IEEE Power and Energy Technology Systems Journal

Received 18 December 2015; accepted 1 January 2016. Date of publication 2 February 2016; date of current version 23 March 2016.

Digital Object Identifier 10.1109/JPETS.2016.2516944

Maintenance Decision Models for Java–Bali 150-kV Power Transmission Submarine Cable Using RAMS

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This work was supported in part by PT Perusahaan Listrik Negara (Persero), Jakarta, Indonesia, and in part by the Bandung Institute of Technology, Bandung, Indonesia.

ABSTRACT The application of reliability, availability, maintainability, and security (RAMS) analysis is currently developing in many fields of an electrical power system. The focus of this paper is to demonstrate the applicability of RAMS to analyze maintenance planning on the 150-kV submarine cables of the Java–Bali power transmission system in Indonesia. In this maintenance decision model, four alternatives of a maintenance scheme are made based on maintenance interval and cable's mechanical protection. Monte Carlo simulation will be used to obtain a RAMS value of each alternative. The decision is made based on a cost-effectiveness parameter using a life cycle cost analysis.

INDEX TERMS Availability, cost benefit analysis, maintenance, Monte Carlo methods, power system security, reliability, risk analysis, under water cable.

I. INTRODUCTION

HIGH-VOLTAGE submarine cable has been widely used around the world to deliver electricity between islands. In contrast to the Europe, where submarine cable has been widely applied, in Indonesia this type of cable is still rarely used. Indonesia is geographically separated between five major Islands. In the future, the application of submarine cable is expected to be increased. It is based on the effort to improve the reliability of the whole power system by connecting the system between the islands.

The first high voltage submarine cable in Indonesia was built in 1990 between Java Island (Banyuwangi substation) and Bali (Gilimanuk Substation). This 150 kV lines has a significant role in transferring electric power from Java to Bali. Load characteristic is shaped by the high demand for electricity in Bali as a rapid tourism area. On the other hand, power plants in Bali are not sufficient to meet the demand of its local electricity [1]. Along with the increasing load demand, two new cable lines (3 and 4) were built in 2013. As shown in Fig. 1, this installation were built with the combination of submarine cable (4.8 km) that lay under the Bali strait, combined with underground cable and overhead transmission line on Java Island and Bali Island.

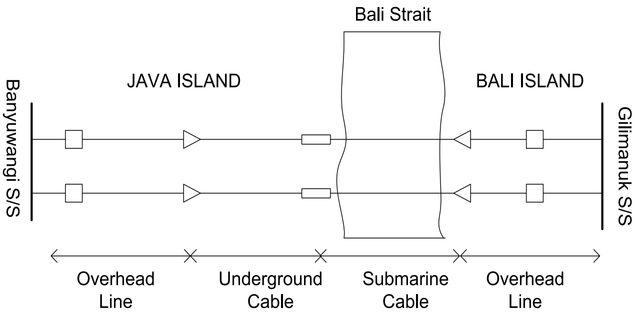

FIGURE 1. **Configuration of Java-Bali 150 kV.**

Due to the rapid development of high voltage cable application in Indonesia, as well as the high cost spent on each project, it is important to do the study of system's cost effectiveness based on engineering performance and cost analysis of the project. The main purpose of this paper is to perform this study in order to obtain the most effective maintenance model that will be applied on the system during its operational life. To achieve this purpose, four alternatives will be generated by varying the mechanical protection of the installed system and the period of routine maintenance.

Analysis will be conducted by determining four parameters of the system and its related equipment: reliability, availability, maintainability, and security. These four parameters, often abbreviated as RAMS, will be combined together to obtain system effectiveness. The concept of RAMS has been progressively developed in many areas, such as transportation, building, industrial manufacture as well as an electrical power system [2]–[4]. Several concepts have been developed to calculate each of these parameters. Nakamura *et al.* [5] have built a mathematical model to calculate the probability of the cable's failure rate based on some parameters, such as: external protection of the cable, characteristic of the sea bed, distance from the closest island, and the operating depth of the cable.

