Failure Bunching Phenomena in Electric Power Transmission Systems

Roy Billinton Gagan Singh Janak Acharya

Power System Research Group
Electrical Engineering Dept.,
University of Saskatchewan
Saskatoon, Canada

Abstract

The physical environment in which a component resides can have a significant effect on the resulting reliability of the system. This is particularly true in electric power systems containing overhead transmission lines. Extreme weather conditions can create significant increases in transmission element stress levels leading to sharp increases in the component failure rates. The phenomenon of increased transmission line failures during bad weather is generally referred to as "failure bunching". This condition should not be misconstrued as a common mode failure. This is an entirely different phenomenon and one that is important for multi-circuit transmission lines on single tower structures. This paper illustrates the inclusion of weather conditions in the reliability analysis of parallel redundant systems. A series of weather models are presented with application to electric transmission lines. The reliability effects of incorporating common mode failures in multi-circuit tower structures and independent events incorporating normal, adverse and major adverse weather considerations in separated parallel line configurations are illustrated and examined.

The applications described in this paper are to electric power transmission lines. The concepts of stress related failure bunching and common mode failures are, however, applicable to a wide range of engineering systems.

Introduction

Transmission circuits are important elements in an electric power system and exist in two basic forms. They can be located underground in the form of cables or above the ground on appropriate tower structures. Cables normally operate in relatively stable environments while overhead circuits are exposed to a wide range of weather conditions. A usual assumption in generation and transmission system reliability studies is that system component failures are independent and therefore the failure of one component is not related to, or influenced by the failure of another component. A blanket assumption of component independence is inherently optimistic and can lead to quite inaccurate assessments of system reliability in conventional transmission systems. This is illustrated in the paper using a simple two transmission line example.

Figure 1 shows two different arrangements for the two three-phase transmission lines. In Figure 1(a), the two circuits are on separate tower structures on the same right of way. In Figure 1(b), the two circuits are located on a single tower structure. This is a very popular practice throughout the world. The right of way and structure material requirements are significantly lower than that required for two separate transmission lines, as shown in Figure 1(b). The utilization of double circuit transmission lines is a common utility practice and in some right of way constrained situations has been extended to triple or higher circuit configurations.

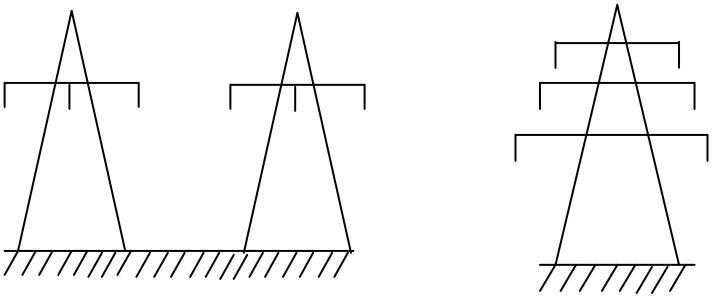

Figure 1(a) Figure 1(b)

Figure 1. Two different arrangements for two transmission circuits

The following basic failure phenomena are illustrated using the basic transmission line example shown in Figure 1. The application in this paper is to transmission lines. The basic concepts, however, are applicable to a wide range of systems.

Mode 1	*Independent failures*: The failure of one component does not influence the failure of the other component.
Mode 2	*Common mode failures*: In this mode, two or more components can fail due to a common cause. The event has a single external cause with multiple failure events that are not consequences of each other [1].
Mode 3	*Stress related failures*: The physical environment in which the system components reside can have a significant impact on the system reliability. The stress created by the physical environment can lead to sharp increases in the component failure rates. The phenomenon of component failures during high stress periods is generally referred to as “failure bunching”. These failures should not be classed as common mode failures. They are independent failure events in a common environment.

The two circuits in Figure 1(a) are physically separated and therefore Mode 2 is considered to be not applicable to this configuration. The two circuits in Figure 1(b) are susceptible to all three modes of failure. The common mode failure rate of the double circuit line may also be influenced by the weather conditions associated with Mode 3. Double circuit towers are susceptible to failure in adverse weather, particularly when this condition is associated with freezing rain, ice or wet snow. High winds of hurricane force accompanied with driving rain can also cause double circuit tower failures. Extreme lightning conditions can also result in multiple arcs and insulator damage on both circuits. Tower damage due to vehicle or aircraft contact invariably results in the simultaneous loss of both circuits.

