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# Multi-objective Optimization of Power Supply System for Shipping LNG Off-loading Process Based on Switching Markov Chain and Genetic Algorithm

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The control of risks is crucial to process safety and loss prevention, such as for the shipping LNG off-loading process. As the transfer arm is the key factor during LNG off-loading process, and the power supply system is the insurance to ensure the transfer arms working normally, the reliability of power supply system for off-loading arms should be quantitatively analyzed. Besides, the inefficient preventive maintenance (PM) plan may also drag the system into a low reliability region, and the budget of power supply system should also be considered to fulfill the low cost and high reliability. The objectives of this paper are to find the mathematical expression for the systematic reliability and cost evaluation, and the multi-objective optimization of this power supply model. Switching Markov chain is adopted to identify the time depended reliability, and genetic algorithm (GA) is chosen to solve multi-objective optimization of power supply system with the consideration of failure rate, repair rate, probability of unsuccessful PM, and the cost. Finally, the best solutions of a power supply model for LNG off-loading arm are collected to meet the acceptable reliability and low cost.

## 1. Introduction

Shipping LNG has become the main transportation method for international LNG market. Since LNG is a kind of hazardous material, and the off-loading activity takes place at some near port areas where other LNG storage tanks already exist, the shipping LNG safety, especially during off-loading process, is very important. According to statistical data from 1964 to 2005, the frequency of accidents during LNG off-loading process is one of the highest among all (Vanem et al., 2008). During the off-loading process, the power supply system is the key factor to ensure the transfer arms operate normally. Therefore, this paper focuses on the reliability analysis and maintenance optimization of power supply system of transfer arms for shipping LNG during off-loading process.

For the reliability analysis during LNG off-loading process, existing research focuses mainly on two areas: reliability prediction and consequence assessment. Event tree analysis (ETA) is adopted to predict the probability of the consequence that LNG spills from transfer arm during loading and unloading process (Vanem et al., 2008). Hazard identification is given to LNG carrier during off-loading operation, and combination of qualitative risk matrix and fuzzy inference are implemented to rank consequences (Elasyed, 2009). For the LNG ignition consequence during off-loading process near terminal, FLACS, specialized CFD software, is taken to evaluate the LNG spilling model during off-loading operation in partly confined area (Gavelli et al., 2011).For another research area, Markov chain is implemented to predict reliability of power supply system for loading arm (Hidalgo et al., 2013). However, so far no consideration has ever been given to the reliability influence of repair rate, PM in running life, and the cost.

The objective of this research is to predict the reliability trend of power supply system with the consideration of not only the failure rate, but also the repair rate, the PM process, and the cost evaluation. Based on the theory of Markov chain, the repair rate, which is the inverse of mean time to repair (MTTR), is used to express the transition rate from abnormal state to normal state, and switching Markov chain is carried out to find the mathematical expression of time depended reliability with the consideration of the conditions under both

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running stage and periodically PM. Thereafter, GA optimization is implemented to find the best parameters with high reliability and low cost.

The remainder of this paper is organized as follow. Section 2 provides an introduction on research methods used in this paper. Section 3 applies the methods to the reliability analysis and multi-objective optimization of power supply system for shipping LNG off-loading process, and finally, a conclusion is given in section 4.

## 2. Switching Markov chain and GA optimization

Switching Markov chain expresses the future state by current state, rather than the historical status (Shu and Zhao, 2014). Before solving the switching Markov chain, each potential state should be listed, then the transfer diagram and transition matrix can be built based on each potential state. Finally, by solving the transition differential equation, the reliability trend of the chosen state can be deduced. Switching Markov chain is suitable for a system that requires the consideration of both normal operation and PM (Mechri et al., 2015). This method can express the linguistic statement through mathematical method.

GA is a numerical search tool that focuses on the optimization of given behaviour represented by an objective function of one or more variables, and possibly subject to some linear or nonlinear constraints (Innal et al., 2015). GA was developed at the University of Michigan by John Holland in late 1960s. This method is inspired from the observation of biological phenomena. Figure 1 gives a flow chart of GA applied to the maintenance optimization in power supply system for shipping LNG off-loading process.

