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EFFECTS OF COMMUNICATION NETWORK ON RELIABILITY OF A WIDE AREA PROTECTION SCHEME

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ABSTRACT

Many utilities around the world have experienced a great pressure to fully utilize their current facilities to the maximum level due to the deficiency of power transfer capability. Special protection system (SPS), also known as remedial action scheme (RAS), is often considered as a cost effective way in achieving this goal. For an SPS that covers a wide area, communication network is essential for successful operations of the SPS. To understand the effects of communication network on reliability of a wide area SPS, an approach based on fault tree methodology is used in this paper for reliability evaluation of the communication and control of the SPS. The SPS devised by Taiwan Power Company (Taipower) for relieving transient and dynamic instability is used for the study. A sensitivity analysis is used to reduce the impacts of uncertain input data on the analysis results. The Taipower system protection scheme is described and the importance of the communication network on the reliable SPS control performance is demonstrated.

KEY WORDS

Special Protection System, Communication Network, Automatic Control, and Reliability Assessment.

1. Introduction

In order to prevent major blackout and enhance system reliability, various types of special protection system (SPS) have been implemented by the utilities around the world [1]. SPS is designed to detect abnormal system conditions and take predetermined and corrective actions to preserve system integrity and provide acceptable system performance. These systems are often considered as a cost effective way in achieving the fully utilization of the utility’s current facilities to the maximum level since they can be placed in service relatively quickly and inexpensively.

An SPS involves the installation of monitoring instruments at the substation buses that are the bottlenecks of the transmission system. Data capture is both event/alarm and/or time-interval driven. The predefined action logic using event-based or response-based scheme is used to trigger the defense system. With the advanced hardware and software in computer and communication technologies, SPS can rapidly detect abnormal system conditions and issue corrective actions to mitigate the consequence of the abnormal condition for maintaining adequate system performance.

An SPS that covers a wide area includes all communication and control functions for the transmission system, such as load shedding, generation rejection, etc.. Communication network is essential to a wide area SPS since the coordinated interaction of different components of the control system relies on the communication network for transferring data and control signals. A good performance of the communication network between the master station and control center and remote control units makes that the remote data collection and automatic control works well and thus creditable events can be identified and proper actions are taken, and therefore system response following a contingency can be significantly improved. The failure of communication network equipments, however, would cause that the SPS fails to accurately detect the defined conditions or fails to carry out the predefined remedial control action, and consequently it may lead to serious and costly consequences [2,3].

Form a system design point of view, it would be worthwhile to evaluate quantitatively the impact of communication networks on the reliability of SPS control functions. The purpose of this paper is to quantity impact of communication network on the reliability of SPS controls. The SPS designed by Taiwan Power Company (Taipower) for relieving transient and dynamic instability is used for the study. The operations of the remedial control action are simulated and the quantitative results concerning reliability of the control function performance are reported. Sensitivity analysis is also performed to reduce the effects of uncertain input data on the reliability analysis results of the SPS. The Taipower SPS and reliability evaluation technique used are described in this paper.

2. Taipower Transient/Dynamic Instability Special Protection System

2.1 System Structure

Taiwan power system shown in Figure 1 is a longitudinal and isolated system with three major areas, namely, North, Central, and South, connected by a number of 345kV transmission lines. Load centers are located in the north and most generating plants are in the central and southern areas. A large amount of powers are transferred from south and central areas to the north through four trunk lines during peak loads. Large power transfers have caused the degradation of the system stability.

On July 29th 1999 (729-incident), nearly eight million customers in Taiwan were affected by a system wide incident and the 16.7 GW of load was lost [4]. To avoid the blackout incident to occur again, Taipower had devised a transient/dynamic instability special protection system (TDI-SPS) in some critical areas for reducing the risk of power system instability caused by increased loading of transmission systems and severe faults.