The two circuit configurations shown in Figure 1 have been analysed using a basic Markov approach. This therefore implies that the transition rates between the various system states are constant and the residence time distributions are exponential. The system is assumed to be in the failure state when both transmission lines are out of service at the same time. The system stochastic transitional probability matrix is obtained from which a truncated matrix is constructed by removing the failure states. The truncated matrix is subtracted from the identity matrix and inverted. The resulting matrix is the matrix of time spent in the different states before entering the failure states. Identifying the starting state and summing the time spent in each state gives the mean time to failure (MTTF). The reciprocal of the MTTF is the average system failure rate. The procedure used to obtain the system average failure rate (λ) and the system unavailability (U), is described in detail in [1].

1. System Studies

The data used in the following studies are given in the Appendix.

1.1 Mode 1

The two transmission lines under this condition can be modelled using the state space diagram shown in Figure 2.

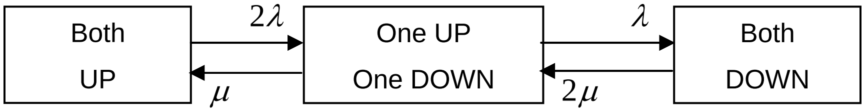

Figure 2. Independent failure events

The system unavailability, $U = 0.0063$ hours/year
The system failure rate, $\lambda_S = 0.0017$ failures/year

1.2 Mode 1 and Mode 2

The two transmission lines shown in Figure 1(b) can be modelled using the state space diagram shown in Figure 3. There are a number of possible models to include common mode failures in a parallel redundant configuration [1]. Most of the variations are associated with repair following a common mode failure [2]. Figure 3 is the simplest model.

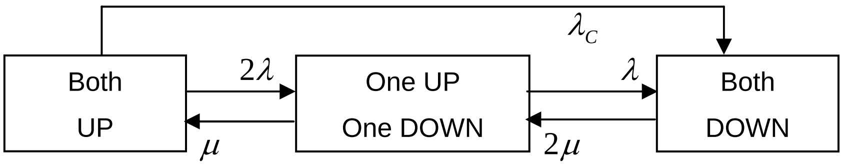

Figure 3. Independent and common mode failures

In Figure 3, λ_C is the common mode failure rate and was varied from 0.01 to 0.1 failures per year. The binomial representation used in Figures 2 and 3 has been extended in the following state space diagrams to include all the individual system states.
Table 1 shows the common mode failure rate as a percentage of the individual component failure rate, and the predicted system failure rate and unavailability in each case. It can be seen from Table 1 that even a small common mode failure percentage has a significant impact on the system indices.

*CM = Common mode failure rate as a percentage of the component average failure rate

Common mode failure rate, CM* (failures/year)	System failure rate (failures/year)	System unavailability (hours/year)
0.01 (CM = 1%)	0.0117	0.04
0.05 (CM = 5%)	0.0516	0.19
0.08 (CM = 8%)	0.0816	0.31
0.10 (CM = 10%)	0.1015	0.39

Table 1. System failure rate and unavailability

1.3 Mode 1 and Mode 3

The combined effects of independent failures and stress related failures are considered in this case using the two state weather model consisting of normal and adverse weather conditions [3]. The state space diagram is shown in Figure 4. It is assumed that no transmission line repairs are done during adverse weather.

