⊠응용논문

A Study on the Application of Composite Reliability to Estimate the EDG Reliability+

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Abstract

A commercial nuclear power station contains at least two emergency diesel generators(EDG) to control the risk of severe core damage during station blackout accidents. Therefore, the reliability of the EDG's to start and load-run on demand must be maintained at a sufficiently high level. Until now, a simple assessment of start and load-run success rates was used to calculate the EDG reliability. However, this method has been found to contain many defects. Recently, the work of Martz et al.(1996) proposed the use of the Bayes estimator to find EDG reliability. Shim(1996) proposed a confidence interval for the Bayes estimator, compare the above two methods.

In this paper, we introduce the notion of "Composite Reliability" to estimate the reliability of nuclear-power plant EDG, and using practical examples, illustrate which method is more appropriate in our situation.

1. Introduction

A nuclear power station contains one or more nuclear power units, and the term nuclear power plant usually refers to a single nuclear unit. If offsite power is interrupted, the availability of onsite alternative-current power supplies is a major factor in ensuring acceptable safety at nuclear power plants. To control the risk of

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severe core damage during station blackout accidents, the reliability of the emergency diesel generator's(EDG's) to start and load-run on demand must be sufficiently high.

The methods for estimating EDG reliability have been studied by many authors. Wyckoff(1986) proposes that the number of successful starts and load-runs must be proportionate to the total number of demanded valid starts and load-runs. He regards the ratio as a proven gauge of EDG reliability and as the most recent method introduced in Korea. Wyckoff's method has been widely used to obtain EDG reliability. The merit of Wyckoff's method is though the use of failure rate and a simple calculation, one can get the reliability. But, Wyckoff's exclusive use of such overly simple variables in his method of computation has caused many discrepancies in outcomes of his estimations.

The first problem is that his method does not reflect the empirical characteristics of the machine. Therefore, if data contains some outliers, then the precision of reliability is in doubt. The second problem is then directly related to the first - according to inherent circumstances, it is impossible for the reliability of a machine to be estimated at or to in practice be 100 percent. The third problem, since there is a severe deviation between a year of mechanical trouble and a year of proper function, questions may be raised about the reliability itself.

The most recent report of Martz et al.(1996) propose the parametric empirical Bayes approach to estimate EDG reliability. The Bayes approach concerns the situation in which, in addition to a collection of assumed sampling models for the observed data over some population (such as a set of stations), some (perhaps all) of the unknown parameters of interest in the sampling models are also assumed to follow an unknown relative frequency-based prior distribution.

At the same time, Chen et al.(1996) propose the "composite reliability" as a measure of the reliability of a collection of heterogeneous but similar items. They proposes a hierarchical Bayes model for estimating the composite reliability of systems whose lifelengths are expressed as binary random variables.

In this paper, we apply the composite reliability and Bayes approach to calculate EDG reliability. We show that the composite reliability has more appropriate than Wyckoff's method in the Korean situation.

Section 2 is devoted to describe the EDG and SDG systems. Wyckoff reliability and the composite reliability of diesel generators are considered in Section 3. Section 4 contains illustrative examples, and Section 5 contains some conclusions.

