TRANSMISSION OUTAGE PERFORMANCE PREDICTION: UNIT OR COMPONENT APPROACH?

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Abstract

The key information required for quantitative evaluation of bulk power system reliability includes frequency and duration of multiple transmission line outages that cause system problems. Two fundamental approaches to reporting and analyzing transmission performance data to predict these multiple outages have evolved in the industry. These have been referred to as "unit" and the "component" approaches.

A third approach "hybrid" has also been suggested. This paper interprets these approaches and discusses their relative advantages. Their relative accuracies are also discussed applying these approaches to Commonwealth Edison Company's 345 kV transmission outage data.

INTRODUCTION

There are two broad steps involved in predicting transmission outage performance using historical outage data. The first step is analysis to determine the basic statistics for transmission components and/or units (groups of components). The second step is the synthesis of performance of components and/or units to predict the outage performance of a group of transmission lines in a network. Outage performance prediction in this paper refers to predicting frequency and duration of different combinations of multiple line outages. Markov models are typically used in this second step. The result of this second step would be the input data to bulk transmission system reliability evaluation models.

In the first step, a very simplistic approach is to develop an average outage rate for use as the basic statistic for the second step. It is generally known that the use of average outage rate underestimates the frequency of multiple outages by not recognizing common mode and dependent outage events. A more refined approach is to classify outages into independent, common mode and dependent outages (referred to in this paper as probabilistic categories). Even with this classification, use of an average outage rate for each category results in an error. It has been shown [1] that advanced regression analysis is a powerful tool to predict individual line outage rates separately. Physical factors such as line length and number of terminals, design vintage, and environmental factors can be properly recognized using regression models. The approach described here, termed as the "unit" approach, is discussed in more detail later.

In contrast, this first step could analyze data on transmission components (line, circuit breaker, bus, protection systems, etc.), and synthesize the component statistics to predict the performance of a unit. This is the "component" approach which is also discussed in more detail later. A "hybrid" approach combines the best features of the unit and component approaches.

These three approaches were first discussed in Reference 2 but the interpretation of these approaches in the industry varies considerably. This paper proposes certain interpretations and terms to describe these approaches and discusses their relative advantages. In addition, the relative accuracy of these approaches to transmission outage performance prediction is discussed.

The results reported in this paper are part of the research efforts in a recently completed EPRI project RP 1468-2 "Prediction of Transmission Outage Performance in System Reliability Evaluations (Final report EL-3880)". This research project is part of the research activities in the area of system reliability technology of the Power System Planning and Operations (PSPO) Program at EPRI. Two earlier completed projects in this area RP 1283 "Bulk Transmission System Component Outage Data Base", and RP 1468-1 "Component Outage Data Analysis Methods", provided valuable inputs to transmission system outage definitions, data collection procedures, and statistical methods for analyzing component outage data. The work in RP 1468-2 extended the efforts of these earlier projects in order to develop mathematical models for predicting the frequency and duration of multiple transmission line outages. It is hoped that these models would provide the needed outage data input to the transmission reliability evaluation models such as SYREL (developed in EPRI project RP 1530-1), GATOR (developed by Florida Power Corporation), RECS (developed by Georgia Institute of Technology) and U of S model (developed by University of Saskatchewan).

BASIC DEFINITIONS

The definitions used in this paper are generally consistent with the IEEE project on Standard 859 [3]. Our work has demonstrated that definitions of several terms must be expanded for clarification. The following definitions are included here for ready reference:

Component is a physical facility which performs a major operating function in a transmission system and which is regarded as an entity for purposes of recording both outage data and exposure data. (e.g.

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overhead transmission line, transformer, bus, circuit breaker, protection system).

Unit is a functional group of components which is identified as a single operating entity by circuit breakers that constitute the primary clearing zone of one or more protective system components. (e.g. transmission line unit, transformer unit, bus unit).

Only forced outages are considered in this paper.

