models and methods and the evolution of data collection and reporting are two complementary aspects that need to be adequately addressed in the development process [8].

A. Basic Component Models

The basic component model in power system reliability studies is the two-state representation in which a component is either in the operable (up) state or an inoperable (down) state, and failure and restoration rates are constant [1]-[7]. Including active and passive failures of components that participate in switching actions of the station involves a three-state model to enhance the basic two-state representation [22].

B. Common-Mode Models and Methods Reviews

Traditionally, common-mode outages are regarded as low probability events. Although the frequency of common-mode failures may be an order of magnitude less than that of independent outages, the probability of system failure can dramatically increase by including the possibility of common-mode outages into consideration.

A Task Force of the Application of the Probability Methods (APM) Subcommittee proposed the definition and a model of common-mode forced outages of overhead transmission circuits in [8], which was later modified by introducing a common-cause repair for the common-cause failure [23]-[27].

C. Dependent Models and Methods Reviews

A state transition diagram of a two-component system considering independent, dependent mode, and dependent mode initiating outages is presented in Fig. 1 [28]. In Fig. 1 λ and μ denote outage and restoration rates, respectively, with the suffixes indicating the element outaged or restored. $P_{2/1}$ denotes the probability of element 2 being outaged for a fault on element 1, and conversely.

The effect of various types of dependent outages on composite system reliability performance is presented in [29]-[37]. Reference [34] considers dependent outages in a security-constrained adequacy evaluation of composite systems.

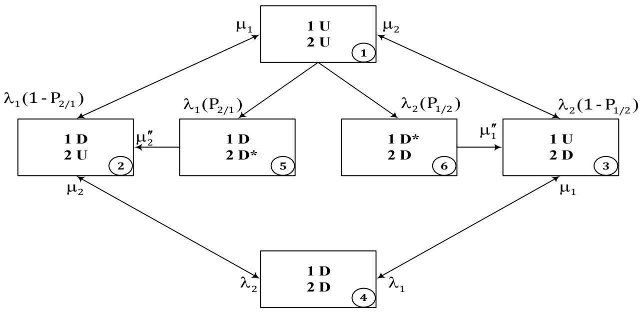

Fig. 1. State transition diagram of a 2-component system considering independent, dependent mode and dependent mode initiating outages (* down state as result of a dependent outage)

1) Environment-Related Outages: Early models of transmission circuits recognized that during stormy periods, environmental conditions may increase the failure rates to a much higher level than during normal weather [3]. Reference [4] uses the Markov approach to model components exposed to a fluctuating environment and presents a thorough analysis of various degrees of failure occurring during stormy weather. It was noted that in adverse weather, even if failures are independent conditional on the weather background, failure bunching may occur due to the increased failure rate leading to a higher probability of overlapping failures. A complete set of equations for calculating the reliability indices for parallel transmission circuits exposed to a fluctuating environment are given in [4], [25]. Modeling extreme (as opposed to adverse) weather in power system reliability evaluation is presented in [24]-[32]. Reference [17] describes a coherent framework and a methodology, developed during the European research project AFTER (2011-2014) [33], to characterize weather events (like storms) in terms of probability distributions of stress variables (such as wind or precipitation rate) over different time intervals (from few minutes to hours).

2) *Substation Originated Outages:* Multiple outages of transmission elements can arise from station-originated causes, such as a ground fault on a breaker, a stuck breaker, a bus fault, or a combination of these conditions. A state transition diagram that includes both independent and station-related outages is presented in [7]. Models of substation-related outages that have been used in the reliability analysis of composite power systems are presented in [34]-[36].

3) *Protection Failures and Misoperations:* Protection failures and misoperations, including hidden failures, are another important source of dependent outages [14]-[18]. The importance of modeling the mechanism of protection failures and how those models have been used in the reliability of composite power systems is shown in [38]-[42].

4) Failures of Cyber Devices and Cyber Attacks: Prior to the 1970s power system protection and control devices were generally associated with a single transmission element and circuit breakers interfacing it to other adjacent elements. The introduction of distributed computer devices communicating through non-dedicated phones and later, internet communications created the possibility of very complex interactions among the sub-systems used for control, communication, protection and defense, and they span a broad range of time frames and cover wide interconnected areas. As a result, system operation is becoming more and more dependent on the dependability and security of information and communication technology (ICT) systems. Possible malfunctions in protection control and communication systems may greatly affect the response of the power system to disturbances. Therefore, modeling and evaluating interdependencies on ICT systems becomes very important, as noted in recent publications [43]-[45].