In this paper, this approach is used to determine the reliability of every section of the cable in its typical condition, as will be seen in chapter 2. On the other hand, availability, maintainability, and security of the cable system can be calculated by adapting some processes that have been widely used in power plant and transmission system [6]. The processes involve some parameters, such as mean time to failure (MTTF), mean time to repair (MTTR), mean time between failure (MTBF), and failure probability of each subcomponent of the system. This approach is relevant for the submarine cable system, because each of these parameters can be calculated based on historical data. In order to determine the cost effective solution, RAMS parameters will be combined with system cost. In this stage, life cycle cost analysis (LCCA) will be used by using the existing data [1].

The main problem that is often faced by the engineer in analyzing the cost effectiveness of a system is the strong correlation between all the parameters involved in it. In the design stage, changing one parameters (as example: maintenance period) will simultaneously affect the others (MTTR, repair cost, etc). In this paper, Monte Carlo simulation is proposed to handle the dependency of many parameters and components. By using this method, each part of the system can also be analyzed by modifying its parameters and looking at the resulting effect to the whole system. The art of using this method is on how to generate alternatives in the early stage of analysis. In this paper, the new approach is made by dividing the cable length into several sections.

At the end of the analysis, one alternative will be chosen as the most effective model. The decision is made by comparing the effectiveness of the alternative in term of engineering and cost, as will be presented in chapter five of this paper.

II. METHODS

A. RAMS PARAMETER

RAMS parameters are used together to determine the effectiveness of the system as integration [6], formulated as

$$\mathit{Effectiveness} = R(t)xAF(t)xM(t)xS. \qquad (1)$$

In this paper, four alternatives are generated based on the maintenance period and the external protection of the cable system, as will be explained extensively in chapter 4. Each of these schemes will be analyzed to obtain the effectiveness and life cycle cost of the system. In order to analyze system effectiveness, Monte Carlo simulation will be used. These two parameters are then combined together to obtain system's cost effectiveness. The whole process of the analysis is described in Fig. 2.

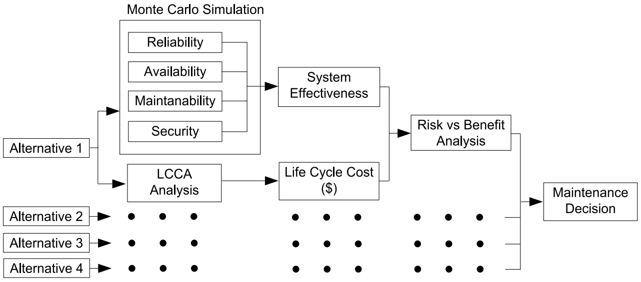

FIGURE 2. **Maintenance decision process diagram.**

1) RELIABILITY

Reliability aspect of submarine cables is calculated with reference to the research [5]. The analysis is applied by using a model based on several parameters including seabed profile, distance of the cable's section from the closest island, and mechanical protection of the cable. Based on other research nearly 80% of submarine power cable failure is due to mechanical origin and most of them are caused by ship anchors and fishing tackles [7]. Based on this, depth and mechanical protection are considered to dominantly affect the potential for the cable to be exposed by ship's anchor. Besides, they also affect the oscillation displacement of the cable caused by ocean currents, and eventually determine the reliability of the installation.

Through this method, the value of reliability is calculated for every section of the cable. The cable is divided into several elements, where each element has a dimension of 0.25 km in length, and 10 meters in depth. The parameters taken into account in this analysis are the external protection of cable (E), sea bed characteristics, distance from the nearest land element (L), and the depth of the element (D). Mathematical modeling, known as dimensional reduction is used to allocate all failures elements (collected from historical data) to each of these parameters. Using this method, each section of the cable will have different reliability. Table 1 shows the description of four parameters used to define the reliability of submarine cable. The similar analysis will be conducted to Java-Bali submarine cable.

The profile of Java-Bali strait that is passed by the cable lines can be seen in Fig. 3. The distance between coast-to-coasts is approximately 4.5 kilometers. From the Java side, the seabed gently slopes away to approximately 15 meters depth at the 500 meters distance from Java Island,

TABLE 1. Parameters of cable failure rate.

