RELIABILITY OF ON-SITE POWER SYSTEM IN NUCLEAR POWER PLANTS

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ABSTRACT

The electrical power system in a nuclear power plant is designed to provide a diversity of reliable power sources which are physically and electrically isolated so that any single failure will affect only one source of supply and will not propagate to alternate sources. The present study discusses the problem of improving the reliability of on-site power system. Trend analysis for diesel generator failures and failure rate estimation, based on actual operational experience, are presented and discussed. The continuous Markov process is utilized to derive the mathematical models for reliability and availability of the on-site power system at different redundancy levels.

1. INTRODUCTION

Most technical specifications of commercial nuclear power plants (NPPs) classify the electric power feeding the plant into two main systems; Emergency Power System (EPS) and Balance of Plant System (BOP) [1]. EPS provides reactor protection power for safe shutdown and Engineered Safety Feature (ESF) power to mitigate the effects of transients and accidents. In contrast, BOP system provides power to those loads which, normally have no safety implications but are required for continuous plant operation and general purposes.

For a typical two unit NPP, EPS consists of [1]:

i. Off-site power (preferred source: consists of two sources for which each one is capable of serving all the emergency power requirements of both units.
ii. On-site A-C power (stand-by source): consists of a number of diesel generators (DGs) according to the redundancy level stated in the plant technical specifications.
iii. On-site D-C power: consists of four sources of 125 V lead-calcium batteries.
iv. Auxiliary equipment: includes transformers, buses, and cables for the distribution of power to ESF systems (ESFSs).

It is a vital part in most safety analysis reports to study the events of loss of off-site power, loss of on-site power, and simultaneous loss of both off-site and on-site power (station blackout).

The reliability of EPS is affected significantly by the redundancy level which can be classified as follows:

Level-1 One DG per unit.
Level-2 One dedicated DG per unit and one DG shared between two units.
Level-3 Two DGs per unit.
Level-4 Two DGs plus four tandem diesels per unit.
Level-5 Two dedicated DGs per unit and one DG shared between two units.
Level-6 Three DGs per unit.
Level-7 Four DGs shared between three units.
Level-8 Four DGs shared between two units.
Level-9 Five DGs shared between two units.
Level-10 Four DGs per unit.

The present study discusses the problem of improving the reliability of on-site power through modeling and analysis of different redundancy levels of DGs.

2. TREND ANALYSIS

Failure trend analysis, based on actual operational experience, highlights different spots causing poor performance of on-site power system. To a great extent, this analysis will contribute in resolving the problem of improving the reliability of the system under consideration. Data on diesel generators failures over three years were extracted from licensee event reports (LERs) from the US commercial NPPs [2]. A total of 298 events were found to involve in diesel generator failures. In the present study, these failures were classified according to:

i. Failure mode.
ii. Event type.
iii. Discovery method.
iv. Failure mechanism.
v. Subsystem involved.
vi. Repair time.

Major contributors to each of the items shown above, together with the corresponding percentages are shown in Table (1). Other two dimensional trend analysis can be conducted as provided in reference [3].

3. MATHEMATICAL MODELS FOR RELIABILITY AND AVAILABILITY

Reliability concepts for different configurations of components can be better understood through the continuous Markov process [4]. The process structure declares all possible transitions between system states allowing repair or not. Following the construction of the transition matrix, a set of linear differential equations can be obtained whose solutions are the state probabilities as function of time. These probabilities are utilized to derive an expression for the system reliability according to the configuration under concern [5]. The derivation is much simplified when the failure and repair rates (λ and μ) are assumed constants. Table (2) presents the formulae obtained for redundancy level-1.

Table 1. Trend Analysis of Diesel Generator Failures.

Classification accordance	Major contributors and corresponding percentages					
Failure mode	Does not start	44	Does not continue to run	26		
Event type	Random*	35	Recurring	32	Common fault	14
Discovery method	During testing	83	During operation	14	During maintenance	2
Failure mechanism	Human error	33	Component failure	29	Contamination	13
Subsystem	Governor	17	Starter	15	Duel oil	12
Repair time	1-4 hr	26	0 - 1hr	23	4-8 h	22

* Lack of information due to deficiencies in the LER reporting system.

Table 2. Formulae Used for Redundancy Level -1.

Parameter	Formula
Reliability	$R(t) = \exp[-\lambda t]$
Mean Time Between Failure (MTBF)	$\theta = \frac{1}{\lambda}$
Unavailability	$U(t) = \frac{\lambda}{\lambda + \mu}[1 - e^{-(\lambda + \mu)t}]$
Availability	$A(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda + \mu)t}$
Infinite Availability	$A(\infty) = \frac{\mu}{\lambda + \mu}$

Table 3. Formulae used for redundancy level-2.