5) *Multiple n-k Outages:* Considerable work on identifying n-k outages that are the result of one or more of the listed above sources of CMD events has been published [46]. Reference [46] examines and addresses the issue of identifying, modeling, and assessing the impacts of multiple n-k outages.

6) *Cascading Failures:* Cascading failures are a special category of dependent events that can result in widespread electric-service interruptions that cannot be restrained from sequentially spreading beyond an area predetermined by studies [47]. The growing interest in analyzing high-impact, low-probability events together with the increasing availability of data coming from on-line monitoring systems are two important drivers for the recent developments of probabilistic risk-based approaches [17].

IV. OUTAGE DATA REPORTING AND ANALYSIS

Reference [10] presents an overview of outage data collection systems in North America and Europe. Much of the data pertaining to outage events in the USA is available from the Generating Availability Data System (GADS) [48]-[49] and the TADS maintained by NERC [21]. Generation data collection under GADS dates began in 1982, but nationwide transmission outage data collection under TADS began only in 2008. Prior to this, there was no uniform practice in transmission outage data collection across the U.S. Canadian utilities have had consistent transmission data collection practices for many decades, and this data is available on the Canadian Electrical Association (CEA) website [50].

Recent publications present representative indices for CMD outages [10], [51]-[52].

The WG paper [10] presents transmission CMD indices for circuits and transformers. Subsequent subsections show the results of CMD indices for transmission and generation.

A. Transmission

Basic common-mode and dependent indices for AC circuits and transformers calculated from TADS (nationwide) outage data for 2008-2014 are presented in Table I.

Basic common-mode and dependent indices for AC circuits and transformers calculated from WECC TRD (western US and Canada) outage data for 2008-2014 are presented in Table II.

Comparing the indices calculated from these two databases indicates the following:

The frequency of common mode outages of transmission circuits is about the same in NERC TADS and WECC TRD but the average duration is much higher in TADS than in TRD. It should be noted that very few lines in the 600-799 kV class are on common towers with another line, which is the most common relationship for lines experiencing a common mode outage. WECC has neither ac lines nor transformers in this class.

The frequency of common mode outages of transformers is about twice as high in TRD for voltage classes 200-299 kV and 400-599 kV and the average duration for voltage class 400-599 kV is significantly higher in TADS than in TRD.

Results for dependent mode outages of transmission circuits from NERC TADS and WECC TRD in Tables I and II show that the frequency index is about the same, but the average duration is higher in TADS than in TRD.

Results for dependent mode outages of transformers from NERC TADS and WECC TRD in Tables I and II show that the frequency index is about the same, but the average duration for voltage classes 300–399 and 400–599 kV is significantly less in TRD than in TADS.

Basic common-mode indices for transmission circuits and transformers, as well as for circuit breakers and terminals, calculated from outage data in the CEA Equipment Reliability Information System (ERIS) from 2008 to 2014 are presented in Table III. Data for voltage classes under 200 kV has been omitted. Because CEA data is focused on components rather than the complete ac circuit or transformer bank, it is not directly comparable to that shown in Tables I and II for TADS and TRD.

Fig. 2 presents the average duration for common-mode outages for transmission lines and transformers calculated from TADS, TRD, and CEA.

TABLE I
TADS Common-Mode and Dependent Mode Indices

Element Type	Voltage Class	Outage Frequency*		Sustained Outage Frequency*		Sustained Outage Duration/Repair Time (hours)	
		Common Mode	Dependent Mode	Common Mode	Dependent Mode	Common Mode	Dependent Mode
Transmission AC Circuits	**ALL**	**0.1656**	**0.3316**	**0.1206**	**0.2199**	**48.8**	**39.7752**
	200-299 kV	0.1967	0.3321	0.1426	0.2275	32.9	34.7950
	300-399 kV	0.1520	0.3861	0.0982	0.2280	62.0	23.9016
	400-599 kV	0.1136	0.2202	0.1061	0.1667	67.3	89.5125
	600-799 kV	0.0282	0.3058	0.0134	0.1989	11.5	16.7084
Transformers	**ALL**	**0.0235**	**0.1216**	**0.0215**	**0.0774**	**251.7**	**331.0781**
	200-299 kV	0.0290	0.1743	0.0166	0.0871	2.2	51.4033
	300-399 kV	0.0298	0.1509	0.0264	0.0767	131.9	493.6428
	400-599 kV	0.0237	0.1052	0.0230	0.0761	336.2	228.5995
	600-799 kV	0.0092	0.1257	0.0077	0.0812	27.9	606.6909