Parameters	Symbol	Num. of levels	Size of levels	Description
External protection	E	-	-	
Bed characteristic	B	-	-	Mud, sand, gravel, rock
Length from land	L	10	0.25 km	
Depth	D	7	10m	

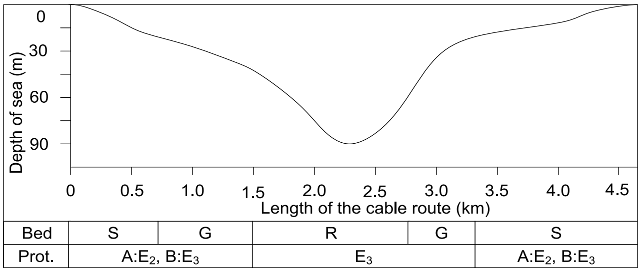

FIGURE 3. Seabed and protection characteristic of installed cable.

extending to 28 meters depth at 1000 meters. The gradient continues until 1500 meters, where a more sudden drop off is experienced, increasing to a maximum of approximately 90 meters at the midway point. Water depth then begins to decrease to 30 meters at the 3000 meters point, and from there shallows out to the beach on the Bali side. Flanked by the Bali Sea to the north and the Indian Ocean to the south, the strait area experiences a high surface current (about 10 knots).

The seabed is predominantly made up of rock and coral interspersed with areas of soft mud. Except in the shallow part, where cable is laid on sand. Based on this profile, the reliability of the cable can be determined as will be shown in part 4 of this paper. In the analysis process of each maintenance alternative, the whole system reliability is calculated using failure rate (λ), by using the following equation [5]:

$$R(t) = e^{-t/MTBF} = e^{-\lambda t}. \tag{2}$$

2) AVAILABILITY

Availability is the aspect of system reliability that takes equipment maintainability into account. In this paper, availability will be used to evaluate the consequences of un-successful operation or performance of the submarine cable and the critical requirements necessary to restore operation or performance to design expectations. The latter includes the time needed to have the system routinely maintained. To measure the availability in the whole system, the availability factor (AF) is used. AF is the ratio between the operating hours of the transmission line to the one cycle period of operation [8]

$$AF = \frac{MTBF}{MTBF + MTTR} = \frac{\mu}{\mu + \lambda}. \tag{3}$$

Where μ is repair rate, and both of MTTR and MTTF value are obtained by Monte Carlo as will be explained in the next section.

3) MAINTAINABILITY

Maintainability deals with duration of maintenance outages or how long it takes to achieve (ease and speed) the maintenance actions compared to a datum. The key figure of merit for maintainability is often the MTTR and a limit for the maximum repair time (t) [6]. Based on the exponential distribution, the formula is defined as follows:

$$M(t) = 1 - e^{-t/MTTR} = 1 - e^{-\mu t}. \tag{4}$$

Maximum repair time for the system is usually obtained from general experiences. For the case of submarine cable, this value is determined as 87 days [7]. Based on this formulation, the failure rates and the maintenance scheme will affect the maintainability value of each alternative. Maintenance time itself is dependent on the fault location and the weather condition.

4) SECURITY

In electrical power system, security can be classified into three categories; relating to personal protection, equipment protection, and environmental protection. It can be defined as ‘‘not involving risk’’, where risk is defined as ‘‘the chance of loss or disaster’’ [2].

Cable transmission has a typical characteristic regarding to this issue. Most of the accidents have a little relation to human and environmental disaster. Based on this fact, we need to modify this aspect. According to (IEEE C 37.2) security relates to the degree of certainty that a relay or relay system will not operate incorrectly. This definition can be developed by putting other similar effect that has a potential to cause the protection systems fail to operate when failure occurred at the cable. These parameters are including supervision systems and human error, as described in Fig. 4.