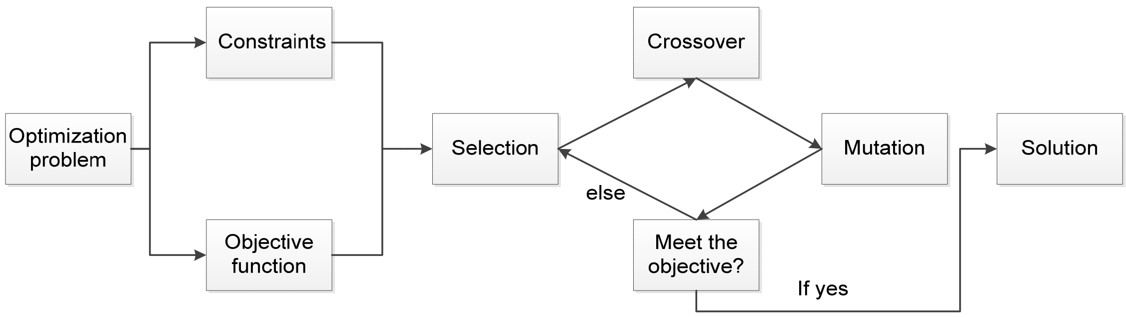


*Figure 1: flow chart of GA.*

## 3. Application of the method

An example of power supply system for LNG transfer arms and their reliability data from an LNG terminal which belongs to Sinopec has been analyzed. The reliability block diagram (RBD) of power supply system shown in Figure 2 contains three subsystems, the first subsystem is the transformer system which contains two transformers arranged in parallel and used to connect with on-shore power network. The second subsystem is the diesel generator system which contains two diesel power generators and two transformers. The third subsystem is the unlimited power supply (UPS) system which involves two UPSs set in parallel.

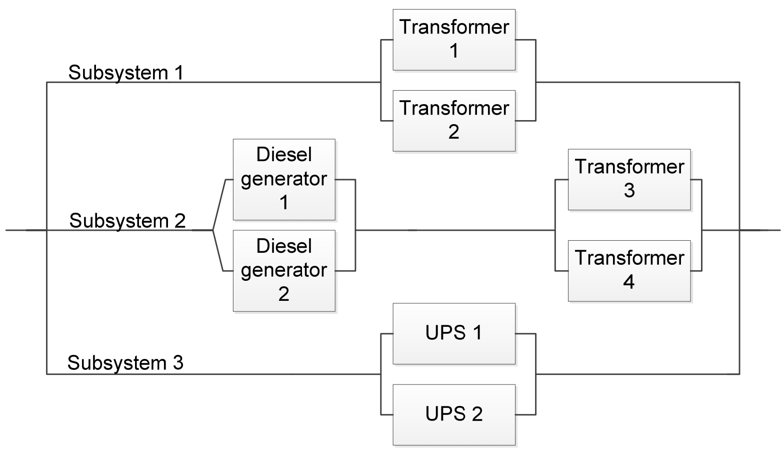


*Figure 2: the RBD of power supply system.*

In this power supply system, both rotating equipment (diesel generator) and static equipment (transformer and UPS) are involved. As the reliability data of UPSs and transformers are much higher than those of diesel generators, it is reasonable to treat them separately to avoid too frequent check to high reliability instruments and not enough inspection to low reliability facilities. Diesel generator belongs to rotating facility, so it will be treated separately with static equipment. Before the switching Markov chain process, the potential states of diesel generator system are listed in Table1.

*Table 1: potential states of diesel generator*

| State No. | State description |
|---|---|
| I | One generator is in operation, the other is on standby |
| Ii | Operating generator fails and under repair, standby generator starts to work |
| iii | The operating one keeps in operation, but the standby one fails and under repair |
| iv | The operating one hasn't finish repair, the standby one losses its function |
| v | The operating one losses its function, the standby one hasn't finish repair |
| vi | Two components all failing |

Diesel generator belongs to rotating facility, so it will be treated separately with static equipment. Before the switching Markov chain process, the potential states of diesel generator system are listed in Table1.
According to Table 1, all of the 6 states can be summarized into 3 statues: 1) state D1 represents both diesel power generators are normal; 2) state D2 means one diesel power generator fails, the other is normal; 3) state D3 represents both diesel power generators fail. Therefore, the transfer diagram is shown as figure 3. The time depended probability of states D1, D2, and D3 can be expressed as $P(t)=[P_{D1}(t)\ P_{D2}(t)\ P_{D3}(t)]^T$.