Parameter	Formula
a. Perfect Redundancy	
* Reliability	$R(t) = 2e^{-\lambda t} + e^{-2\lambda t}$
* MIBF	$\theta = 3/(2\lambda)$
b. Imperfect Redundancy	
* Reliability	$R(t) = 2e^{-\lambda t} - e^{-\lambda t(2-\beta)}$
* MTBE	$\theta = \dfrac{3-2\beta}{\lambda(2-\beta)}$
c. Full Redundancy	
* Reliability	$R(t) = \dfrac{1}{d-c}\{[(3-2\beta)(\lambda+\mu)-c]e^{-ct} - [(3-2\beta)(\lambda+\mu)-d]e^{-dt}\}$
* MTBE	$= \dfrac{(3-2\beta)(\lambda+\mu)}{\lambda^2(2-\beta)+\beta\lambda\mu}$
* Unavailability	$U(t) = G - Ae^{-at} + De^{-bt}$
* Infinte availability	$A(\infty) = 1 - \dfrac{\lambda[\lambda(2-\beta)+\beta\mu]}{\lambda^2(2-\beta)+2\lambda\mu+\mu^2}$

For redundancy level-2 (and higher levels), the evaluation of transition probabilities, and hence the system reliability and availability, is very complicated. The complexity comes from the consideration of common mode failures (CMF), repair policies, and standby operations. Redundancies within those levels could be classified as [3]:

i. Perfect redundancy: neither repair nor CMF is considered.
ii. Imperfect redundancy: only CMF is considered.
iii. Full redundancy: both repair and CMF are considered Table (3) presents the formulae obtained for redundancy level-2.

4. ESTIMATED FAILURE RATE FOR DIESEL GENERATORS

For all mathematical models in reliability analysis, a best estimate for failure rate is needed.

Data on DG failures from some NPPs was surveyed over two years. Nine plants were selected; three belong to redundancy level-1 and six to redundancy level-2. Estimated values for failure rate ($\hat{\lambda}$) and mean time to failure (θ) were computed. The χ^2 distribution [6], with confidence level α = 0.95, is utilized to obtain lower and upper bounds for those parameters. The formulae used are

$$a,b = \frac{(3-\beta)(\lambda+2\mu)}{2} \pm [\lambda^2(1-\beta)^2 + 2\lambda\mu(3-2\beta) + 3\mu^2]^{1/2}$$

$$c,d = \frac{(3-\beta)(\lambda+\mu)}{2} \pm [\lambda^2(1-\beta)^2 + 6\mu\lambda(1-\beta) + \mu^2]^{1/2}$$

$$G = \frac{\lambda[\lambda(2-\beta)+\beta\mu]}{\lambda^2(2-\beta)+2\lambda\mu+\mu^2}$$

$$A = \frac{\beta\lambda - cb}{a-b}, \quad D = \frac{\beta\lambda - ca}{a-b}$$

$\beta \equiv$ Fraction between 0 (weak coupling between DGs) and 1
(Strong coupling)

$$\hat{\lambda} = \frac{\sum_j N_j}{\sum_j n_j t_j}$$

$$\hat{\theta} = \begin{cases} \dfrac{1}{\hat{\lambda}} & \text{, for redundancy level-1} \\ \dfrac{3}{2\hat{\lambda}} & \text{, for redundancy level-2} \end{cases}$$

$$\lambda_L = \hat{\lambda}\,\frac{\chi^2_{(1-\frac{\alpha}{2}),\,2N}}{2N},\quad \lambda_U = \hat{\lambda}\,\frac{\chi^2_{\frac{\alpha}{2},\,2(N+1)}}{2(N+1)}$$

$$\theta_L = \hat{\theta}\,\frac{2(N+1)}{\chi^2_{\frac{\alpha}{2},2(N+1)}},\quad \theta_U = \hat{\theta}\,\frac{2N}{\chi^2_{(1-\frac{\alpha}{2}),2N}}$$

where:

λ_L, λ_U ≡ Lower and upper limits of λ

θ_L, θ_U ≡ Lower amd upper limits of θ

n_j, N_j, t_j ≡ Number of DGs, number of failures, operating time for the jth plant.

For the three plants under redundancy level-1, and the six plants under redundancy level-2, the following results were obtained.

It is clear that the failure rate under redundancy level-2 is lower, and consequently the MTBF is higher, compared to redundancy level-1.

The dependance of the MTBF on redundancy type (in case of redundancy level-2) can be investigated through the estimation of $\hat{\theta}$ in each type. Taking $\hat{\lambda}$ = $3.6 * 10^{-4}$ hr^{-1}, β=0.1, and $\hat{\mu}$ = 10 $\hat{\lambda}$, the following results were obtained:

For perfect redundancy, $\hat{\theta}$ = 4167 hr

For imperfect redundancy, $\hat{\theta}$ = 4094 hr

For full redundancy, $\hat{\theta}$ = 29502.

These results indicate that the contribution of CMF decreases the value of MTBF, while the contribution of both CMF and repair policy increase the value of MTBF.

Using estimated values of failure rate, and the calculated values of lower and upper bounds, one can compute the estimated system reliability and availability (as well as their bounds) at any time using the formulae provided in section (3).

Redundancy level	Parameter					
	$\hat{\lambda}$ (hr^{-1})	λ_L (hr^{-1})	λ_u (hr^{-1})	$\hat{\theta}$ (hr)	θ_L (hr)	θ_u (hr)
1	1.6*10-3	1.1*0-3	2.2*10-3	625	446	948
2 (perfect redundancy)	3.6&10-4	2.3*10-4	5.1*10-4	4167	2917	6499

5. CONCLUDING REMARKS

Based on the computations conducted in the present work, the following concluding remarks can be extracted.

i. 33 % of failures were due to human errors while 29 % of the failures were due to component failure. Also 83 % of the failures were discovered during testing. Based on these figures and other trends, appropriate recommendations could be easily postulated.

ii. As the redundancy level increases, failure rate decreases and MTBF increases. Cost-benefit analysis is helpful, in this respect, to get the optimum level.

iii. The rates of system reliability and availability decrease with the operational time is greatly affected by redundancy level and type

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