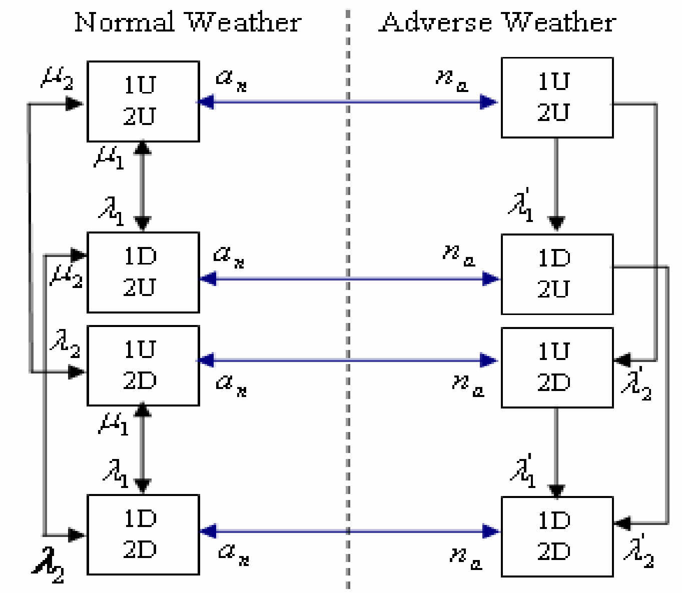

Figure 4. Independent failure events with a two state weather model

As shown in the Appendix, the annual failure rate of a transmission line in this study is 1.0 failure/year. Most electric power utilities calculate the annual failure rate of their transmission elements. They do not, however, normally calculate adverse and normal weather failure rates. This involves recording the number of failures in adverse weather and in normal weather and the amount of time spent in each of these states. Failures are, however, usually identified in terms of cause codes, one of which is adverse weather. The number of actual failures that occur in adverse weather is therefore usually recorded. The contribution of various causes to the overall annual failure rate of a range of transmission line designs and voltage levels is illustrated in an annual report entitled "Forced Outage Performance of Transmission Equipment" published by the Canadian Electricity Association [4]. Adverse weather makes a major contribution to the number of failures in virtually all cases. The actual durations of adverse weather, including those periods of time that adverse weather existed and no failures occurred, are not usually recorded.

As an example, using the data in the Appendix, if 50% of the annual transmission line failures occur in adverse weather, then the adverse weather failure rate is 50.5 failures/year of adverse weather [3]. The stress placed on a transmission line during relatively short periods of adverse weather is considerably higher than in normal weather. If both transmission lines are in the same adverse weather environment then the likelihood of both failing during this relatively short period is considerably higher than in normal weather. This can be seen in Table 2 where the system failure rate, when 50% of the annual transmission line failures occur in adverse weather, is 7.5 times the value predicted using the average annual failure rate.

The predicted system failure rate, obtained using overall component failure rates that mask the fluctuating stress levels associated with changing weather patterns, can be extremely optimistic. This can lead to under-investment in the design and construction phase of a project and costly modifications and reinforcements at a later stage. Realistic prediction of transmission and distribution system reliability is an important aspect of system planning and development. This requires consistent and comprehensive collection of transmission element failure and repair data together with relevant information on the environment within which the elements reside. As noted above, many utilities record the cause of a failure and most utilities recognize adverse weather as a significant cause. They do not, however, collect the associated weather data. There can be a wide range of stress levels associated with adverse weather, each of which creates the likelihood of failure bunching. This is illustrated further in Section 2 dealing with multi-state weather models.

Table 2 shows the system failure rate and unavailability for a range of normal and adverse weather conditions. The percentage of transmission line failures in adverse weather was varied from 0 to 100% in 10% increments. The influence on the system indices of recognizing failure bunching due to adverse weather can clearly be seen in Table 2.

% of line failures occurring in adverse weather (F)	System failure rate (failures/year)	System unavailability (hours/year)
0	0.0017	0.01
10	0.0022	0.01
20	0.0035	0.02
30	0.0058	0.03
40	0.0089	0.05
50	0.0128	0.07
60	0.0176	0.10
70	0.0232	0.13
80	0.0295	0.17
90	0.0367	0.21
100	0.0446	0.26

Table 2. System failure rate and unavailability

1.4 Mode 1, Mode 2 and Mode 3

The combined effects of independent, common mode and weather related failures are considered in this case. These conditions apply to the transmission configuration shown in Figure 1(b). The state space diagram is shown in Figure 5.

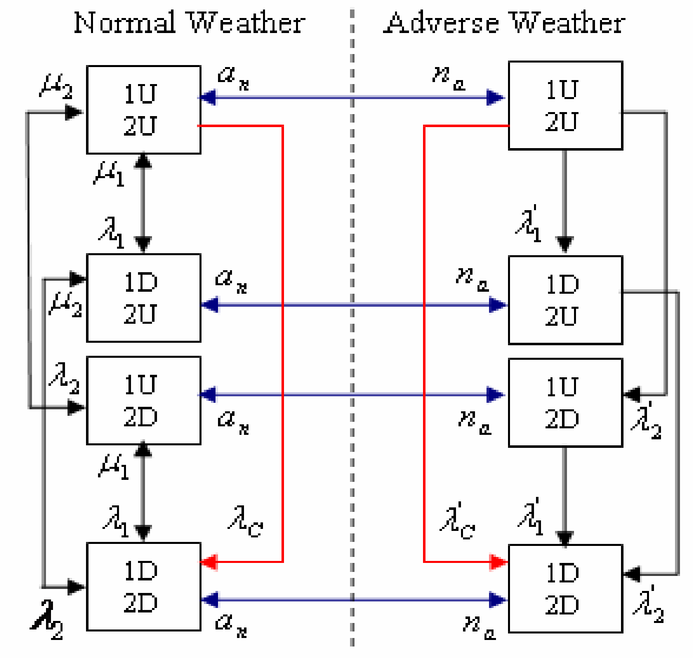

Figure 5. Independent and common mode failure events with a two state weather model