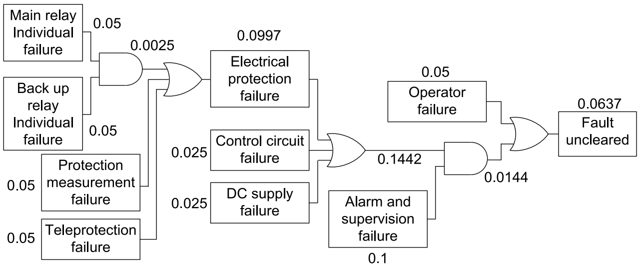

FIGURE 4. Logic diagram of system's security.

Each of these parameters has its probability based on the operational data (as shown in the diagram). Based on this configuration, all parameters are calculated by using the following formulas [8]:

$$P(AND) = p_1 x p_2 \tag{5}$$

$$P(OR) = 1 - (q_1 x q_2) \tag{6}$$

where p is the probability of each component to be the failure, and q is the complement of p. The results give the security value of all components to be 0.9363. In the maintenance scheme, each alternative are to be focused on the mechanical protection aspect of the cable. Therefore, the security value is the same for all alternatives.

B. MONTE CARLO SIMULATION

In this paper, Monte Carlo simulation is used to obtain RAMS parameters of each alternative, the logic of the simulation are shown in Fig. 5.

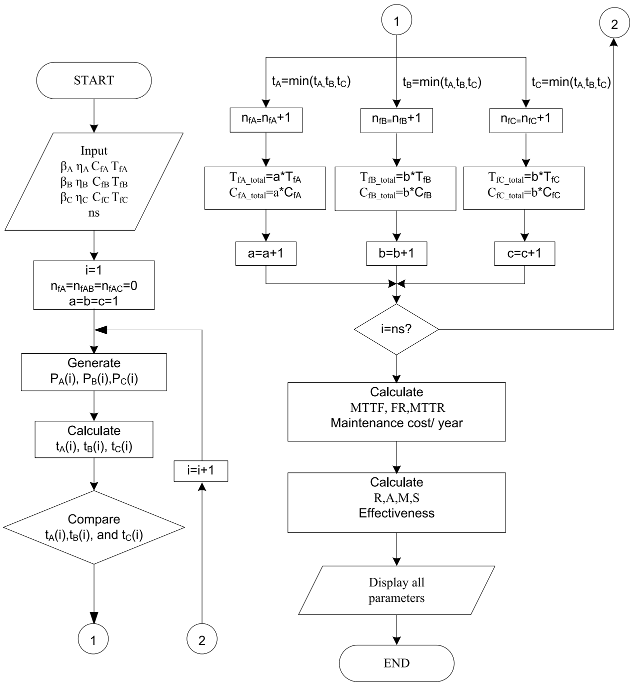

FIGURE 5. **Monte Carlo simulation flowchart.**

This flowchart describes the process to calculate all parameters for one alternative. The process is initialized by determining probability distribution coefficient of all components (i.e. Weibull shape factor β and Weibull characteristic life η). In this figure, there are three components to be analyzed, denoted by A, B, and C. This number of components can vary depending on the number of sections to be made in the cable lines (five section chosen in this paper).

Weibull distributions are used for this case based on the reason that mechanical protection of the cable could be deteriorating along with its service time. Other parameters are failure cost (C) and the repair time of each component (T). These parameters are strongly defined by the fault location, one that will affect some activities such as: mobilization of the vessel, uncovering process of the cable, waiting period for weather window, and reparation process [7]. The simulation will be run in several number of cycle (ns). In each cycle (i), random number (Pi) is generated by the computer to simulate the failure probability state of each component at a certain time. Based on Weibull cumulative distribution function formula, we can determine the time at when each component will suffer the failure by using (7)

$$t_A(i) = \eta_A \left[-\ln\left(1 - P_A(i)\right)\right]^{\frac{1}{\beta_A}}. \tag{7}$$

In the next step, the failure time of each component will be compared together. The component which has the smallest failure time will be considered to be the failure component in the cycle (Fig. 6). The number of failure and failure cost in the particular cycle are then being added to the failure component. After all cycle being executed as many as ns, all parameters related to the maintenance alternative will be counted, including MTTF, failure rates, maintenance cost per hour and effectiveness of the scheme.