2. Emergency Diesel Generator and Standby Diesel Generator

2.1 Emergency Diesel Generator(EDG)

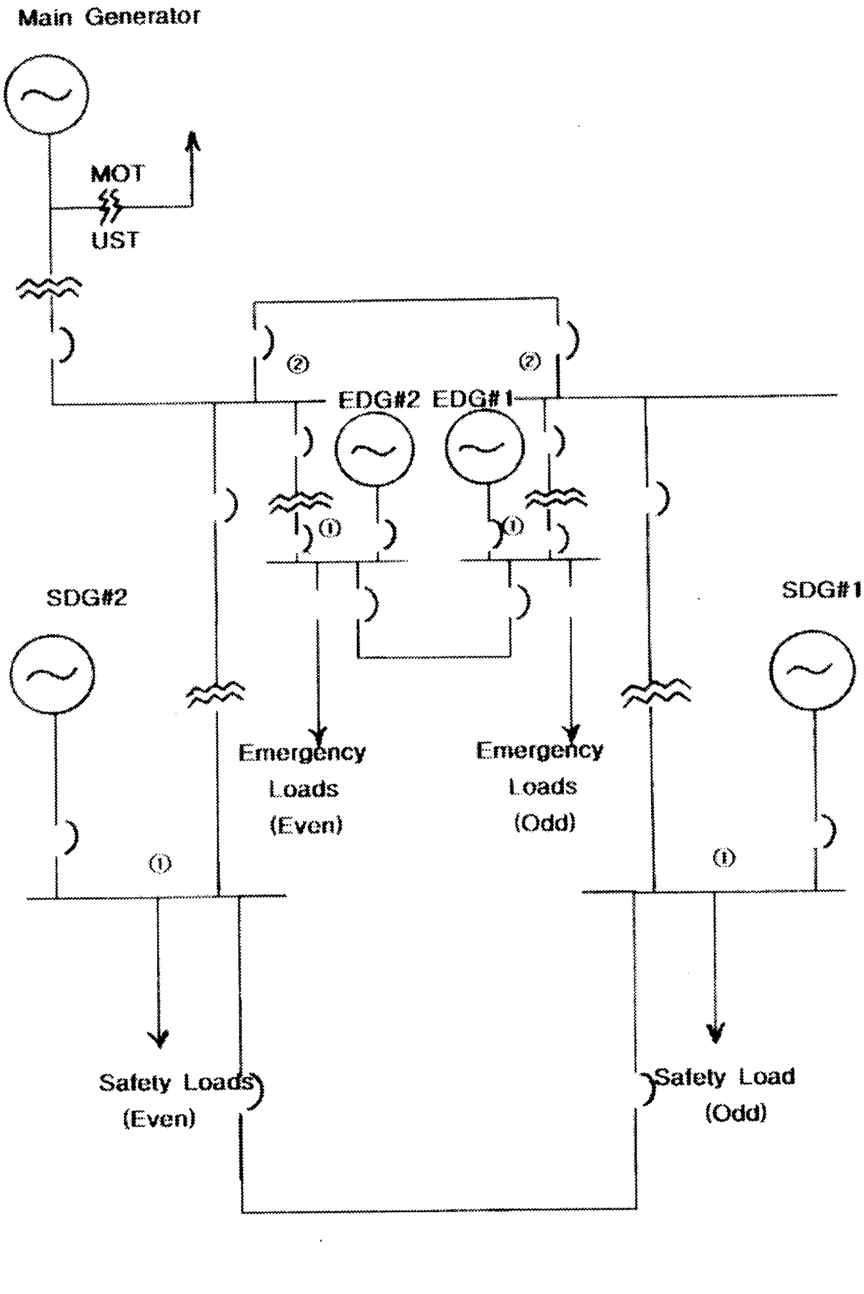
This system and its buildings are seismicaly qualified to be operational after an earthquake. The system provides a backup for one group of safety systems if normal electric supplies become unavailable or the main control room becomes uninhabitable. The system comprises two diesel generating sets, housed in separate fire resistant rooms, which are selfcontained and completely independent of the station's normal services. There is adequate redundancy provided in both the generating distribution equipment and the loads.

2.2 Standby Diesel Generator(SDG)

The Station Service power supplies are classified in order of their levels of reliability requirement. The reliability requirement of these power supplies is divided into four classes, that is Class I, Class II, Class III, Class IV, that range from uninterruptible power to that which can be interrupted with limited and acceptable consequences.

Standby power for the Class III loads is supplied by two or more diesel generator sets, housed in separate rooms with fire resistant walls. Each diesel generator can supply the total safe shutdown load of the unit. The Class III shutdown loads are duplicated, one complete system being fed from each diesel generator. In the event of failure of Class IV power, the two diesel generators will start automatically.(see Figure 1).

The generators can be up to speed and ready to accept loads in less than two minutes. The total interruption time is limited within three minutes. Each generator automatically energizes half of the shutdown load through a load sequencing scheme. There is no automatic electrical tie between the two generators, nor is there a requirement for them to be synchronized. In the event of the failure of one of generators, the total load will be supplied by the other generator. <Figure 1> shows the structure of the EDG system SDG system.