Table 3 shows the system failure rate and unavailability for varying percentages of line failures occurring in adverse weather. In Figure 5, λ_C and $\lambda_C^{'}$ are the common mode failure rates in failures per year of normal and adverse weather respectively. They also vary in the same percentages as shown in Table 3, for the line failures.

% of line failures occurring in adverse weather (F)	System failure rate (failures/year)	System unavailability (hours/year)
0	0.0117	0.04
10	0.0122	0.05
20	0.0135	0.06
30	0.0157	0.07
40	0.0188	0.09
50	0.0227	0.12
60	0.0274	0.15
70	0.0329	0.18
80	0.0392	0.22
90	0.0463	0.27
100	0.0541	0.31

Table 3. System failure rate and unavailability for $CM = 1\%$

Table 3 was calculated assuming that the common mode failure rate is 1% of the component average failure rate. Table 4 shows the results when the common mode failure rate is increased to 10% of the component average failure rate.

% of line failures occurring in adverse weather (F)	System failure rate (failure/year)	System unavailability (hours/year)
0	0.1016	0.38
10	0.1020	0.41
20	0.1032	0.43
30	0.1052	0.47
40	0.1079	0.50
50	0.1114	0.54
60	0.1157	0.59
70	0.1207	0.64
80	0.1263	0.69
90	0.1327	0.75
100	0.1397	0.81

Table 4. System failure rate and unavailability for $CM = 10\%$

Table 4 shows that the system indices are dominated by the common mode event parameters when the common mode failure rate is 10% of the system failure rate. The system failure rate as a function of the percentage of line failure occurring in adverse weather for different percentage values of the common mode failure rate is shown in Figure 6.

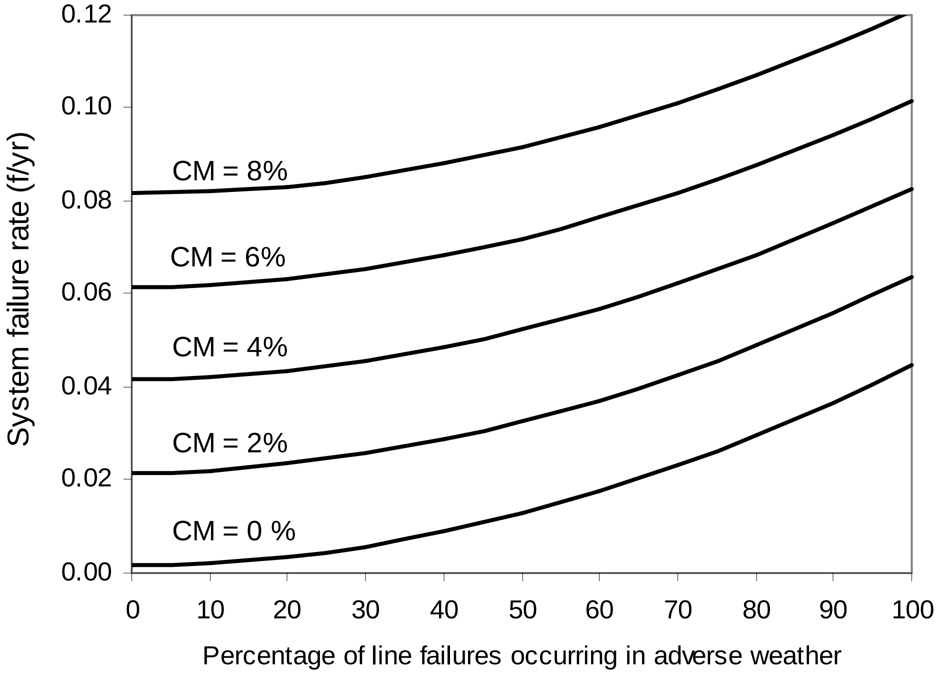

Figure 6. Effect of independent failure, common mode failure and adverse weather on the system failure rate with a two state weather model

In Figure 6, the system failure rate profile for $CM = 0\%$ is applicable to the system in Figure 1(a). The remaining profiles represent different common mode conditions for the system in Figure 1(b). The system in Figure 1(a) is inherently more reliable than that in Figure 1(b) and under certain conditions is considerably more reliable. This fact should be integrated with the economic and environmental factors when selecting single and double circuit line configurations.