Outage (Unit) describes the state of a unit when it is not performing its intended functions due to all events directly and indirectly associated with that unit.

Outage (Component) describes the state of a component when it is not performing its intended function due to some event directly associated with that component.

The unit outage definition is based on functional unavailability whether due to a failure of a component of the unit, failure of another unit's component or for causes not involving component failures. However, Component outages involve only failures or misoperations. This difference in definitions is necessary for consistency with the unit and component approaches for transmission outage performance prediction as developed in this work. All components have a category of failure mode termed active in this paper. Two components, circuit breaker and protective system, have an additional category of failure mode which has been termed passive in this paper:

Active Failure is the termination of a component's ability to perform its continuously required function.

Passive Failure is the termination of a component's ability to function in response to a command to operate (e.g. stuck breaker, stuck relay).

This paper defines different types of transmission unit relationships useful in the analysis of related outages. The reference (transmission) unit is the transmission unit whose performance is being investigated. A related unit is a transmission unit whose proximity to the reference unit results in common-mode and/or dependent outage events. Suggested hierarchies of common-mode and dependent related unit exposures are summarized in Figure 1.

The important unit relationships for analysis of common mode outages include common tower, common right of way, common terminal and other proximity [2]. This work has identified interfacing unit as an important subset of common terminal meriting separate recognition. Interfacing Unit Exposure is the exposure of a reference unit to a related unit arising from a common circuit breaker which is the interface between them.

Particular relationships between related units which are useful in the analysis of dependent outages include the following: Interfacing Unit Exposure, Common LBB Exposure, Common Terminal (Electrical or Geographic) Exposure and Other Proximity Exposure.

Two subsets of the interfacing unit exposure are necessary to distinguish dependent outages as complete or open ended. A dependent outage is complete if all circuit breakers are opened and the unit is de-energized. An open ended unit outage results if the circuit breakers are opened at one termination but the unit is still energized from other terminals. The two exposure categories are as follows:

Direct Exposure is the exposure of the reference unit to an interfacing unit arising from electrical configuration, such that the reference unit experiences a dependent outage for every forced outage of the related unit normally cleared. This dependent outage would be an open ended line. Being network configuration oriented, dependent outages due to direct exposure are not attributable to any reference unit component failures.

Indirect Exposure is the exposure of a reference unit to a related unit arising from electrical proximity other than direct exposure, such that the reference unit experiences a dependent outage for forced outages of the related unit only due to a passive failure of either unit's protection system or switching components (e.g., stuck or slow clearing circuit breaker, protection system failure to function, or overreach). All exposures of related units other than interfacing are also of the indirect type.

Common LBB Exposure is the exposure of a reference unit to a related unit such that the reference unit experiences a dependent outage as a consequence of the operation of a local breaker backup (LBB) protective system following the passive failure of an interfacing circuit breaker. The exposure is identified by the clearing zone which is common for the two units.

These different exposures are illustrated in Figure 2.

APPROACHES TO TRANSMISSION OUTAGE PERFORMANCE PREDICTION

The objective of transmission outage performance prediction is to develop the basic component and/or unit outage statistics such as outage rate, restoration rate, and passive failure probability (the first step), and predict the outage frequency and duration of different combinations of transmission units (the second step). The basic model used in the second step is the Markov model whose solution is well documented [4]. The development of Markov models to represent independent, common-mode and dependent outages has been discussed in the previous literature [5, 6]. The Markov model for a two transmission unit system in two weather states is illustrated in Figure 3, showing the possible states and the transitions between pairs of states. The transitions include independent, common-mode and dependent outages, restorations, and changes in the weather conditions. The steady state probability vector of the Markov model can be used [4] to determine the frequencies and durations of different states. Combining appropriate states, the frequency and duration of any outage event involving outages of specific units can be predicted.