① means 4.16KV (Class III) ② means 13.8KV (Class IV)

< Figure 1 > Electric Power Systems.

3. Wyckoff reliability and the Composite reliability

3.1 Wyckoff reliability

Wyckoff(1986) calculates the failure rates of the EDGs in start condition and load-run condition and used them to estimate EDG reliability. There are two phases of EDG operation which are the start phase and the load-run phase. The start phase ends when the EDG begins a countable load-run or is shutdown.

A start demand is considered as a success if the EDG was stable at the rated voltage and frequency within 5 minutes from the first start attempt. The load-run phase is considered to begin when one of the following criteria is applied to the EDG.

① An intention to meet the plant's load and duration specifications for its 1-month, 6-month, 18-month or other Tech. Spec. required test.

② Any load and load-run duration that derive from an automatic or manual real demand, whether valid or inadvertent. A real load-run is not preplanned and is made because of an apparent plant safety need, not because the condition of the EDG needs to be verified.

Demand to load is occurs only after a successful start. Thus a failure to start is not counted as a failure to load-run just as a successful start is not counted as a successful load-run. Therefore, for the purpose of determining the impact on plant risk, EDG reliability is to be considered in terms of two elements, namely, start reliability and load-run reliability as ,follows:

$$\text{Start reliability} = \frac{\text{Number of successful starts}}{\text{Total number of valid demands to starts}} \tag{1}$$

and

$$\text{Load-run reliability} = \frac{\text{Number of successful load-runs}}{\text{Total number of valid demands to load-runs}}. \tag{2}$$

Wyckoff(1986) defines the EDG reliability in the following form,

$$\text{Wyckoff reliability} = (\text{start reliability}) \times (\text{load-run reliability}) \tag{3}$$

3.2 Composite reliability

The problem of estimating the EDG's composite reliability boils down to estimate many binomial parameters, all of which are small, and are generated by a common distribution, which are also must be estimated. To proceed further, we focus on the start phase of the EDG operation.

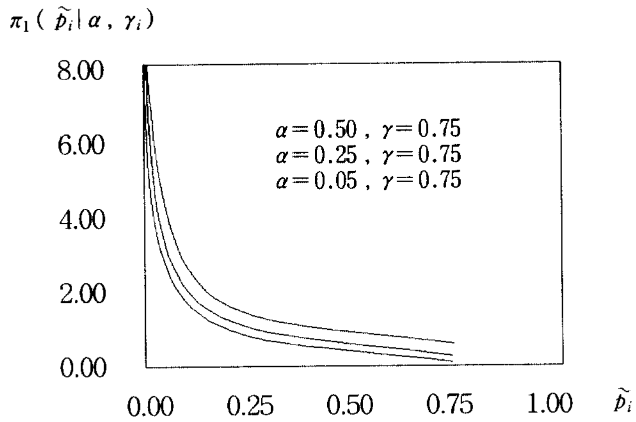
We let p_i be the start(or the load-run) phase reliability of the ith EDG; $\tilde{p}_i = 1 - p_i$, the unreliability of the ith EDG; the collective $\mathbf{p} = (p_1, p_2, \cdots, p_m)$ expressed as a joint distribution; n_i = total number of demands to start per year for the ith EDG; X_i = number of total times that the ith EDG fails to start in the n_i demands; $\mathbf{d}_i = (n_i, X_i)$; $\mathbf{d} = (d_1, d_2, \cdots, d_m)$; and $\tilde{\mathbf{p}} = (\tilde{p}_1, \tilde{p}_2, \cdots, \tilde{p}_m)$, $i = 1, 2, \cdots, m$, where m is the total number of EDG's in all plants. Because the EDG's are designed to be highly reliable and are operated and monitored under the same federal regulations, these $\tilde{p}_i$'s are assumed to be small and similar. Our task is to estimate each $\tilde{p}_i$ based on prior information about $\tilde{\mathbf{p}}$ and on all of the data $\mathbf{d}$.

We propose a particular joint prior distribution for the $\tilde{p}_i$'s. Our rationale is explained by first focusing on a meaningful prior an individual $\tilde{p}_i$, and then extending the construction to cover the collection of all the $\tilde{p}_i$'s.