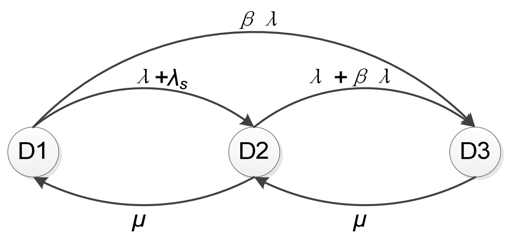

*Figure 3: the transition diagram for diesel generators.*

With the transfer diagram, the transition matrix **M** can be written as:

$$\boldsymbol{M} = \begin{bmatrix} -\lambda - \lambda_s - \beta\lambda & \mu & 0 \\ \lambda + \lambda_s & -\mu - \lambda - \beta\lambda & \mu \\ \beta\lambda & \lambda + \beta\lambda & -\mu \end{bmatrix} \tag{1}$$

where: β is the beta factor which represents the ratio of common cause failure rate to total failure rate (according to international standard IEC61508, it can be estimated at 0.1), λ is the failure rate of in-operation equipment, $\lambda_s$ is the failure rate of standby instrument, and μ is the repair rate. In the matrix **M**, for (i≠j), $M_{ij}$ represents the transition rate from state $D_j$ to state $D_i$, for(i=j), $M_{ij}$ is the corresponding rate out of state $D_i$. The mathematical expression to deduce the reliability function of a chose state is shown as Eq(2).

$$d\boldsymbol{P}(t)/dt = \boldsymbol{MP}(t) \tag{2}$$

Laplace transforms will be adopted to solve this ordinary differential equation. For the PM process which involves checking lubrication oil pump, checking air filer, checking band carrier, and cleaning lubrication oil groove, and so on, Table 2 lists all potential states during PM, and Figure 4 shows the transfer diagram among each state in PM process.

*Table 2: potential states of preventive maintenance*

| State No. | State description |
|---|---|
| M1 | The PM succeeds (success) |
| M2 | The PM fails, and operators realise the failure (failure) |
| M3 | The PM fails, and no people realise that (failure) |

In Figure 4, state M1 is the success state; it will go to state M2 when the PM is unsuccessful, and people realise that; it will go to state M3, when PM is failing, and no one realises. State M2 is the state that the PM is failing, and failure is detected. This state is deemed as the failure state since the failure may not be found immediately, which may lead the equipment running under high risks. State M3 is the state that the PM is failing and operators also fail to deal with the failure; it will go to state M2, when operators realise the failure of PM.

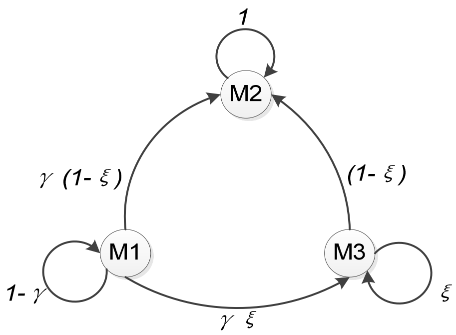


*Figure 4: transition diagram for preventive maintenance process.*

Based on the transition diagram, the transition matrix **Q** can be determined, which is displayed as below:

$$\boldsymbol{Q}=\begin{bmatrix} 1-\gamma & 0 & 0 \\ \gamma(1-\xi) & 1 & 1-\xi \\ \gamma\xi & 0 & \xi \end{bmatrix} \tag{3}$$

where γ is the probability of unsuccessful PM which is assumed from 0.001 to 0.01, ξ is the probability of people fail to realize the error. In the PM process only state M1 is successful state, and based on Eq(2),the reliability function of state M1 can be expressed as: $P_{M1}=(1-\gamma)P_{M1'}$, where $P_{M1}$ is the probability in next beginning stage.$P_{M1'}$ is the probability of state M1 under current condition, and the initial probability of state M1 is 1. Besides, after PM work, the reliability trend of diesel power generators will follow the reliability function deduced from Eq(1). Therefore, the mathematical expression of reliability of diesel power generator system in the 8,640 hs can be written as below:

$$\mathrm{R}_n(t) = (1-\gamma)^n \times P(t - n \times T_{PM}),\ \ (n \times T_{PM} \le t \le (n+1) \times T_{PM},\ n = 0,1,2,\cdots,11) \tag{4}$$

where $T_{PM}$ is the PM time interval set at 720 hs (one month), $n$ is the $n$th PM with value from 0 (January) to 11 (December). At the next GA optimization process, as after 8,640 hs' working, an overhaul will be implemented in the LNG terminal, and some components may be replaced, which will produce a new reliability trend, the reliability objective of diesel generator system is design to still over 0.9 after 8,640 hs' working before the overhaul. Besides, the cost is less than 53,000 USD which includes the cost of purchasing (49,000 USD) and the budget of PM in 8,640 hs (4,000 USD). For the cost evaluation, "E&A" model can be chosen (Elegbede and Adjallah, 2003). This model deems the lower failure rate, the higher price, and the lower repair rate, the higher maintenance cost. The mathematical model is shown as below:

$$Z = \mathrm{a}\lambda_x^p + b\mu_x^q \tag{5}$$

where: Z is cost of purchase and maintenance, a, b, p, and q are real numbers, $\lambda_x$ is the failure rate of component x, $\mu_x$ is the repair rate of component x.