2. Multi-state Weather Models

Recent research [5] has shown that it is important to recognize weather conditions in addition to the two states of normal and adverse weather. The influence of extreme adverse weather was recognized in IEEE Standard 346 published in 1973 [6]. Work has been done to model the weather into three states, designated as normal, adverse and extreme adverse weather. The transmission line failure rates in these states are determined by assigning a percentage of the total average line failure rate to each weather condition. A similar process was used to determine the respective common mode failure rates for the three weather conditions. The following presents a series of studies that illustrate the effects of using a three state weather model in the analysis of the two configurations shown in Figure 1.

2.1 Mode 1 and Mode 3

The two transmission lines under this condition can be modelled using the state space diagram shown in Figure 7.

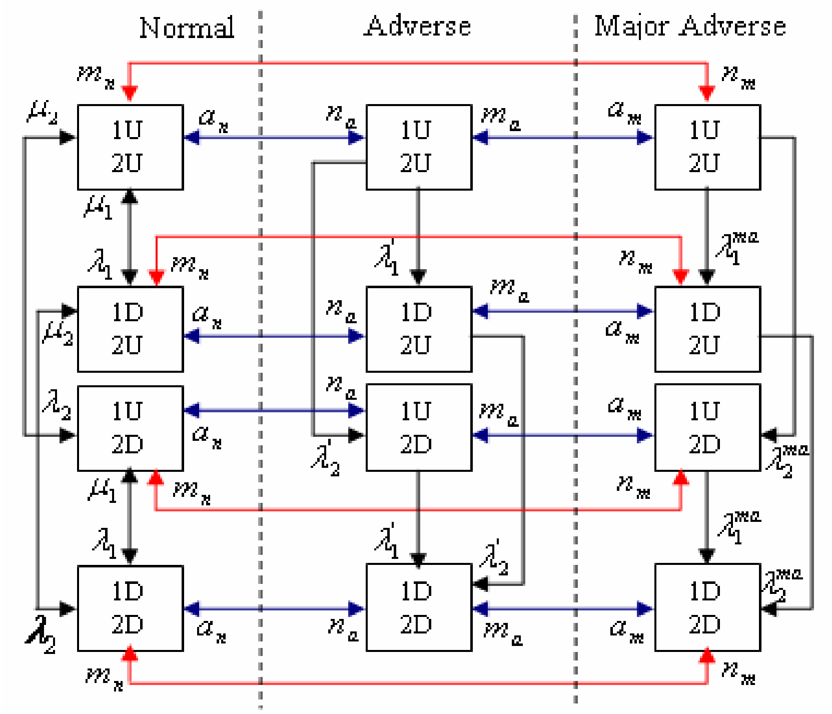

Figure 7. Independent failures with a three state weather model

% of line failures occurring in bad weather (F)	System failure rate (failures/year)	System unavailability (hours/year)
0	0.0017	0.01
10	0.0023	0.01
20	0.0040	0.02
30	0.0068	0.04
40	0.0106	0.06
50	0.0154	0.09
60	0.0211	0.12
70	0.0278	0.16
80	0.0353	0.20
90	0.0437	0.25
100	0.0529	0.31

Table 5. System indices with 10% of the bad weather failures in major adverse weather

The adverse and major adverse weather conditions are collectively designated as bad weather. The predicted reliability indices are highly influenced by the designated contribution of bad weather failures that occur in the two subsets of adverse and major adverse weather. Table 5 shows the system indices when 10% of the bad weather failures are assumed to occur in major adverse weather.

Table 6 shows the system indices when 50% of the bad weather failures are assumed to occur in major adverse weather.