This paper concentrates on the approaches to determining the transition rates required for the Markov model of a group of specified transmission units. These transition rates can be developed from outage history using the three approaches mentioned earlier--unit, component and hybrid. In the current work, two levels of detail--the "Simple" and the "Detailed"--were considered for the unit approach. Similarly, two levels of detail--"Basic" and "Extended"--were considered for the component approach.

The Unit Approach

The unit approach considers that the unit is a functional group of components which are identified as an operating entity by circuit breakers that constitute the primary clearing zone of one or more protective system components. The performance indices for a specific unit (a reference unit) must be developed from that unit's outage event data and the unit's physical exposure relationship to other units.

The simple unit approach requires a relatively small effort to compile the outage data. The approach compiles the outage history of each transmission line independent of the operating status of any other unit, i.e. it ignores related outages. This approach also considers only the length of lines and number of terminals in predicting the total outage rate of a line. The analysis steps to develop transition rates using the simple unit approach are shown in Figure 4.

Figure 5 shows the analysis steps to develop transition rates using the detailed unit approach as defined in this paper. The history of single and multiple unit outages is disaggregated by probabilistic categories. Common-mode and dependent outage events are disaggregated by exposures as shown in Figure 1. A key point is that the events themselves are observed and performance indices are computed as numerical averages. In contrast, only individual line outages are analyzed ignoring whether they are a part of a multiple related outage event or not in the simple unit approach.

The unit approach can include any level of detail selected by the analyst through disaggregation or regression analysis to increase the precision of the model predictions. The level can be extended to other characteristics in addition to line length and number of terminals if desired. Statistical tests can be utilized to indicate when the analysis has reached a practical limit [1].

The Component Approach

In a component approach to data collection and outage performance analysis all data collected is disaggregated by major components without any reference to the unit of which it is a part. A key point of the component approach is that all performance indices must be computed from the component outage history and synthesized into unit performance for identifying primary outages assuming independence of the component categories. A second point is that all secondary outage events must be predicted from passive failure probabilities of circuit breakers and protective systems considering the network and station configuration. Some component data collection schemes currently in use omit passive failures or do not distinguish them from active failures. Most omit outages not attributable to equipment failures (e.g. operating errors, unknown cause) resulting in underestimation of unit outage rate. These are inherent shortcomings of a strictly component approach.

Various levels of reporting component outage performance are also possible as with the unit approach depending on the precision desired or the amount of effort justified. A minimum approach recommended by [2] is based on the major components. This is referred to as the "basic" component approach wherein further subdivision based on subcomponent characteristics is not considered. An "extended" component approach is possible wherein data is compiled at the subcomponent level considered as optional in [2]. The major components are analyzed considering their design at the subcomponent level. Figure 6 summarizes the required analysis of data for developing the transition rates for the Markov model. First, the active and passive performance indices are computed for the major components from their outage histories. Next, the unit performance indices are determined considering the individual physical configuration of components in the unit. The active component failures result in primary outages (independent and common-mode) while the passive failures result in dependent outages. From this analysis transition rates for the Markov model can be determined.

The Hybrid Approach

The hybrid approach suggested in [2] allows data to be collected on transmission units or the components which make up the unit. This paper has interpreted the hybrid approach as one which combines the best features of both unit and component approaches and compiles the minimum level of detail required for a desired precision of outage performance prediction.

The hybrid approach uses the detailed unit approach for analyzing primary outages and the component approach for analyzing dependent outages. This approach eliminates some shortcomings of the component approach (lack of data on outages due to non-equipment failures) in predicting unit outage performance. Figure 7 summarizes steps in the analysis of unit outage history and the component operations to develop transition rates for the hybrid approach. Circuit breaker and protective system response history is the only component data required to compute passive failure probabilities. Dependent events are synthesized from the primary outage indices, network and station configurations and the passive failure probabilities. Dependent outage modeling on a component basis employing circuit breaker and protective system passive failure probabilities is a preferred approach over unit modeling of the primary/secondary events in view of the sparsity of such events.