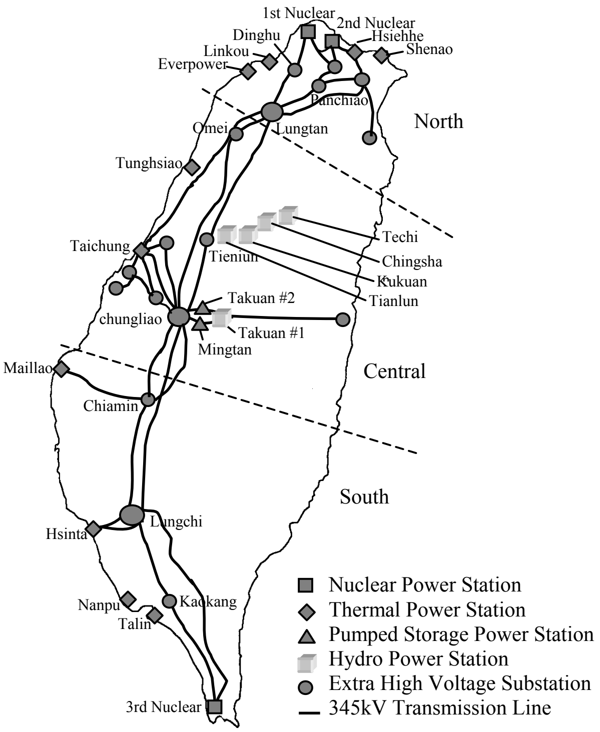
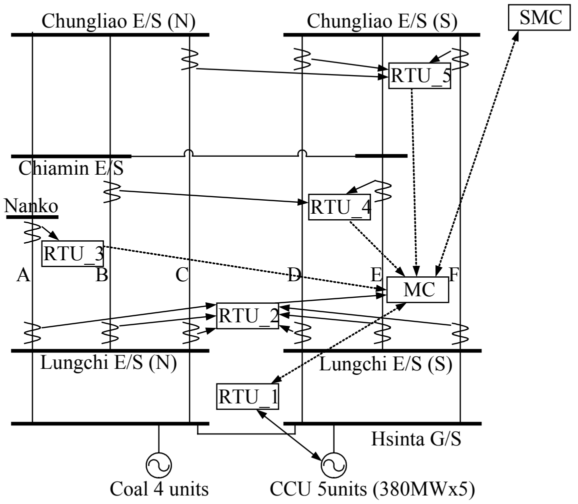


Figure 1 The geography of Taiwan Power System

A large number of contingency studies with extreme N-3 criterion under various load conditions had been conducted by Taipower. Study results indicated that any triple line outage at the North Lungchi Inter-ties (NLI) composed of a 345kV triple circuit line between Lungchi and Chiamin (one line through Nanko), and another 345 kV triple circuit line between Lungchi and Chungliao could cause transient/dynamic stability problems.

To resolve the transient instability problem, the TDI-SPS is designed by Taipower. Basic remedial action to be taken by the TDI-SPS is generation rejection (GR) in the southern area. The TDI-SPS is designed to monitor six critical transmission lines of North Lungchi 345-KV substation and trip the generation units in one of the power plants in Hsinta power station. The combined cycle units (CCU) are considered for generation rejection due to quick restart characteristics [4]. The structure of the TDI-SPS is shown in Figure 2.



E/S: extra high voltage substation
G/S: generation substation
MC: master controller
SMC: system master controller
RTU: remote terminal unit
·······► : fiber optic cables and microwave
———► : RS232

Figure 2 The structure of the TDI-SPS

In Figure 2, the TDI-SPS is composed of remote terminal units (RTUs), master controller (MC), system master controller (SMC), and communication media part. The RTUs installed in North Chungliao extra high voltage substation (E/S), South Chungliao E/S, Chiamin E/S, Nanko, and Lungchi E/S are responsible for collecting information on the severity of the incident. The MC installed in the Lungchi substation decides the amount of generation to be tripped. The RTU installed in Hsinta power station executes the remedial control command issued by the MC. The SMC that is installed in the central dispatch control center (CDCC) of Taipower is equipped with an effective Man-Machine Interface (MMI) for data acquisition and supervising SPS operations.

The generation amount of Hsinta power station and the CB status of the six trunk lines are monitored. The analog data including voltage, current, active power and reactive power for transmission lines are also monitored. When the system is in normal condition, the RTUs will send the steady-state measurements to the MC to update real-time information database. The MC will report alarms to the SMC if the power transfers on NLI exceed the setting value. When a fault is detected on any two lines of NLI and the total transfer level on NLI is higher than a certain amount, the MC will issue the control command to the RTU installed in Hsinta power station to execute generation rejection, and at the same time the event data during pre-fault and post-fault are recorded by each RTU.