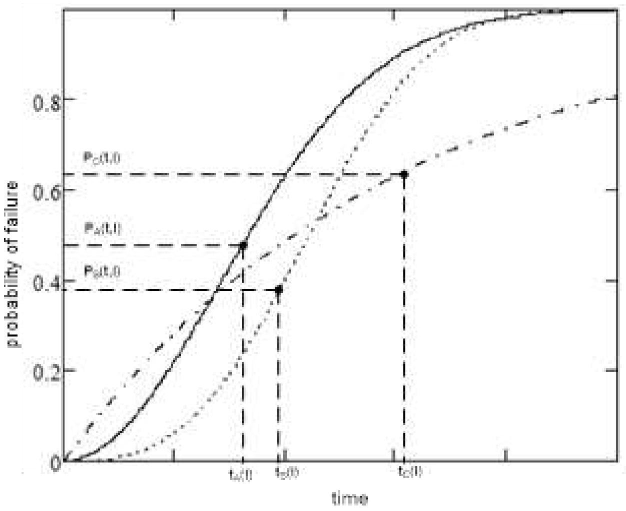

FIGURE 6. **Failure decision of Weibull life characteristic.**

C. LIFE CYCLE COST ANALYSIS (LCCA)

To analyze the cost effectiveness of each alternative, LCCA needs to be done based on technical aspects, historical maintenance data, cost information, load and demand characteristic, as well as sensitivity testing to ensure the objective of the installation in a long term period. In submarine cable system, all of the life cycle cost (LCC) aspects have to consider the integration of operations and maintenance issues to achieve the continuity of power delivering process.

In this system, LCC can be consisted of capital cost, periodical maintenance, failure, energy not served (ENS), and savings. Capital cost and all that related to construction process of the installation are shown in Table 2. Both of ENS and

TABLE 2. **Detailed capital cost of installation.**

Detail Work	Total cost (US$)
Material cost	12,288,727
Civil work	46,811.587
Electrical construction Cost	4,852,698
Survey & commissioning	646,987

savings are calculated based on power delivery capability of the cable and not including the load growth characteristic on the receiving side of the system. Annual saving is obtained from the benefit which is resulted by the difference of energy cost between Java Island and local generating system in Bali Island (8). Currently, Bali load demand is supplied by local power plants powered either by gas, diesel or coal give a total combined energy supply of 1,022 MW. The average cost of this local supply is US$ 0.1389 per kWh, while the cost of energy delivered from Java is US$ 0.0783 per kWh [1]. In an outage condition, this cable system will be unable to deliver the energy to the receiving side. This amount of energy will be taken into a part of the cost analysis as ENS (9)

$$Savings = P_C x(C_L - C_I)xT_{PL} \tag{8}$$

$$ENS = P_C x(C_L - C_I)xT_O \tag{9}$$

where

P_C = cable delivery capacity (240 MW)
C_L = cost of local generated energy ($/kWh)
C_I = cost of imported energy ($/kWh)
T_{PL} = peak load duration per year (hours)
T_O = outage duration per year.

In the above formula, annual peak load duration is assumed to be five hours per day in 365 days in a year. On the other hand, outage duration is composed by MTTR (obtained from the simulation result) and maintenance duration, calculated in average days per year. In calculating these parameters, cable installed capacity (PC) are limited to 80 percent of the total installed capacity (300 MW). In putting the cost during 30 years life cycle, all costs will be summed in present value to yield system net income and cost. To decide the most suitable maintenance scheme, all alternatives will be compared by using its system cost effectiveness parameter

$$Cost \cdot Effectiveness = \frac{Effectiveness}{Total \cdot Cost}. \tag{10}$$

Total cost is the summation of total failure cost, maintenance cost, and energy not served (ENS) in each alternatives.