Two-weather state techniques for modeling the bunching of outages during adverse weather were utilized for the hybrid approach. The same weather, adverse or normal, was assumed throughout the network.

RELATIVE ACCURACY OF THE APPROACHES TO PREDICT TRANSMISSION OUTAGE PERFORMANCE

An important part of this work was to evaluate the relative accuracy of the three approaches. A computer code called TOPP Macro using the Statistical Analysis System (SAS) has been developed to apply these approaches to specified groups of transmission units, and compare the predicted performance indices with the historical performance indices for evaluating the accuracy of prediction.

Validation of a model requires an objective measure of the model's predictions. A review was made of the available statistical tests which could compare actual and predicted performance. The methods which can be applied to predictions of multiple outages within a small group of lines should be those not requiring a large number of observations, as multiple outages are relatively uncommon events. Furthermore they should be capable of being reduced to scaled values independent of the number of observations so that the validity of models for different groups of lines can be compared.

In comparing actual and predicted outage performance, the measure used is the number of multiple outages within the test network during the study period. The actual number is compared with the product of the predicted multiple outage rate and the length of the

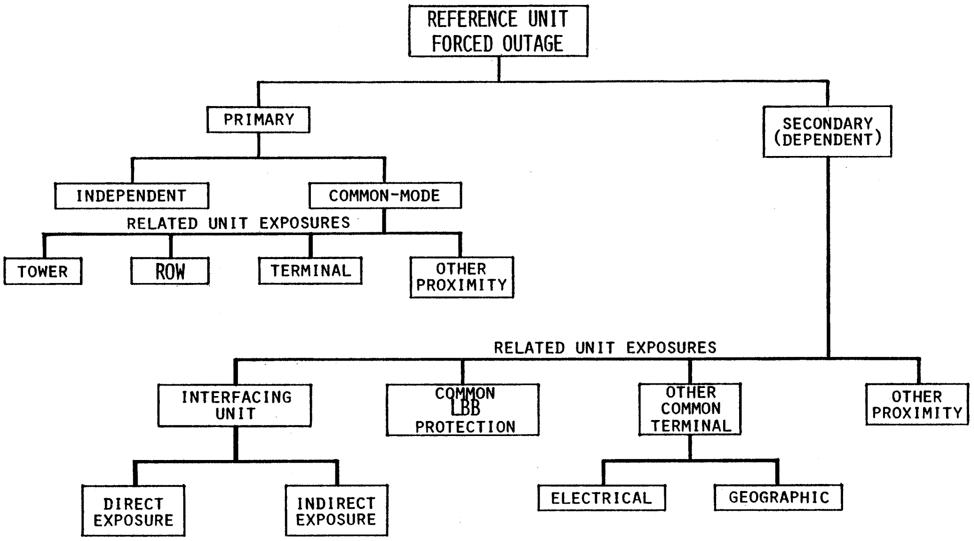

Figure 1 Hierarchy of Transmission Unit Forced Outage Classifications

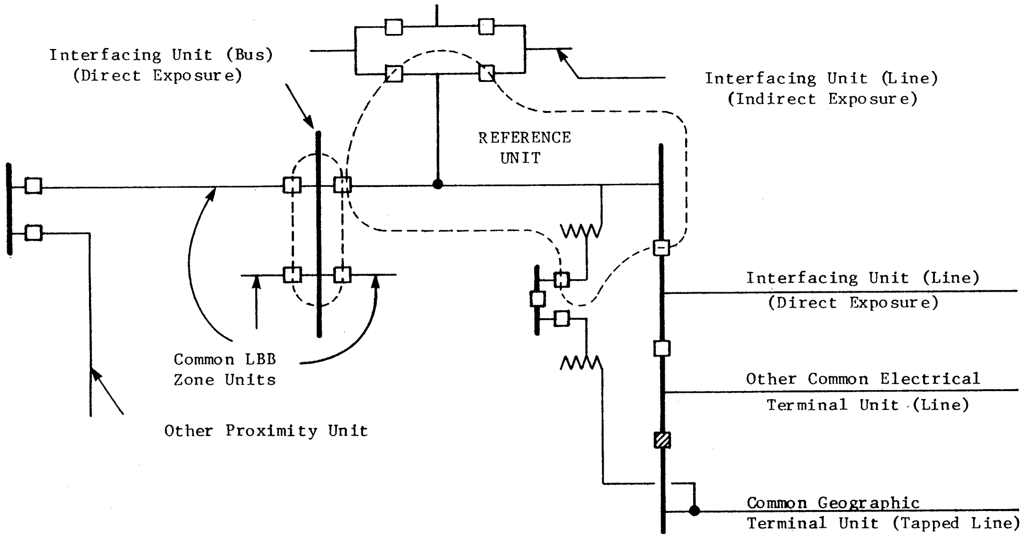