As automation is introduced into the TDI-SPS, the above communication and control operations can become automated. The TDI-SPS with automatic communication and control functions offers an integrated system approach to monitoring, protection, and control for improving system operations. By transferring operation data and control signals via communication networks, the transient/dynamic stability can be automatically enhanced by identifying extreme emergency events and controlling the automatic switches, and thus a blackout incident can be avoided or the impact of the blackout can be minimized.

2.2 Communication Network

The communication network between the master controller and the RTUs is a very important part of the TDI-SPS. To ensure the successful operations of the TDI-SPS, the communication links between any monitored sites use two independent channels for redundancy. Data acquisition and control are performed by the local system and data are transmitted to and from the master controller and system master controller. With the communication network, the desired remedial control actions are possible. Without it the remote data collection and automatic remedial controls would be impossible.

The communication paths for the data transmission can have different physical shapes with different characteristics. The communication media used among SMC, MC and RTU's are 64 kbps microwave and fiber optic cables with RS-422/RS-530 or OCU-DP+DSU interface [5]. The main advantages of the microwave are that it is separate and independent of the status of the SPS, and that its capital costs are relatively lower than those of fiber optic cable systems. The main advantages of the fiber optic cables, however, are that data transmission is more reliable, and that its data link speed is generally higher than that of other communication media.

Figure 3 shows the communication scheme of the TDI-SPS shown in Figure 2. The main components of the microwave include transmitters, receivers, antennas, and power supply units, and they are transmitters and receivers for the fiber optic cables. The messages originate at a transmitter, and received by the corresponding receiver. The master controller and each RTU are equipped with a router (RO) which is composed of the antenna, transmitter, receiver, and power unit. The local systems are local automation equipments including the RTU, router, and switching device. These equipments are connected via connection cables (C). The data transmission between the local system and the master controller is through fiber optical cable and microwave. For communication between the RTU and master controller at Lungchi E/S, the signals are transferred through connection cables.

All communication components have self-diagnosis features to detect and alarm the failures of some important components. In case of failures of communication components, run out of memory space case or data loss event are detected, the system will issue alarms to CDCC and/or Lungchi substation to alert the system operators.

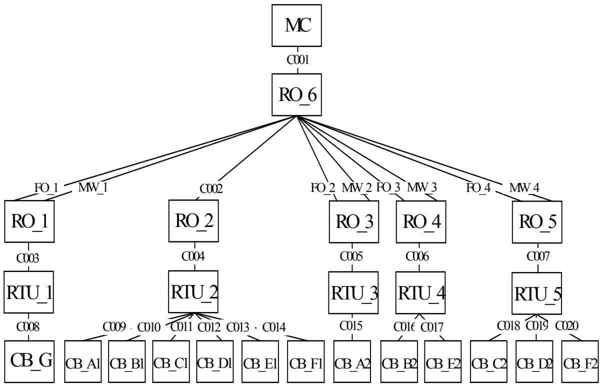


Figure 3 Communication scheme for the TDI-SPS

The reliable data communication is essential to the successful operation of desired remedial control actions. Like all other remote automation systems, the data communication is subject to possible failures of communication equipment. When the communication components fail, the signals between the master controller and the RTUs can not be communicated, and the desired remedial control action is not possible. In order to illustrate this impact, the TDI-SPS control operations are simulated and reliability evaluation is performed.

3. Reliability Evaluation Approach

The evaluation process required for the reliability prediction of automatic control procedures is generally complex since a lot of automation components and a number of control sequential actions are involved in the system operations. To simplify the reliability analysis process, a modular approach used in [6] is adopted in this paper. This approach divides the system into modules that could be analyzed separately. All modules are then combined together and the impacts of communication module on the system control function can be identified.

Several reliability assessment methods have been developed for the reliability prediction of complex automatic control procedures to provide useful aid in the systematic system availability and in identifying potential bottlenecks that might degrade system performance [7,8]. The fault tree analysis (FTA) widely used in the industries is used in this paper for SPS reliability evaluation.