III. MAINTENANCE DECISION MODEL

The major challenge in operating the submarine cable system is how to extend the life time of the system. The main factors to be considered are protection of the subsea cable, assessment of component's condition and maintenance schedule. In a maintenance decision process, condition based maintenance are designed and implemented to detect degradation, identify certain incipient faults and/or provide diagnoses of failed equipment in a more intelligent way. One of the most important aspects of a robust equipment condition monitoring system is its ability to identify degradation and failure modes and effect, then to detect and locate a fault when it occurs, and to predict incipient failures so that potential damage can be avoided.

Generally, XLPE submarine cable installations are designed to be free of maintenance in term of its electrical property. However, the maintenance process still can be applied to the mechanical properties of the cable. This process can be done by doing routine inspection to the mechanical protection in such period of time and at the same time by making reparation in case that the mechanical protection is broken. In doing this maintenance process, the reliability of the cable is expected to be increased. The best period of maintenance process has to be optimized using maintenance cost as a constraint. In this paper, the alternatives are made by simulating the maintenance process every two years (model A) and four years (model B) period. The different period of maintenance action will affect the change in parameter of all subsystems. For the cable, more frequent maintenance allows better treatment to the mechanical protection. This will lead to reduce expected number of failure in each section and subsequently change the β and η parameter. Higher maintenance frequency will also increase the average of outage time per year, and subsequently rise the ENS value.

IV. GENERATING ALTERNATIVES

This paper uses two schemes of mechanical protection as the alternatives. Both alternatives are focused on the shallow area of the cable route (1.5 km from shore), where the risk of failure is much higher compared to the deep section. For the first alternative, cable is protected in accordance with the initial design where it is buried one meter under the sand along one kilometer from each island (mode E_2). Gravel is used as a protection for the second type, in which the cable is buried under 0.75 meter (mode E_3).

The difference in mechanical protection mode will give the different characteristic to cable reliability, like shown in Fig. 7. In this model, cable lines are divided into five sections, all of which are combined as a serial component. In the simulation process, four alternatives are generated by combining all of the mechanical protection schemes and two different period of routine maintenance, as we can see in Table 3.

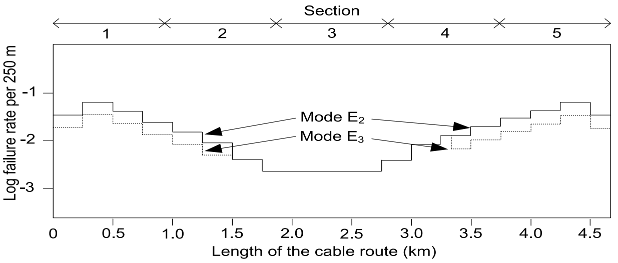

FIGURE 7. **Failure rate distribution of cable.**

By applying E_2 as a protection, routine maintenance action including inspection and repairing will cost $248.669, while for E_3, it is estimated to be $373,003.5. Additional cost for enhancing mechanical protection to E_3 requires 5 percent of civil cost ($2,340,579).

TABLE 3. **Maintenance and protection model.**

Model	Alt 1	Alt 2	Alt 3	Alt 4
Mech. Protection	E_2	E_2	E_3	E_3
Maintenance	A	B	A	B

The important issue in this method is to determine each subsystem failure characteristic, denoted as β and η for Weibull characteristic. Theoretically, these variables used to be calculated by using several data. These data are describing failure probability of the system at a certain time of operation. In this simulation, η values are approached by calculating the expected time for each section to suffer one failure, while β values is chosen around 6.9 – 7.0 depending on the protection and maintenance scheme of each component, as shown in Table 4. All of these parameters will give different consequences to the repair time, as well as failure cost which are determined by the type of material, service, and loss of potential energy to be delivered. Repair cost in each alternative will have the same value because it is merely determined by the material and accessibility of the failure's location.