Figure 2 Illustration of Different Exposures to Dependent Outages

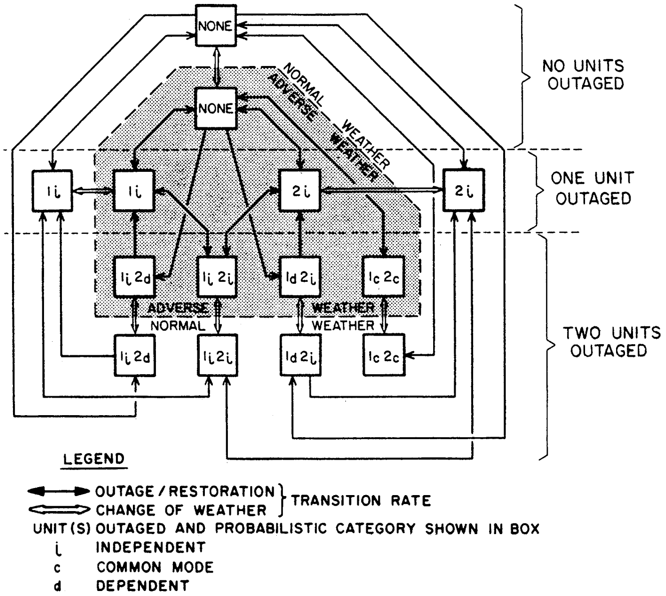

Figure 3 Markov Model for Two Transmission Units in Two Weather States

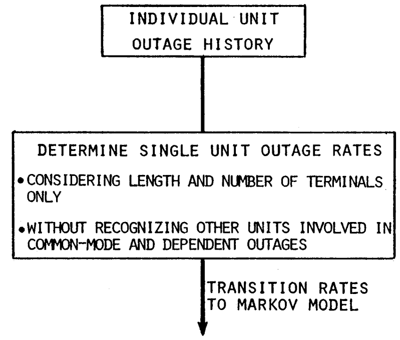

Figure 4 The Simple Unit Approach

period. The expected number of multiple outages (not necessarily an integer) can be used as the parameter of a Poisson distribution. The 5% and 95% points of the cumulative distribution are confidence limits for the actual number of multiple outages if the model is satisfactorily predicting multiple outages.

Accuracy Evaluation of Models

To evaluate the accuracy of the outage prediction approaches, 115 test networks with up to eight transmission units were selected from the Commonwealth Edison Company's 345 kV system. Five models were compared using the SAS TOPP Macro: Simple Unit, Basic Component, Extended Component, Hybrid-Single Weather State, and Hybrid-Two weather states.

A detailed unit model was not tested. The principal difference between a detailed unit model and a hybrid model is the representation of dependent outage events. In a detailed unit model the rate of such events is directly provided as input, while in a hybrid model the primary outage rate and the dependent outage probability are multiplied in the program. It was judged that the two approaches would give approximately equivalent results but the data required for the unit approach would be far more voluminous, as a rate for each possible primary/secondary event would be separately required. The hybrid models were intended to incorporate the maximum precision of prediction attainable from the component and/or unit data bases.