*Note: The unit for transmission AC circuits is per hundred miles per year, and for transformers is per element per year.

TABLE II
WECC TRD Common-Mode and Dependent Mode Indices

Element Type	Voltage Class	Outage Frequency*		Sustained Outage Frequency*		Sustained Outage Duration/Repair Time (hours)	
		Common Mode	Dependent Mode	Common Mode	Dependent Mode	Common Mode	Dependent Mode
Transmission AC Circuits	**ALL**	**0.1648**	**0.2545**	**0.1409**	**0.2108**	**16.7**	**30.1**
	200-299 kV	0.1831	0.2634	0.1537	0.2197	19.0	26.2
	300-399 kV	0.1410	0.2711	0.1111	0.2101	25.4	2.6
	400-599 kV	0.1386	0.2327	0.1317	0.1967	5.0	60.6
Transformers	**ALL**	**0.0310**	**0.1594**	**0.0283**	**0.0861**	**7.4**	**53.5**
	200-299 kV	0.0375	0.2566	0.0250	0.1252	2.2	53.7
	300-399 kV	0.0174	0.2788	0.0131	0.1089	9.1	5.6
	400-599 kV	0.0353	0.1035	0.0345	0.0730	7.6	79.8

*Note: The unit for transmission AC circuits is per hundred miles per year, and for transformers is per element per year.

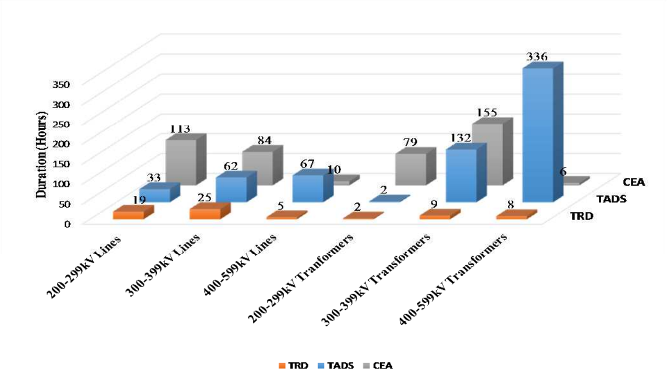

Fig. 2. Average Duration of Common-Mode Outages for Transmission Lines and Transformers Calculated from Outage Data in TADS, TRD, and CEA

TABLE III
CEA ERIS Common-Mode Indices

Common Mode	All EHV Classes	Transmission AC Circuits	Transformers	Terminlas	Circuit Breakers
Frequency ***	200-299	0.0004	0.0194	0.0015	0.0174
	300-399	0.0008	0.0618	0.0043	0.0134
	400-599	0.0002	0.0188	0.0155	0.0195
	600-799	0.0003	0.0596	0.0093	0.0211
Mean Duration (h)	200-299	113.3	78.8	84.9	76.5
	300-399	83.7	155.1	9.8	66.4
	400-599	10.3	6.3	1.8	122.6
	600-799	1006.9	608.5	4.6	566.7
Unavailability (h/y)	200-299	0.0453	1.5277	0.1293	1.3292
	300-399	0.0670	9.5812	0.0417	0.8891
	400-599	0.0021	0.1174	0.0282	2.3976
	600-799	0.3021	36.2365	0.0428	11.9707

***Note: The unit for transmission AC circuits is per hundred miles per year, and for other elements is per element per year.

B. Generation

Compared to transmission outages, outages on the generation side have some different features. In general, they are more complex than transmission outages from the perspective of their causes. This is because a generating unit has more elements located in a limited space (i.e., power plant) with many moving or dynamic parts. With regard to the CMD outages, the generation facilities have both internal and external outage events according to the location of the causes.