TABLE 4. **Failure probability characteristic.**

Section	(failure rate) (β, η)			
	Alt 1	Alt 2	Alt 3	Alt 4
1	(0.049) (6.9),(28)	(0.051) (6.5),(24)	(0.020) (7.5),(55)	(0.032) (7.1),(31)
2	(0.019) (7.3),(46)	(0.020) (6.9),(4.2)	(0.013) (7.8),(84)	(0.013) (7.4),(79)
3	(0.002) (7.9),(180)	(0.002) (7.9),(180)	(0.002) (7.9),(180)	(0.002) (7.9),(180)
4	(0.025) (7.3),(38)	(0.032) (6.9),(3.4)	(0.013) (7.7),(84)	(0.016) (7.3),(63)
5	(0.052) (6.8),(27)	(0.064) (6.3),(23)	(0.02) (7.6),(55)	(0.032) (7.2),(32)

V. SIMULATION AND ANALYSIS

A. RAMS SIMULATION RESULT

In the Monte Carlo simulation process, each of the alternatives is simulated in 5000 cycles. Typical results of alternative 3 are shown in Table 5. In this table, it is shown that most of the simulated failures occurred at the shallowest and closest section to the land (Sections I and V). Based on this result, further calculation can be done to the other parameters, using all equations that have been stated in the previous sections. All parameters in the four alternatives are shown in Table 6.

It is obvious that the parameter's values between one alternative and another only have a slight difference, whether it is compared as a part or as integration. It can be regarded as a result of the long duration taken for the cable to be a failure, relatively compared to its life cycle (30 years). In other systems which have a high failure or replacement intensity (as example: power plant), a significant margin will be found between all alternatives [2].

TABLE 5. **Detailed result of Monte Carlo simulation for alternative 3 after 5000 cycle.**

Sub system	1	2	3	4	5
β	7.1	7.4	7.9	7.3	7.2
η	32	79	180	63	32
Repair cost ($M)	0.95	1.42	1.90	1.42	0.95
Repair Time (days)	61	69	86	69	64
ENS /fault ($M)	2.86	3.24	4.04	3.24	3.00
F(t)= RAND( )	0.249	0.948	0.497	0.600	0.472
Time (eq.7)	9	35	73	28	12
Total failure	2,476	4	0	14	2,506
Total failure time (h)	66,470	116	0	411	67,613
Total repair time (h)	151,036	276	0	966	160,384
Failure cost ($M)	2,346.01	5.68	0	19.89	2,374.43

TABLE 6. **Simulation result of system effectiveness.**

Parameter	Alt 1	Alt 2	Alt 3	Alt 4
MTBF (years)	23.00	19.44	41.50	36.88
Failure rate (1/year)	0.0435	0.0514	0.0317	0.0372
MTTR (days)	59.00	58.23	72.54	70.53
MTTF (years)	22.99	19.43	41.49	36.87
Availability	0.93	0.98	0.93	0.97
Reliability	0.92	0.90	0.97	0.96
Maintainability	0.77	0.77	0.75	0.75
Security	0.94	0.94	0.94	0.94
Effectiveness	0.619	0.638	0.636	0.656

Higher availability is obtained in alternative 2 and 4, as a consequence of the longer period in maintenance action. The result also shows that the enhanced mechanical protection applied in alternative 3 and 4 gives a higher reliability value. On the other hand, the application of E_2 mode will give a shorter period for the system to be repaired and will lead to a lower maintainability value.

B. LCCA FOR EACH ALTERNATIVE

Based on the Monte Carlo simulation result, some important parameter can be used to construct LCCA for each alternative. Total failure cost is counted as a result of the failure rate, repair time, material and service cost, and ENS.

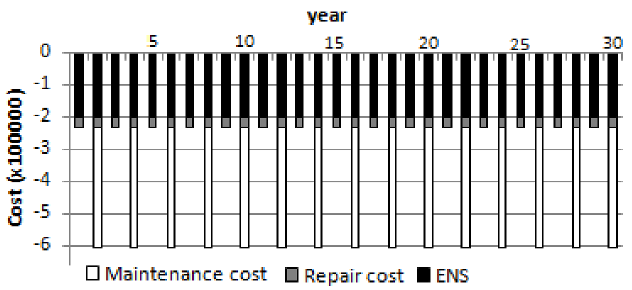

FIGURE 8. **Graphical representation of maintenance, ENS, and repair cost (alternative 3).**

Fig. 8 shows the chart containing the maintenance cost, repair cost, and ENS for alternative 3. All summed failure cost are shared evenly to every year in life cycle.