% of line failures occurring in bad weather (F)	System failure rate (failures/year)	System unavailability (hours/year)
0	0.0017	0.01
10	0.0062	0.03
20	0.0174	0.10
30	0.0330	0.19
40	0.0514	0.30
50	0.0716	0.41
60	0.0928	0.54
70	0.1145	0.66
80	0.1365	0.79
90	0.1585	0.92
100	0.1803	1.04

Table 6. System indices with 50% of the bad weather failures in major adverse weather

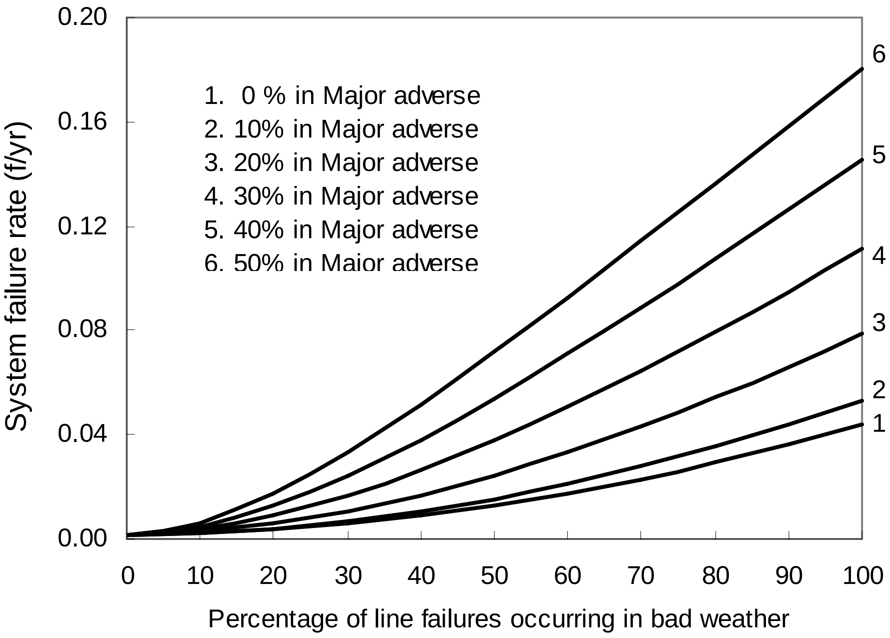

Figure 8. Effect of independent failure and adverse weather on the system failure rate with a three state weather model

The failure modes used in the results shown in Tables 5 and 6 relate to the transmission configuration in Figure 1(a) and can be compared with those in Table 2. The results shown in Table 5 and 6 are presented pictorially in Figure 8. This figure clearly shows the impact of “failure bunching” due to bad weather and the portion of bad weather failures that are attributed to major adverse weather.

The analysis can be extended to recognize the common mode conditions present in the transmission configuration shown in Figure 1(b). The state space diagram in this case is shown in Figure 9.