Because each $\tilde{p}_i$ is presumed to be small, we start by specifying for any $\tilde{p}_i$ an L-shape prior distribution with an upper bound of γ_i, $\gamma_i < 1$. This is prior, which captures the belief that large values of $\tilde{p}_i$ are less likely than small values. The density function of this prior, given hyperparameters α and γ_i is

$$\pi_1(\tilde{p}_i \mid \alpha, \gamma_i) = \alpha \, \tilde{p}_i^{\alpha-1} / \gamma_i^{\alpha} \quad \text{for} \quad 0 < \tilde{p}_i < \gamma_i. \tag{4}$$

This is a beta distribution on $(0, \gamma_i)$ with parameters α and $\beta = 1$. To reflect our belief of small values of $\tilde{p}_i$, we choose $\alpha \in (0, 1)$; see <Figure 2>. Chen et al.(1996) show that the distribution of $\tilde{p}_i$ becomes approximately uniform on $(0, \gamma_i)$ as $\alpha \to 1$. When $\beta > 1$, the distribution of $\tilde{p}_i$ will still be L-shaped, but values of $\tilde{p}_i$ closed to 1 seldomly occur. Thus choosing $\beta = 1$ is preferable to choosing $\beta > 1$.(see Chen et al.(1996))



< Figure 2 > Prior distribution of $\tilde{p}_i$ conditional on $\gamma = 0.75$

The stage 2 prior is designed to describe our uncertainty about the hyperparameter γ_i. Even though we are unsure about γ_i, we find it unlikely that γ_i will take extremely small values. Thus a meaningful prior for γ_i would be one that is approximately uniform on $(0, 1)$, but with a steep decrease toward zero. Chen et al.(1996) showed that this behavior could be achieved by choosing a beta distribution on $0 < \gamma_i < 1$, with $\beta_2 = 1$ and β_1 greater than but close to 1.

$$\pi_2(\gamma_i | \beta_1, \beta_2) \propto \gamma_i^{\beta_1 - 1}(1 - \gamma_i)^{\beta_2 - 1} \quad (5)$$

It is noted that a prior judgment about small values of $\tilde{p}_i$ being more likely than large values is captured by choosing α to be small. One way to satisfy the requirement that β_1 be greater than but close to 1 is to let $\beta_1 = 1 + \alpha$. The choice for β_1 is by no means mandatory. However, it has two advantages. The first is that the ensuring calculations get simplified and the second is that a prior distribution of $\tilde{p}_i$ becomes a distribution with a single hyperparameter - namely, α.

With $\beta_1 = 1 + \alpha$, it is easy to verify that unconditionally on γ_i, the prior on $\tilde{p}_i$ becomes a beta distribution as follows :

$$\pi(\tilde{p}_i | \alpha) = \alpha(\alpha + 1)\ \tilde{p}_i^{\alpha - 1}(1 - \tilde{p}_i),\ 0 < \tilde{p}_i < 1. \quad (6)$$

Suppose that the EDG reliabilities are independent. Then the joint prior for $\tilde{\mathbf{p}}$ is

$$\pi_I(\tilde{\mathbf{p}} \mid \alpha) = \prod_{i=1}^{m} \left\{ \alpha(\alpha+1)\, \tilde{p}_i^{\,\alpha-1} (1-\tilde{p}_i) \right\},\ \text{for}\quad 0 < \tilde{p}_i < 1. \qquad (7)$$

3.3 The posterior distributions

Because each X_i is a binomial random variable, the likelihood function of $\tilde{\mathbf{p}}$, $L(\mathbf{d} \mid \tilde{\mathbf{p}})$, is proportional to

$$\prod_{i=1}^{m} \tilde{p}_i^{\,x_i} (1-\tilde{p}_i)^{n_i - x_i} \qquad (8)$$

When $\tilde{p}_i$'s are independent, the posterior of each $\tilde{p}_i$ depends on the beta prior of $\tilde{p}_i$ and d_i alone and is consequently a beta distribution. Specifically, the posterior of $\tilde{\mathbf{p}}$ is

$$\prod_{i=1}^{m} \pi_I(\tilde{p}_i \mid \alpha, d_i) \qquad (9)$$

,where $\pi_I(\tilde{p}_i \mid \alpha, d_i) \propto \tilde{p}_i^{\,x_i+\alpha-1} (1-\tilde{p}_i)^{n_i - x_i + 1}$, for $0 < \tilde{p}_i < 1$ and $i = 1, 2, \cdots, m$.