The internal CMD outage events are those for which the cause of a generator outage was within the same plant. Such outage events are largely related to failures of elements providing shared service in the plant. Units under 100 MW, for which shared facilities offer significant economies, are more common for hydro and gas turbine units than for fossil, combined cycle or nuclear units. Typical shared components in current plants include step-up transformers or GSUs, fuel handling systems, and dam and gates in hydro plants. In the past common header steam supplies feeding several small generators created similar vulnerabilities.

External CMD outage events are referred to generator outages that are related to causes outside the plant. These types of outage event are usually out of management control of the power plant. Some typical examples are failures of the transmission lines, which connect the plant for power delivery; the problems of gas supply pipelines, which are not the property of the power plant; and the natural catastrophes, which are usually due to extreme weather conditions, such as tornadoes, hurricanes, and floods.

Unlike a transmission line being simply reported as on outage, a generator can have different abnormal states which are reported as either full outages or as partial outages (deratings). As a result, the Equivalent Forced Outage Rate (EFOR) is a widely used measure of performance rather than the basic Forced Outage Rate (FOR). In current probabilistic reliability studies, these performance indices are assumed to be constant. If CMD outages are considered, these generation indices could possibly no longer be constant values depending on the health of the system and the limitations of repair resources [11].

In practice, important generation parameters, such as FOR and EFOR, are usually derived using statistical information of outage events over a specific period of time from generation data collection systems. It would be useful to know the nature of CMD outages if information on the portion of these outages among all forced outages could be found in a generation data collection system.

GADS is the most important generation data collection system used in the North American regions under the jurisdiction of NERC. In GADS, outage information for the majority of generators throughout the U.S. and Canada has been reported and maintained for years. It is, however, difficult to separate CMD outages from other outages, especially for internal-cause events. This is because GADS is designed to report data separately for each generator. An outage event could be either independent or CMD even for the same cause code.

Nevertheless, two categories of outage events have been successfully queried from GADS, both of which are identified as external CMD outages based on their cause codes. One category is generation outage events that are related to transmission failures excluding power plant switchyard problems. The other category is generation outage events caused by catastrophes, which are mainly associated with extreme weather conditions or other natural disasters. The statistical information of these two outage categories for NERC units from 2012 to 2014 is shown in Tables IV and V. Table IV gives the percentage indices for the two categories of CMD outages based on all forced outages (including deratings) of NERC units.

There are two indices in Table IV (i.e., percentage of occurrences and percentage of total MWh loss). The percentage of occurrences is an index without consideration of capacity. This index simply shows the portion of the number of events for the CMD outages among all forced outages. Since capacity is an important factor for generators, outages (either full or partial) for generators with different capacities are obviously not the same. Thus, the percentage of total MWh loss is capacity weighted to address this concern. This index actually shows the portion of the impact of CMD outages among all forced outages.

It can be seen from Table IV that when all units are considered, the CMD outages cannot be simply neglected. If the number of outage events is considered, the transmission-related CMD outages could reach approximately 5% of the total occurrences. When outage consequences are considered, the catastrophe related CMD outages could contribute nearly 4% of the total impact.

These data are consistent with the intuition that generator operation can be influenced by failures of the transmission system and that catastrophes can be more harmful to operation than normal outages. Given that these two categories are only a part of all possible CMD outages collected in the GADS database, the percentage of all CMD outages can only be more significant in all forced outages using logical reasoning.

In order to see the difference between various generation types, the percentage indices are also shown in Table IV for five different types of generators (i.e., fossil-steam, gas turbine, nuclear, hydro [including pumped storage], and combined-cycle reported as a block unit [CC-Block]). Data show that hydro and gas turbine units have much higher percentages of CMD outages than other unit types, especially when transmission-related outages are considered. On the other hand, fossil-steam and nuclear units have relatively lower percentages. In general, fossil-steam and nuclear units have slow output ramping rates and are mainly dispatched for the base load, while hydro and gas turbine units have fast output ramping rates and relate more to the peak load of power systems. The observance of such CMD outage difference indicates that non-base-load generation units seem to be more vulnerable than base-load ones to transmission system problems, which might be associated with consideration of tolerable interruption level during the stage of interconnection design.