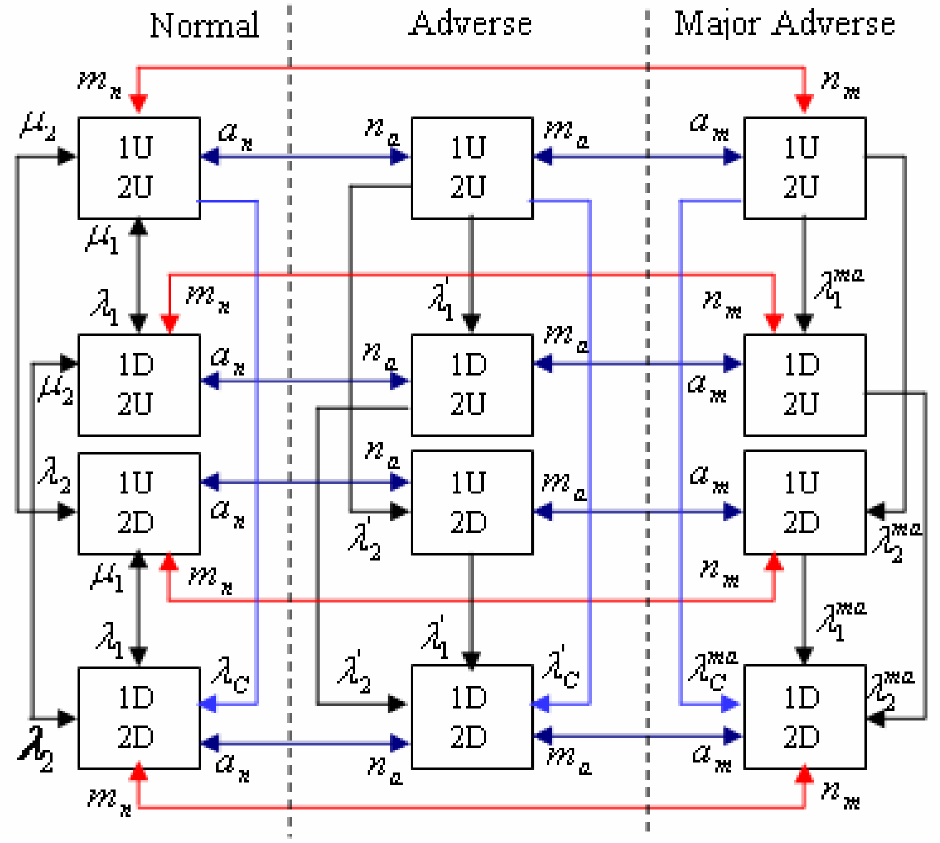

Figure 9. Independent and common mode failures with a three state weather model

Table 7 presents the system indices under the conditions that the common mode failure rates are 1% of the independent failure rates and that 10% of the bad weather failures occur in major adverse weather. The system indices are again dominated by the influence of common mode failures in the analysis shown in Table 7. This is further illustrated in Figure 10.

% of line failures occurring in bad weather (F)	System failure rate (failures/year)	System unavailability (hours/year)
0	0.0117	0.05
10	0.0123	0.09
20	0.0140	0.14
30	0.0167	0.19
40	0.0205	0.24
50	0.0252	0.29
60	0.0309	0.35
70	0.0375	0.41
80	0.0449	0.48
90	0.0532	0.55
100	0.0623	0.62

Table 7. System indices with $CM = 1\%$ and 10% of the bad weather failures in major adverse weather

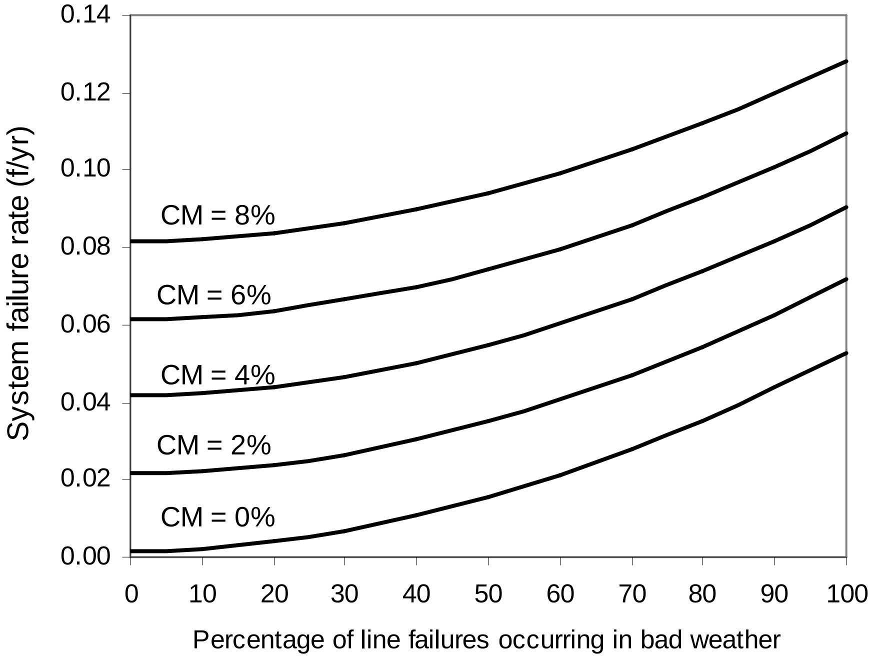

Figure 10. Effect of independent failures, common mode failures and bad weather using a three state weather model with 10% of the bad weather failures in major adverse weather

Figure 11 shows similar system failure rate profiles when 50% of the bad weather failures are attributed to major adverse weather. The results shown in Figure 11 relate to the transmission configuration shown in Figure 1(b) and can be compared with those shown in Figure 6.