Because

$$E_I(\tilde{p}_i \mid \alpha, d_i) = \frac{\alpha + x_i}{\alpha + n_i + 2}, \qquad (10)$$

the composite reliability of the collection of m EDG's is

$$\frac{1}{m} \sum_{i=1}^{m} \frac{\alpha + x_i}{\alpha + n_i + 2} \qquad (11)$$

under the assumption of a priori independence of $\tilde{p}_i$'s.

4. An actual illustration

The methods of this article are applied to some data from Wolsung nuclear power plants. We use start data, from 1985 to 1993, of EDG of Wolsung nuclear power plant unit 1 in Korea to calculate their reliability. Wolsung unit 1 has two EDGs and two SDGs, and they are able to withstand and recover from a station blackout of a specified duration.

<Table 1> and <Table 2> show the number of starts and failures of SDG #1 and SDG #2, respectively. <Table 3> and <Table 4> show the number of starts and failures of EDG #1 and EDG #2, respectively.

<Table 1> and <Table 2> present reliability values based on the Wyckoff reliability and composite reliability from each SDG. <Table 3> and <Table 4> show reliability values based on the Wyckoff reliability and composite reliability from each EDG.

In expression (10) and (11), our choice of $\alpha = 0.05, 0.10$ is based on the recommendation of a staff of the Nuclear Regulatory Commission(NRC) who has claimed experience with the failure of EDG's.

< Table 1 > The estimated reliabilities of Wolsung unit1 SDG #1

Year	SDG #1				
	number of starts	number of failures	Wyckoff reliability	Composite reliability $\alpha = 0.05$	Composite reliability $\alpha = 0.10$
1985	35	1	0.9714	0.9717	0.9704
1986	28	0	1.0000	0.9983	0.9967
1987	32	1	0.9697	0.9700	0.9677
1988	34	2	0.9444	0.9431	0.9418
1989	30	0	1.0000	0.9984	0.9969
1990	33	0	1.0000	0.9986	0.9972
1991	41	0	1.0000	0.9988	0.9977
1992	45	0	1.0000	0.9989	0.9979
1993	29	1	0.9667	0.9662	0.9646
total	307	5	0.9837	0.9827	0.9812

As a general rule, Wyckoff estimators are calculated by applying expression (3), leading Kim(1993) to argue that there is difficulty in distinguishing the start and load-run conditions of nuclear related data in Korea now. Therefore, he regards successful start rates with the Wyckoff reliability and though there exists some adverse criticism, we follow his opinion.

< Table 2 > The estimated reliabilities of Wolsung unit1 SDG #2

Year	SDG #2				
	number of starts	number of failures	Wyckoff reliability	Composite reliability $\alpha=0.05$	Composite reliability $\alpha=0.10$
1985	34	2	0.9412	0.9431	0.9418
1986	30	1	0.9667	0.9672	0.9657
1987	23	0	1.0000	0.9980	0.9957
1988	32	1	0.9687	0.9700	0.9677
1989	30	0	1.0000	0.9984	0.9969
1990	37	1	0.9730	0.9731	0.9719
1991	44	3	0.9318	0.9338	0.9328
1992	35	0	1.0000	0.9987	0.9973
1993	35	4	0.8857	0.8907	0.8895
total	300	12	0.9600	0.9637	0.9621

< Table 3 > The estimated reliabilities of Wolsung unit1 EDG #1

Year	EDG #1				
	number of starts	number of failures	Wyckoff reliability	Composite reliability $\alpha=0.05$	Composite reliability $\alpha=0.10$
1985	25	3	0.8800	0.8872	0.8856
1986	26	1	0.9615	0.9626	0.9609
1987	24	0	1.0000	0.9981	0.9962
1988	26	0	1.0000	0.9982	0.9964
1989	31	0	1.0000	0.9985	0.9970
1990	28	0	1.0000	0.9983	0.9967
1991	33	0	1.0000	0.9986	0.9972
1992	37	4	0.8919	0.8963	0.8951
1993	38	3	0.9211	0.9238	0.9227
total	268	11	0.9590	0.9624	0.9609