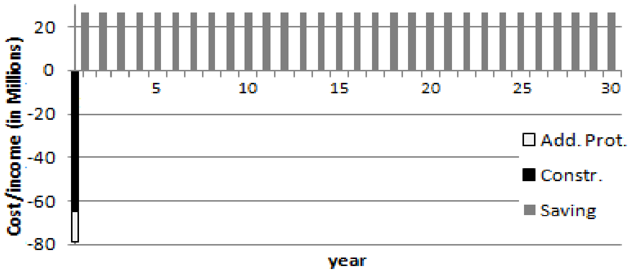

FIGURE 9. **Graphical representation of capital cost and annual saving (alternative 3).**

Separately, capital cost and saving are shown in Fig. 9, in which alternative 3 is also taken as example. It can be seen that the additional cost for E_3 mechanical protection in alternative 3 will increase capital cost. The benefits gained from the lower tariff are being added in each year of the life cycle as a saving.

Total calculations of each alternative are calculated to give net present value to income and total cost as shown in Table 7.

TABLE 7. **Simulation result of LCCA (in million USD).**

Parameter	Alt 1	Alt 2	Alt 3	Alt 4
Total Income	129.45	127.65	129.61	128.11
Total failure cost	1.267	1.493	0.905	1.059
Total Maintenance cost	3.730	1.989	5.595	2.611
Total ENS	6.625	5.227	5.986	4.454
Additional protection	0	0	2.340	2.340
Total Cost	11.622	8.710	14.826	10.464
Cost effectiveness	0.053	0.071	0.043	0.063

C. COST EFFECTIVENESS AND MAINTENANCE DECISION

Up to this point, RAMS effectiveness and net present value (NPV) for all parameters have been obtained in each alternative. Each of these parameters will give the quantitative measurement in term of engineering and financial aspect relevant to the maintenance decision making. The goal is to have higher system effectiveness and NPV at the same time, which can be measured by simply calculating the ratio of both parameters (10). The result, known as cost effectiveness of alternatives is graphically presented in Fig. 10.

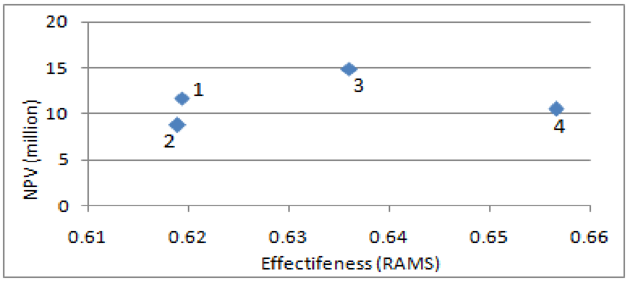

FIGURE 10. **Cost effectiveness diagram.**

The decision is made by choosing the maximum value of cost effectiveness. From Fig. 10, it is shown that alternative 2 has the highest cost effectiveness value and can be considered as the best to be applied compared to the other alternatives.

VI. CONCLUSION

The whole process of the maintenance decision making has demonstrated strong correlation between maintenance scheme, system effectiveness, and total cost. The application of Monte Carlo simulation gives a great advantage in handling dependency of many parameters and components. Many other schemes can be developed in various ways regarding to the characteristic of the system being analyzed. Submarine cable, as has been shown, has a unique characteristic. It typically has a very high capital cost compared to the maintenance and failure cost, relatively long life cycle, and constructed by non-replaceable and solidly integrated components. This characteristic will give a low sensitivity result in the system's effectiveness and NPV to the change made in the maintenance scheme. Large opportunities are wide open to the development of methodologies constructed in this paper. Some parameters, such as cable life characteristic, system's cost, and repairing scheme are dynamically dependent on the financial situation, load demand characteristic, and environmental condition.

ACKNOWLEDGMENT

The authors would especially like to thank PT PLN (Persero) P3B for providing information about the maintenance process of Java-Bali under water cables and data for the analyses, and also C. Sinisuka for sharing ideas and reviewing the grammar of this paper.

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