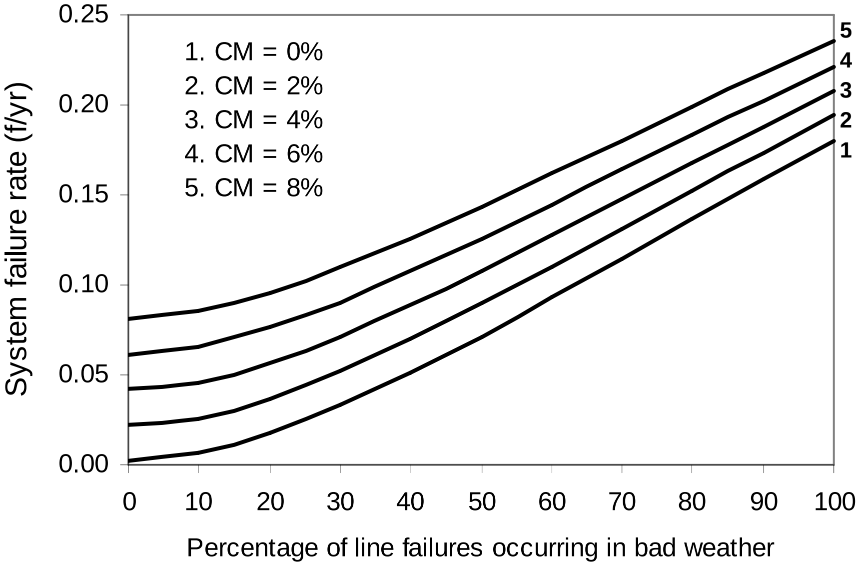

Figure 11. Effect of independent failures, common mode failures and bad weather using a three state weather model with 50% of the bad weather failures in major adverse weather

3. Conclusion

The two transmission circuits shown in Figure 1 are considered as a parallel redundant system in the analysis described in this paper. In Figure 1(a), the transmission circuits are physically located such that a common mode failure of both circuits is assumed to be negligible. In Figure 1(b), the two circuits are located on the same tower structures and therefore are susceptible to common mode failures. The system reliability indices of failure rate and unavailability are determined for a series of studies involving independent, common mode and stress related failures associated with weather conditions. The focus on the paper is on transmission line analysis. The concepts and general results are, however, applicable to a wide range of systems in which independent, common mode and stress related failures can occur.

The analysis shows that common mode failures, while having a relatively low probability of occurring, have a major impact on the reliability of a parallel redundant configuration and dominate the predicted system failure rate and unavailability. The effects and likelihood of common mode failures are normally minimised by good design practices. The economic, environmental and political benefits of using double circuit transmission lines have, however, made their utilization relatively common throughout the world. It should be appreciated that these benefits are accompanied by increased risks that should be incorporated in the analysis.

Recognition and incorporation of stress related failures due to bad weather can have a significant effect on the predicted system reliability indices of transmission systems. This applies to both the configurations shown in Figure 1. Utility data shows that common mode failures have a higher likelihood of occurring in bad weather than in normal weather. The most important impact of bad weather, however, is on the incidence of overlapping independent failures of the two transmission lines. Incorporating the increased failure rates created due to the bad weather in which both lines reside results in a significant increase in the system reliability indices. The studies presented in this paper illustrate that using a single component average failure rate can result in optimistic assessments of parallel redundant configurations such as two transmission lines located outdoors. Research has shown that the two state weather model incorporating normal and adverse weather considerations is a significant improvement over the simple single weather state approach. The studies described in this paper clearly illustrate that the "failure bunching" phenomenon associated with bad weather can be incorporated in the evaluation using more than two weather states. The analyses shown in this paper illustrate the impact of incorporating normal, adverse and major adverse weather in determining the predicted system indices. Further research is being conducted in this area.

4. References

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4. Canadian Electricity Association, "Forced Outage Performance of Transmission Equipment, January 1, 1998 to December 31, 2002", April 2004, pp. 1-146.
5. Billinton and G. Singh, "Incorporating Extreme Adverse Weather Considerations in Transmission System Reliability Evaluation", Proceedings of the IX Symposium of Specialists in Electrical Optimal and Expansion Planning, Brazil (May 2004).
6. IEEE Standard 346:1973, "Terms for Reporting and Analyzing Outages of Electrical Transmission and Distribution Facilities and Interruptions to Customer Service".

Appendix

Data used in the analysis

Average failure rate of each component, $\lambda = 1.0$ failure/year
Average repair rate for each component, $\mu = 1168$ repairs/year
Average duration of normal weather, N = 200 hours
Average duration of adverse weather, A = 2 hours
Average duration of major adverse weather, MA = 1 hour

The transition rates between the different weather conditions in occurrences/hour:

$n_a = 1/200$, $n_m = 1/8760$, $a_n = 1/2$, $a_m = 1/8760$, $m_n = 1/2$, $m_a = 1/2$

where n_a represents the transition rate from normal weather to adverse weather. The other parameters follow the same reasoning.