TABLE IV
Percentage Indices for Common-Mode and
Dependent Outages from GADS

Unit Type	Forced Outages/Deratings	Percentage of Occurrences	Percentage of Total MWh Loss
All Units	All Forced Outages/Deratings	100.00%	100.00%
	Transmission related CMD	4.87%	1.98%
	Catastrophe related CMD	1.48%	3.72%
Fossil-Steam	All Forced Outages/Deratings	100.00%	100.00%
	Transmission related CMD	0.74%	1.14%
	Catastrophe related CMD	0.26%	0.89%
Gas Turbine	All Forced Outages/Deratings	100.00%	100.00%
	Transmission related CMD	4.78%	3.19%
	Catastrophe related CMD	1.30%	13.92%
Nuclear	All Forced Outages/Deratings	100.00%	100.00%
	Transmission related CMD	0.60%	0.21%
	Catastrophe related CMD	2.32%	1.43%
Hydro	All Forced Outages/Deratings	100.00%	100.00%
	Transmission related CMD	5.66%	3.51%
	Catastrophe related CMD	1.45%	3.58%
CC_Block	All Forced Outages/Deratings	100.00%	100.00%
	Transmission related CMD	1.55%	2.06%
	Catastrophe related CMD	0.91%	5.50%

Table V gives two non-percentage indices for the same categories of CMD outages, as well as all forced outages (including deratings) of NERC units from 2012 to 2014.

TABLE V
Non-percentage Indices for Common-Mode and Dependent Outages from GADS

Unit Type	Forced Outages/Deratings	Occurrences per Unit Year	MWh Loss per Occurrence
All Units	All Forced Outages/Deratings	9.31	4593
	Transmission related CMD	0.46	1869
	Catastrophe related CMD	0.14	11529
Fossil-Steam	All Forced Outages/Deratings	33.58	4702
	Transmission related CMD	0.25	7234
	Catastrophe related CMD	0.09	16177
Gas Turbine	All Forced Outages/Deratings	4.93	3771
	Transmission related CMD	0.24	2518
	Catastrophe related CMD	0.06	40413
Nuclear	All Forced Outages/Deratings	7.25	52648
	Transmission related CMD	0.04	18335
	Catastrophe related CMD	0.17	32479
Hydro	All Forced Outages/Deratings	16.75	1061
	Transmission related CMD	0.95	658
	Catastrophe related CMD	0.24	2625
CC_Block	All Forced Outages/Deratings	15.67	4234
	Transmission related CMD	0.24	5608
	Catastrophe related CMD	0.14	25572

The first index is the occurrences per unit year, which is one not weighted by capacity. This index is actually the statistical information of frequency of CMD outages for a general unit. The second index is the MWh loss per occurrence, which is a capacity-weighted index. This index provides the duration of the CMD outage for a general unit. If this value is divided by the designated capacity of a unit, the result is the duration in hours of the CMD outage for this unit. From the data, it is evident that hydro units have much less MWh loss per occurrence compared to other unit types.

V. FUTURE RESEARCH DIRECTIONS

This paper reviews state-of-the-art research and practical applications in the area of data collection, modeling, and assessment of CMD outage events in power systems. Based on the review, several challenges and opportunities for future research have been observed, four of which that the WG considers important are detailed below.

A. Enhancing the Collection Data Systems

The review of existing outage data collection systems indicates that a variety of outage-event recording procedures in use by electric utilities lack the complexity needed to record CMD outage events.

CMD outages in current collection schemes are generally reported without specifying what type of restoration process occurred (automatic, manual, etc.). A more detail recording of the restoration process will permit calculation of meaningful restoration-time related statistics. In traditional common-mode modeling, a single repair (recovery) time is assumed. It has been observed in actual data collection, however, that the two or more components in a common-mode outage have different repair times in many cases.

Difficulties still exist when compiling the number of elements which were exposed to each event and the associated restoration times to determine the probability that an initiating outage will be a CMD outage type.

Adverse weather conditions can create a significant increase in transmission element stress that usually leads to an increase in component failure rates. Research shows that failure rates disaggregated by weather conditions are extremely difficult to obtain from existing data systems, such as TADS and GADS. Reporting weather at the time and place where an outage occurs will significantly enhance the accuracy of reliability index estimates. Recognition of only two weather states is an approximation, but gathering data for multi-states is extremely difficult.