FTA that uses a top-down approach for the identification of failure modes is a systematic and deductive procedure to derive and analyze potential failures and their potential influence on system reliability. In the FTA, its apex is defined as a predefined undesired system event. The analysis consists of determining the subevents and the combinations of subevents within a system that will result in the predefined system event. The possible combinations and sequences of events that could contribute to this undesired event are graphically depicted by use of logic symbols. By proper connection of these symbols and identification of the unique gate functions that each symbol represents, a logic diagram is produced. Once the logical relationships among the components of the system are established, the cause and effect relationships in the system operation can be studied, and the fault tree for a predefined undesired system event is developed. Based on the obtained fault tree, the probability of occurrence of the undesired event is estimated by using Boolean logic methodology [8].

The effect of the communication network on the SPS reliability is performed by the following steps:

1. Divide the SPS into modules which may contain a small or large number of individual components. Based on functional or operational features, each module is defined such that these component modules have no shared components and are considered as independent.
2. Identify the operational procedures for the SPS remedial control action being analyzed and define the SPS failure to operation as an undesired TOP event.
3. Examine each possible event to see whether it could cause the TOP event.
4. Determine the primary events that lead to the TOP event and the subevents that cause each of the primary events are determined.
5. Connect the set of events using proper Boolean logic gates.
6. Develop the system fault tree of the control procedure in terms of the component modules. This fault tree gives all possible outcomes of the system component modules and relates the modules to the undesired event.
7. Perform the TOP event probability evaluation. The impact of the communication network on the SPS reliability is evaluated.

4. Test Results and Discussions

The communication scheme of the TDI-SPS shown in Figure 3 is used for the study. Table 1 gives reliability data of these modules, where Unavailability is the inability of a module to perform its required function under a stated condition of a stated period of time. The reliability for a communication unit measures the ability of the communication unit to operate and signal successfully. These reliability data can be either readily derived by reliability analyses or obtained by a data collection scheme.

For the system shown in Figure 2, when a fault is detected on any three lines of NLI and the total transfer level on NLI is higher than a certain amount, the MC will issue the control command to RTU to execute generation rejection of Hsinta generation units. The predefined fault condition can not be accurately detected or the generation rejection control action can not be performed if the TDI-SPS failure caused by the communication components breakdown or malfunction.

Consider again the system shown in Figure 2. For generation rejection switching operations, assume that when a fault occurs on the lines D, E, and F, the sequence of event data transfer is that the CBs (CB_D1, CB_E2, and CB_F2) closing to the fault trip and the CBs' status data are transmitted to the corresponding RTUs (RTU_2, RTU_4, and RTU_5). The RTUs then pass the data for this event to the MC through the routers and communication data links. When all of data for this event are received by the MC, it processes the data and issues the generation rejection control command to the RTU (RTU_1) and the CB (CB_G) at Hsinta power station through the routers (RO_6, RO_1) and communication links to execute the control action.

Table 1 TDI-SPS hardware module reliability data

Module	Description	Unavailability ($\times 10^{-6}$)
MC	Master controller associated with software and support processes	10
RO_x	Router	100
RTU_x	Remote terminal unit	100
FO_x	Fiber optical link	100
MW_x	Microwave link	100
CB_G	Circuit breaker	300
CB_x	Circuit breaker associated with 52b relay contact	300
Cxxx	Connection between components	0

Representing the TDI-SPS of Figure 3 in term of its component modules, a fault tree for the generation rejection control procedure is developed which is shown in Figure 4. The TDI-SPS failure defined as the SPS fails to operate generation rejection control action is used as a top event. Using the reliability evaluation procedure mentioned above, the basic events for the TDI-SPS failure are identified.

Figure 4 shows the fault tree for the TDI-SPS. The event probabilities considered in the tree are the probabilities that each module will induce to the top event. As can be found from Figure 4 that the top event TDI-SPS failure is induced by the failure of any one of the MC, RO_6, Hsinta power station data transfer, and the monitored substations data transfer. Since the communication link between the MC and RTUs is redundancy, the communication link failure is deduced from both the fiber optic and microwave failures. For an intermediate event that basic events must all occur, the probability of occurrence of the event can be calculated from the product of the appropriate event probabilities. For an intermediate event that anyone of the basic events occurs, the probability of occurrence of the event can be obtained by summating the path probabilities. Using the reliability data given in Table 1, the following probabilities of intermediate events can be evaluated and the probability of occurrence of top event is calculated:

$$P(\mathrm{Hsinta})=1-(1-P_{RO\_1})\times(1-P_{RTU\_1})\times(1-P_{CB\_G})\times(1-P_{FO\_1}\times P_{MW\_1})=4.994\times10^{-4}$$

$$P(\mathrm{Lungchi})=1-(1-P_{RO\_2})\times(1-P_{RTU\_2})\times(1-P_{CB\_D1})=4.993\times10^{-4}$$

$$P(\mathrm{Chiamin})=1-(1-P_{RO\_4})\times(1-P_{RTU\_4})\times(1-P_{CB\_E2})\times(1-P_{FO\_3}\times P_{MW\_3})=4.994\times10^{-4}$$

$$P(\mathrm{Chungliao})=1-(1-P_{RO\_5})\times(1-P_{RTU\_5})\times(1-P_{CB\_F2})\times$$

$(1-P_{FO\_4}\times P_{MW\_4})= 4.994\times10^{-4}$

$P_{failure}=1-(1-P_{MC})\times(1-P_{RO\_6})\times(1-P(Hsinta))\times(1-P(Lungchi))\times(1-P(Chiamin))\times(1-P(Chungliao))= 2.10803\times10^{-3}$

where

P_i= probability of failure of the component i

$P(*)$= probability of failure of the data transmission of the power station or monitored substations

$P_{failure}$= probability of failure of the TDI-SPS

As can be seen that the probability of the TDI-SPS failure is about 2.11×10^{-3}. This means that if there were 1000 events that SPS should operate as designed, about 2 cases would result in failure to operation at any time of the period due to the failure of communication equipments. The probabilities of different data transmission paths are almost the same. The data transmission of Lungchi E/S has the lowest probability of failure of the data transferred from the substation. This is because Lungchi E/S is directly connected to the master controller, and no communication links could affect the data transfer between the RTU and master controller.

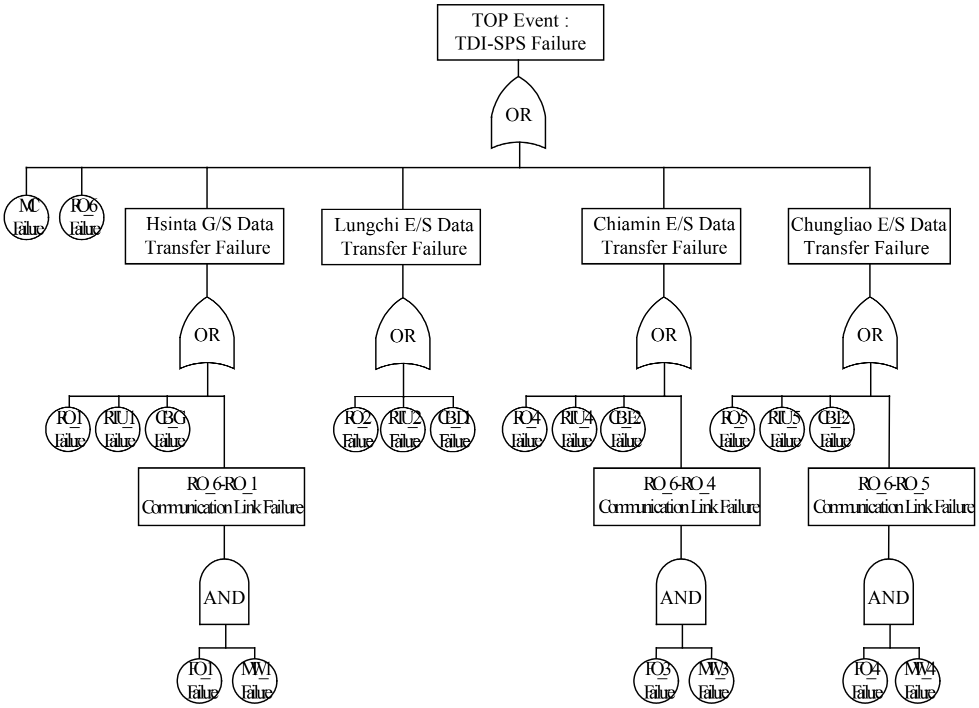


Figure 4 Fault tree for the TDI-SPS

To reduce the effect of the uncertainty associated with input parameters on analysis results and to determine the critical components that have large effects on the reliability of the system, a sensitivity analysis is also performed. Two test cases were studied. Case 1: using the result (Base case 1) with input data in Table 1 as the reference, the SPS failure probability is calculated with each component made perfect (with an unavailability of zero) once at a time. Case 2: the SPS failure probability (Base case 2) is computed with all components assigned the same unavailability that is the average of the data shown in Table 1 except for the connection component, each component is then made perfect and the results are compared to Base case 2.