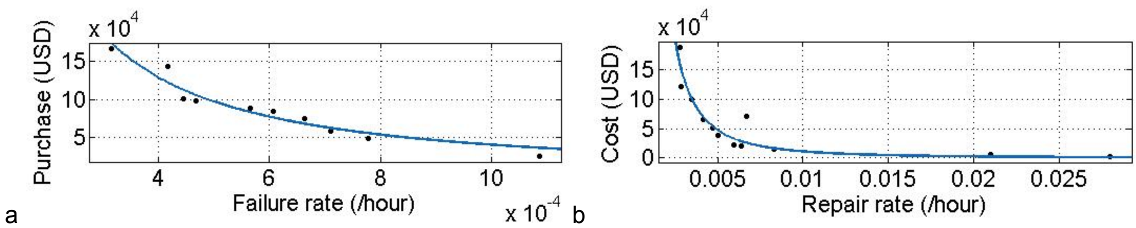


*Figure 5: (a) Diesel generator purchase curve, (b) Maintenance cost fitting curve.*

Thereafter, with the statistical data which is from maintenance data base of Sinopec, and through MATLAB curve fitting toolbox, the curve fitting is shown in figure 5.: Therefore, mathematical expression of cost evaluation is shown as Eq(6).

$$Z_D = 6.989\lambda_D^{-1.255} + 0.7575\mu_D^{-2.083} \quad (6)$$

where: $Z_D$ is the cost of purchase and maintenance of diesel power generator, $\mu_D$ is repair rate of diesel generator, $\lambda_D$ is failure rate of diesel generator. The design objective reliability function $R_{11}(t)=(1-\gamma)^{11}\times P(t-720\times 11)$, the constraints of this GA optimization process are: 1) $R_{11}(t)>0.9$, 2) $Z_D<53{,}000$.
Thereafter, the best solution of λ, $\lambda_s$, μ, and γ can be determined by MATLAB GA toolbox, λ is $1\times 10^{-3}$ /h, $\lambda_s$ is $4\times 10^{-4}$ /h, μ is 0.1 (MTTR=10 hs), and γ is 0.008. Besides, Figure 6 shows reliability curve with the optimized data. In addition, based on "E&A" model, and with the optimized data, the total cost is about 41,000 dollars which are less than the previous budget 53,000 dollars, and after 8,640 hs' running the reliability is still over 0.9.

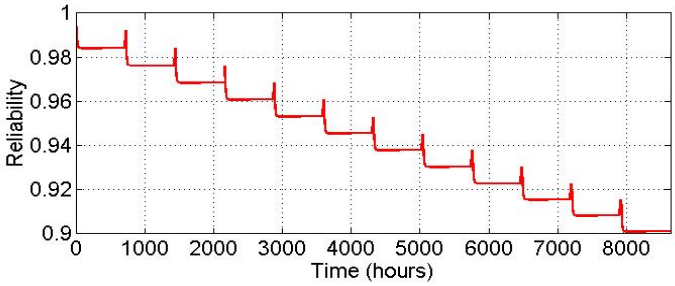


*Figure 6: the reliability trend of diesel generators.*

For the transformer and UPS, the reliability constraints of them are that: the reliability of transformer should be at least higher than 0.95 after 5 ys' in operation as well as that of UPS, and the total budget of transformer and UPS are up to 5,000 dollars and 50,000 dollars in each. Besides, the PM interval of transformer and UPS $T_{PM}$ = 8,640 hs. Table 3 gives a description on each potential state.

*Table 3: Potential states of static equipment*

| State No. | State description |
|---|---|
| S1 | Both instruments are in normal condition. |
| S2 | One instrument is failing, the other is normal. |
| S3 | Both instruments are failing. |

According to Table 3, the transfer diagram can be drawn, which is shown in Figure 7.