Substation-originated outages due to protection failures and misoperation have a significant impact on power system reliability and therefore should be properly reported and classified. The reliability indices associated with protection equipment operation are still difficult to obtain from actual reported data (e.g., failure and repair statistics, intervals between operating and testing, frequency of maintenance, etc.).

Outage data on transmission and generation equipment are, in most cases, recorded separately, and there is an obvious difficulty in cross-referencing a single cause of simultaneous outages of transmission and generation equipment.

In general, the above issues present challenges on how to classify CMD outages, how to calculate their repair times, and how to calculate the CMD outage-related indices according to the classed equipment groups.

Outage data systems are becoming an integral part of the planning and operation of utilities and therefore, data collection systems need to be constantly improved.

B. Improving Power System Models

Traditional “bus-branch” models can no longer satisfy the requirements of probabilistic reliability calculations in modern power systems. The main disadvantage of these models is that basic bus-branch data ignore the substation breaker configuration and thus limit the assessment of the substation equipment’s impact on system reliability.

A better alternative is to use “node-breaker” representations, which are being increasingly used for reliability studies of modern systems with new technologies and variable energy resource integration. Introducing such models will help in predictive reliability calculations but will require further research in this area.

It also is important to recognize the advantages of explicit breaker-oriented system models in accounting for the impact of substation-originated outages which are related to the topology and switching actions inside the station. This approach is illustrated in detail in [34]-[36], and [53].

Assessing the impact of protection system failures and misoperations on system reliability requires “node-breaker” models.

Mathematical models developed to take into account weather dependency in general usually recognize two weather states. This is a simplification since adverse weather, for instance, can be characterized by several conditions, such as wind speed, temperature, precipitation, ice accumulation and tornado, each of which could be of variable intensity. The effect of failure bunching due to adverse weather conditions has been studied but needs further research.

Research is needed in the area of incorporating transmission and generation equipment aging failures in bulk power system reliability calculations and correlating expected reductions in the element performance on system reliability [54]-[56].

There is a lack of a clear link between outage data collection practices and the methodologies for predicting system reliability (which require populating the models with appropriate data). The lack of wide acceptance of probabilistic reliability studies by industry is due to the fact that there are relatively few good, practical commercially available tools. However, the utility industry is moving in the direction of evaluating investments from risk and least-cost analyses. In order to fix the broken link between models and practical data collection regarding CMD outage events, extra effort is needed to re-examine the standards, such as IEEE Std 762 and IEEE Std 859, and to re-evaluate the existing outage data collection systems such as GADS and TADS. It is necessary to consider new definitions and indices that can accommodate the existence and relationships of CMD events.

C. Modeling of Interdependencies

Review of the published work indicates that power system reliability does not solely depend on the infrastructure of the power grid, but it is also related to other infrastructures, such as communication networks, natural gas infrastructure, and smart grid technologies [54].

Models for incorporating protection system failures and their impact on composite power system reliability have been developed. However, due to the existence of new technologies and the complexity of cyber-physical interdependencies, it is challenging to evaluate the impact of protection failures on composite system reliability. Understanding how the control and communication systems of a power grid affect its reliability is a challenge for further research. Rapid developments in new technologies require a definite enhancement to the currently known models.

Not modeling and evaluating interdependencies of various components and subsystems related to CMD events and functional dependencies (e.g., protection misoperation, hidden failures) can provide misleading reliability results.

In addition to power grid components, future research will require introducing and modeling other types of components, such as SCADA, so the impacts from cyber attacks can be evaluated.

D. Uncertainty Quantification in Risk Model Outputs

A fundamental part of any applied statistical study is placing uncertainty bounds on estimates – there is a great difference if a central estimate of a quantity (say LOLE) being 1 and between having confidence that the true value lies between 0.9 and 1.01, and believing that it could lie anywhere between 0.1 and 10. General methods exist for making such uncertainty quantifications – see e.g. [58] for methods in a reliability context, and [59] for resources on comprehensive uncertainty quantification applicable to a broad class of computer models.

There has been little research on uncertainty quantification in power system reliability model outputs. Section 2.9 of [1], and [60] consider uncertainty in generator availability properties, while [61] considers consequences of sparse component failure data. Increased activity in this area would bring great potential benefits to the industry in practical decision making.

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