The statistical comparisons of actual performance of the selected networks and that predicted by each of the five approaches applied are summarized in Table 1. In this comparison, the Poisson distribution was used to determine whether the actual number of multiple outages was consistent with that predicted by the model. A Poisson distribution is appropriate for the number of events if the rate at which events occur is constant. If a model is ideal, these Poisson probabilities should be uniformly distributed across the range from 0 to 1. Specifically 5% of the cases should fall below P = .05 (overpredicted) and 5% above P = .95 (underpredicted).

It will be noted in Table 1 that all of the models tended to underpredict more cases than they overpredict. This is shown by the median Poisson probability which was .789 or higher for all models. The more complex models performed better than the simpler models. A simple unit model which ignored probabilistic relationships between outages underpredicted 52 cases (46%) at a level which was statistically significant. A basic component model was only slightly better even though probabilistic relationships were considered, in part because the physical data about the components was restricted to the average experience of the major components, ignoring significant subcomponent data.

The hybrid approach utilizing unit data for primary outages and component data for dependent outages reflected the maximum precision that could be obtained. From another viewpoint such a model represents the ultimate obtainable without weather and/or seasonal disaggregation. As might be expected, this model was intermediate in accuracy between the simple models and the two-weather model, predicting 60 cases (53%) accurately.

Although simple unit or component models could recognize two weather states, the best (hybrid) approach was chosen for this refinement. The two-weather hybrid model predicted 68 cases (59%) accurately. This is encouraging for a first test, but leaves much to be desired from the weather modeling viewpoint.

One limitation of the test networks selected is that many of the observation periods were quite short, less than a year. This was not recognized until the model was implemented. In some such cases, the expected number of multiple outages was less than .05. Even if the actual number of multiple outages was zero, the corresponding Poisson probability was grater than .95. Such cases were regarded as inconclusive.

CONCLUSIONS

This paper proposes certain interpretations of unit, component and hybrid approaches to data collection, analysis and prediction of transmission performance prediction. Important exposure relationships between units involved in multiple outage events have been identified and are defined as related unit exposures. Different hierarchies of these categories are suggested for common-mode and dependent event analysis. Using a computer code and a large number of test networks, the accuracy of prediction of single and multiple unit outages by the three approaches has been tested by comparison with actual experience.

Multiple unit outage events are mainly of the common-mode and primary/secondary probabilistic types and are not adequately predicted by assuming all outages to be independent. Use of single unit average performance indices, without recognition of network relationships, predicts less than half of the multiple outage events accurately.

A precision of approximately 60% is attained for multiple outage prediction using a hybrid data collection approach based on physical characteristics including the following: line length, common tower construction, number of terminals, major differences in line design, unusual environmental exposure and network configuration including common terminal and common interfacing breaker.

A two-weather state Markov model based on normal and adverse weather conditions with different outage rates which are assumed constant over the weather period provides a marginal increase in the precision of predicted multiple outage rates. Further work is required to improve the weather modeling by identification of different types of adverse weather and by recognition of the spatial and intensity variations in weather exposure of different transmission lines in the system.

Either a unit, component or hybrid approach can be selected for a data collection system. The choice must recognize a tradeoff between data collection efforts and the resulting precision in predicting multiple transmission unit outages.

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REFERENCES

1. A. W. Schneider, Jr. et al. "Analysis and Prediction of Transmission Unit Performance Using Advanced Regression Models," IEEE/PES Summer Meeting, Paper No. 84 SM 598-9, July 1984.