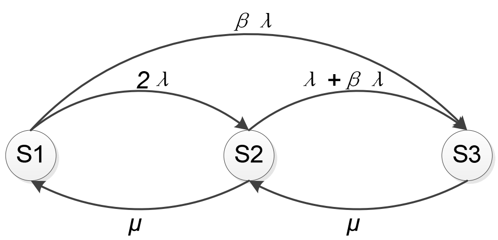


*Figure 7: transition diagram of transformer and UPS.*

Therefore, the transition matrix **N** for static equipment is shown as Eq(7).

$$\boldsymbol{N} = \begin{bmatrix} -2\lambda - \beta\lambda & \mu & 0 \\ 2\lambda & -\mu - \lambda - \beta\lambda & \mu \\ \beta\lambda & \lambda + \beta\lambda & -\mu \end{bmatrix} \quad (7)$$

Through the E&A model and MATLAB curve fitting toolbox, the cost functions of transformer and UPS are shown as Eq(8) and Eq(9).

$$Z_T = 0.2699\lambda_T^{-0.7759} + 0.07575\mu_T^{-2.083} \quad (8)$$

$$Z_U = 170.9\lambda_U^{-0.5043} + 0.07575\mu_U^{-2.083} \quad (9)$$

where $Z_T$ is the cost of purchase and maintenance of transformer, $Z_U$ is the cost of purchase and maintenance of UPS, $\mu_T$ is repair rate of transformer, $\mu_D$ is repair rate of UPS, $\lambda_T$ is failure rate of transformer, $\lambda_U$ is failure rate of UPS. Thus, through GA toolbox, the best answer of the failure rate of transformer is $1.4\times10^{-5}$ /h, the repair rate is 0.083 so MTTR can be set up to 12 hs, the probability of unsuccessful of PM is $3.0\times10^{-3}$, the and the total cost is about 1,600 dollars which is much less than the budget that is 5,000 dollars. The failure rate of UPS is $3.8\times10^{-5}$ /h, the repair rate is $3.33\times10^{-3}$ so MTTR can be set up to 300 hs, the probability of unsuccessful PM is $3\times10^{-3}$, and the total cost is about 46,000 dollars, which is less than 50,000 dollars budget. Figure 8(a) and 8(b) present the reliability trend.

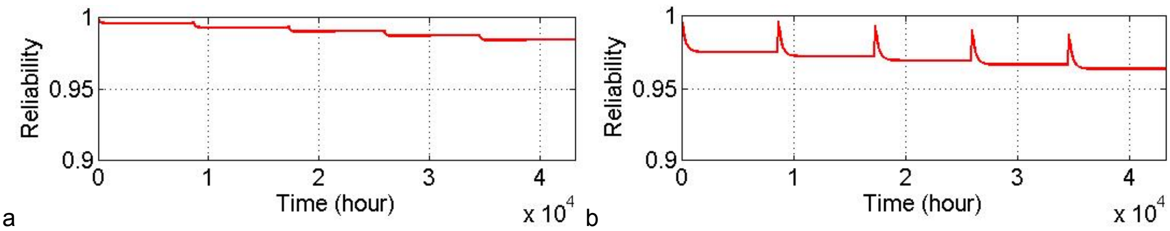


*Figure 8: (a) The reliability curve for transformer, (b) The reliability curve for UPS.*

## 4. Conclusion

In this paper, a method involves switching Markov chain and GA optimization is implemented to determine the time depended reliability function and the best solution of cost, repair rate, and failure rate of a power supply system for shipping LNG off-loading arm of a Sinopec LNG terminal. The reliability curves of diesel generator, transformers, and UPS in this power supply system for this LNG terminal are given in Figure 6, Figure 8(a) and 8(b) respectively. Besides, in this power supply system, the best solutions for diesel generator are that: total cost is 30,000 USD, failure rate of in operation instrument is $1\times10^{-3}$ /h, failure rate of standby facility is $4\times10^{-4}$ /h, MTTR can be set up to 10 hs, and the probability of unsuccessful PM is 0.008. Meanwhile, the best solutions of transformer and UPS in this power system are that: the cost can be set at 8,000 USD and 46,000 USD for transformer and UPS in each, the failure rates of transformer and UPS are $1.4\times10^{-5}$ /h and $3.8\times10^{-5}$ /h respectively, the MTTRs for transformer and UPS can be optimised at 12 hs and 300 hs individually, and the probabilities of unsuccessful PM for transformer and UPS are all $3.0\times10^{-3}$. In this project, an assumption has been given to the probability of unsuccessful PM, whereas this probability has close relationship with human factors, so there will come a following paper to discuss the probability of unsuccessful PM.

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