< Table 4 >The estimated reliabilities of Wolsung unit1 EDG #2

Year	EDG #2				
	number of starts	number of failures	Wyckoff reliability	Composite reliability $\alpha=0.05$	Composite reliability $\alpha=0.10$
1985	113	0	1.0000	0.9996	0.9991
1986	23	0	1.0000	0.9980	0.9960
1987	26	0	1.0000	0.9982	0.9964
1988	29	0	1.0000	0.9984	0.9968
1989	29	0	1.0000	0.9984	0.9968
1990	32	1	0.9688	0.9692	0.9677
1991	32	0	1.0000	0.9985	0.9971
1992	32	0	1.0000	0.9985	0.9971
1993	29	1	0.9655	0.9662	0.9646
total	355	2	0.9944	0.9917	0.9902

According to <Table 1> and 2, we see that Wyckoff reliabilities have a significant difference values between years in which there occurred many failures and years of zero failures attempt. For instance, in the case of EDG #1, for the year 1991 the Wyckoff reliability is 1.00, while on the other side in 1992 the estimate is 0.8919. But composite reliability has constant values within the same period of time.

5. Conclusion

We consider two methods for estimating the reliability of EDG and apply them to the data from Wolsung nuclear power plants. The comparison of two methods results in the following conclusions:

First, Wyckoff reliabilities are the simple result of the proportion of number of successful starts and load-runs to total number of valid demands of starts and load-runs in a given year. Therefore, it is the flaw of the Wyckoff reliability as a method that it does not reflect the empirical character of each machine, so that if no failures were occur, then the unreliability estimate would be zero. For instance in 1991 EDG #1's Wyckoff reliability was 1.00, while in 1992 EDG #1's Wyckoff reliability was 0.8919.

Second, the composite reliability is calculated when collection of assumed sampling models for the observed data over some population (such as a set of stations) and some (perhaps all) of the unknown parameters of interest in the sampling models are assumed to follow an unknown relative frequency-based prior distribution. Therefore, it is easy to reflect the empirical character of each machine, and is less influenced by the Wyckoff method by influential data. For instance, the 1991 EDG #1 Bayes estimator result was 0.9986 while the result in 1992 was 0.8963.

Therefore, we recommend to use the method of a composite reliability when one wants to obtain the more accurate reliability of EDG.

References

[1] Chen, J. and Singpurwalla, N.D.(1996), "The Notion of Composite Reliability and Its Hierarchical Bayes Estimation," *Journal of the American Statistical Association*, Vol. 91, No. 436, pp. 1474-1484.

[2] Martz, F.M. and Waller, R.A.(1982), *Bayesian Reliability Analysis*, (New York: John Wiley and Sons, Inc.).

[3] Martz, F.M. Kvam, H.K. and Abramson, L.R.(1996), "Empirical Bayes Estimation of the Reliability of Nuclear Power Plant Emergency Diesel Generators," *Technometrics*, 38(1), pp. 11-24.

[4] NUREG/CR-2989 (1993), "Reliability of Emergency AC Power Systems at Nuclear Power Plants," U.S. NRC.

[5] Reg. Guide 1.155 (1988), "Station Blackout," U.S. NRC, June.

[6] Weiler, H.(1965), "The User of Incomplete Beta Functions for Prior Distributions in Binomial Sampling," *Technometrics*, Vol. 7, pp. 335-347.

[7] Wyckoff, H.(1986), "The Reliability of Emergency Diesel Generators at U.S. Nuclear Power Plants," EPRI.

[8] Kim, T.W.(1993), "Survey and Analysis of the Loss of Off-Site Power Events on Korean Nuclear Power Plants and the Reliability/Unavailiability of Emergency Diesel Generators of Kori Units 3,4," Korea Atomic Energy Research Institude Reactor Safety Assessment Department.

[9] Shim, K.B.(1996), "Bayes Estimate for the Reliability of Nuclear-Power Plant Emergency Diesel Generator," *Journal of the Korean Society for Quality Control,* Vol. 25, No. 3, pp. 108-118.