Figures 5 and 6 show the analysis results. It can be seen from the results that the probability of the SPS failure to operation is greatly affected by the circuit breakers, master controller, routers, and RTUs that are a vital part in the system or exit in large quantities. The implication of the study result is that the overall performance of the SPS can be enhanced with increasing the reliability level of these equipments.

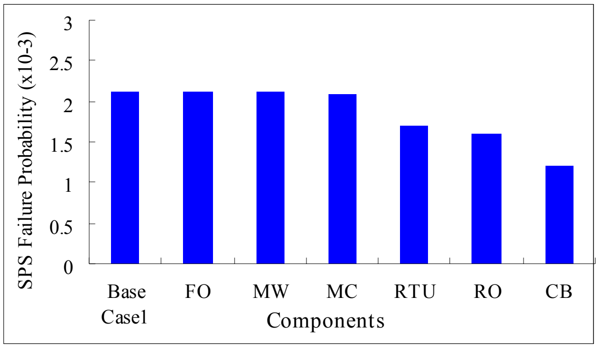


Figure 5 Sensitivity analysis of Case-1

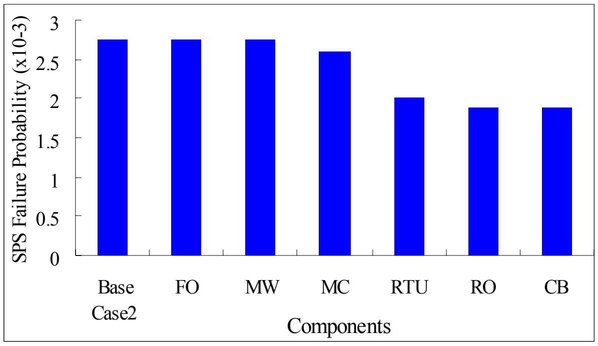


Figure 6 Sensitivity analysis of Case-2

5. Conclusion

This paper has demonstrated the importance of communication network for a wide area SPS. Two sensitivity analysis cases are performed to reduce the effect of uncertain input data and to identify the critical components for the overall system reliability. Test results have indicated that the reliable communication system is essential to the reliable operation of the SPS. The communication equipment that is a vital part in the system or exists in large quantities is a critical component for the overall system reliability. With the results obtained, system designers could adopt available options to increase reliability of the components or to devise alternative structure for maintaining an adequate performance of the SPS system.

REFERENCES

[1] CIGRE Task Force 38.02.19 (Convener: D. Karlsson), System Protection Schemes in Power Networks, 2001.

[2] J. D. McCalley and W. Fu, “Reliability of special protection systems,” *IEEE Trans. on Power Systems*, Vol. 14, No. 4, November 1999, pp. 1400-1406.

[3] W. Fu, S. Zhao, J. D. McCalley, V. Vittal, and N. Abi-Samra, “Risk assessment for special protection systems,” *IEEE Trans. on Power Systems*, Vol. 17, No. 1, February 2002, pp. 63-72.

[4] T. Y. Hsiao, C. N. Lu and Y. H. Liu, ”Defense plan design in a longitudinal power system,” *Proceedings of the 14th Power Systems Computation Conference*, Spain, 24-28 June 2002.

[5] C. L. Su, “Simulation study of a special protection system with reference to communication performance,” *International Journal of Electrical Power and Energy Systems*, Vol. 26, No. 2, February 2004, pp. 91-96.

[6] Y. He, L. Soder, and R. N. Allan, “Distribution automation: impact of communication system on reliability of automatic control,” *Proceedings of the IEEE Porto Power Tech Conference*, Porto, Portugal, 10-13 September, 2001.

[7] E. J. Henley and H. Kumamoto, P*robabilistic Risk Assessment*, New York: IEEE Press, 1992.

[8] R. Billton and R. N. Allan, *Reliability Evaluation of Engineering Systems- Concepts and Techniques (2/e)*, Plenum Press, 1992.