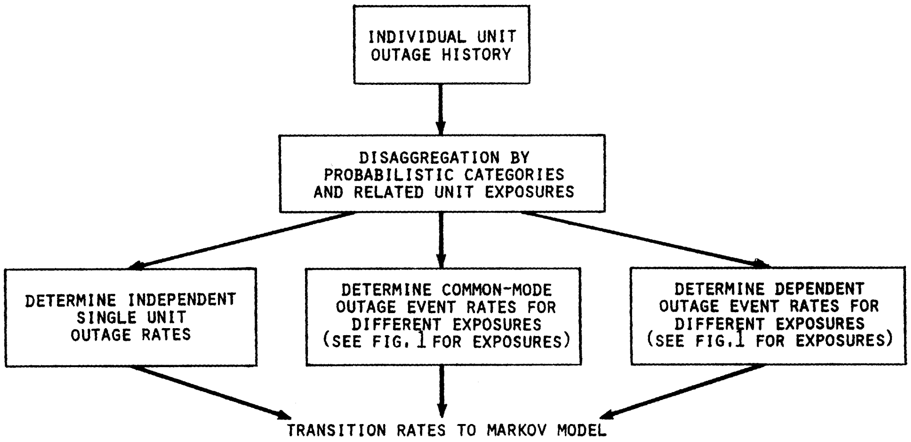

Figure 5 The Detailed Unit Approach

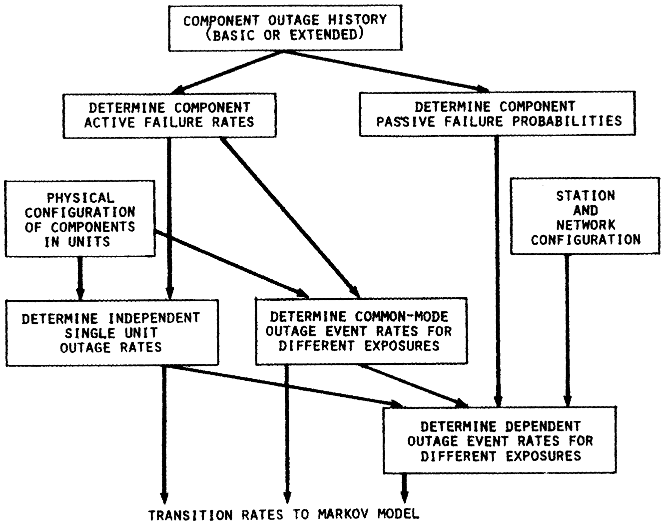

Figure 6 The Component Approach

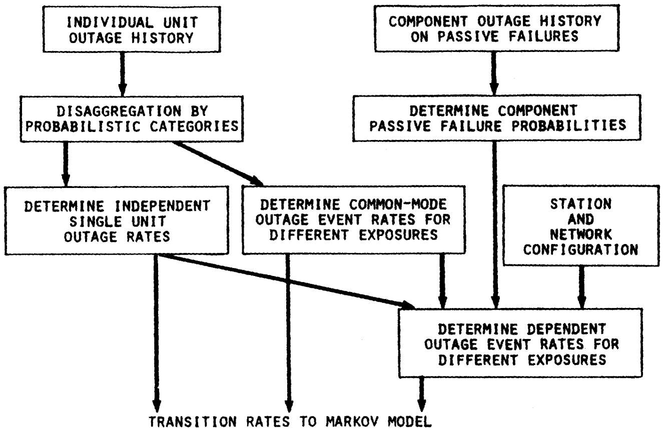

Figure 7 The Hybrid Approach

Table 1

Relative Accuracy of Computing Multiple Outages for Various Models

	Simple Unit	Component		Hybrid		Target
		Basic	Extended	Single Weather	Two Weather	
Cases Analyzed	115	112	114	108	115	115
Poisson Probability (P) -- Median	.907	.928	.926	.835	.789	.5
- Cases with						
$P < .05$ (Overpredicted)	14	9	6	6	10	6
$.05 < P < .95$	49	52	57	60	68	103
$.95 < P$ (underpredicted)	52	51	51	42	37	6
Accuracy*	.4375	.4643	.5000	.5357	.5913	.9
Relative accuracy	(BASE)	106%	114%	122%	135%	

*Cases with $.05 < P < .95$ as percent of cases analyzed.

2. EPRI, "Bulk Transmission System Component Outage Data Base", Final Report EL-1797, April 1981.

3. IEEE T&D Outage Definitions Task Force, "Proposed Terms for Reporting and Analyzing Outages of Electrical Transmission and Distribution Facilities", IEEE/PES Winter Meeting, Paper No. 84 WM-042-8, February 1984.

4. R. Billinton, K. E. Bollinger, "Transmission Reliability Evaluation Using Markov Processes", IEEE Trans. (PAS), February 1968, pp. 538-547.

5. R. Billinton, T. K. P. Medicherla, M. S. Sachdev, "Application of Common-Cause Outage Models in Composite System Reliability Evaluation", IEEE Trans. (PAS), July 1981, pp. 3648-57.

6. R. Billinton, T. K. P. Medicherla, "Station Originated Multiple Outages in the Reliability Analysis of a Composite Generation and Transmission System", IEEE Trans. (PAS), August 1981, pp. 3870-78.

APPENDIX

TRANSITION RATES FOR THE MARKOV MODELS

Table 1 shows an evaluation of the five approaches to transmission outage performance prediction. Markov models were used in this evaluation, and the outage rates used in these models are shown in Table A. The probabilities of dependent outages used in component and hybrid models are 0.00926 (under fault) and 0.00526 (under no fault) for interfacing unit exposure, 0.00173 for geographic terminal exposure (under fault), and 0.00229 for electrical terminal exposure (under fault). The weather transition rates used are 254 for normal to adverse and 1314 for adverse to normal. Mean duration for primary outages is in the order of 15 hours for line, bus or circuit breaker, 145 hours for transformer component, and 35 hours for common tower or common right-of-way. Mean duration of outage is about 2 hours for line or bus protection, and 20 hours for transformer protection component. Mean duration of dependent outage is 2 hours. These data were based on an analysis of 17 years of outage history of the Commonwealth Edison Company's 345 kV transmission system.

TABLE A

OUTAGE RATES FOR THE MARKOV MODEL

Unit/Component	Simple Unit Model	Component Model		Hybrid Model		
		Basic	Extended	All Weather	Normal Weather	Adverse Weather
Line unit/component						
Intercept	.6766	-	.134	.337	.236	.101
Third Terminal	1.2306	-	.414	1.013	.786	.227
Quarry exposure	-	-	4.380	4.188	.513	3.675
Kincaid station	-	-	-	1.109	.578	.532
Single circuit design	.0257**	.0203**	.0170**	.0279**	.0167**	.0112**
Early design	.0257**	.0203**	.0338**	.0316**	.0195**	.0121**
Late design	.0257**	.0203**	.0062**	.0138**	.0094**	.0044**
Line protection component	-	.308	.308	-	-	-
Bus unit/component	.0196	.003	.003	.0196	*	*
Bus protection component	-	.007	.007	-	-	-
Transformer unit/component						
345/138kV	.225	.116	.116	.225	*	*
765/345kV	.390	.116	.116	.390	*	*
Aux. - nuclear sta.	.166	.116	.116	.166	*	*
- fossil sta.	.654	.116	.116	.654	*	*
Transformer protection component	-	.054	.054	-	-	-
Circuit breaker component/ interfacing unit(CM)						
SF6	-	.010	.183	.183	*	*
Other	-	.010	.010	.010		
Common tower (CM)						
Quarry exposure	-	-	.6012	.6012	.1996	.4016
Early design	-	.00501**	.00114**	.00114**	.00089**	.00025**
Late design	-	.00501**	.00074**	.00074**	.00029**	.00045**
Common right-of-way(CM)	-	.00059**	.00059**	.00059**	*	*

All outage rates are in occurrences per year unless specified otherwise.
* - not disaggregated by weather ** - per mile-year CM - common mode outage rates