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Availability modelling of submarine high voltage cable systems

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SUMMARY

As the penetration of submarine power cables is increasing in the power systems, it is steadily becoming more important to have a proper detailed model for the estimation of the cables availability. The submarine cables are used as interconnectors, export cables from offshore wind farms and will also be a key component of the future offshore HVDC grids implying their significant role in reliability of the future renewable dominant power systems. Failures in submarine cables have two distinguished causes, internal and external. Internal failures are because of threats such as transient over voltages, over loading, design and manufacturing defects due to inadequate test regimes. External failures can among others result from environmental threats and human activities. Examples are anchors, trawls and seabed mining that may impact and damage the cables. An extensive overview on the cable failure causes are investigated in the CIGRE technical brochures TB 815 and TB 825. Failures of submarine cables are not so frequent, however, the repair process is highly time consuming and expensive, which can lead to critical consequences in terms of the system reliability. Different barriers are considered to prevent a threat to develop into a failure. One of the most effective barriers is mechanical protection against external threats such as burying in the seabed. It is critical to ensure that the cable burial is maintained over the cables life time. One effective measure to evaluate the cables burial condition is periodic route survey/inspection.

In addition, there are also barriers that can negatively influence submarine cables repair process. Adverse weather condition is one of the most important of these, which can delay the offshore operations for a considerably long time. A proper model to evaluate the cables availability should consider the above mentioned influencing factors enabling the cable system operators to have an overview on the reliability indices as realistic as possible.

The main contribution of this paper is to present such a model for availability modelling of submarine cables. The proposed model is based on Markov method and is detailed to consider the adverse weather condition as an influencing factor on an offshore operation and the route survey/inspection as an efficient failure preventive action. Cables availability, forced outage, planned outage as well as mean time to failure and mean down time are the most important outputs of the model. Besides, sensitivity analysis can be performed using the proposed model to study the impact of each influencing factors on the desired outputs.

KEYWORDS

Submarine cable systems, Availability modelling, Markov process

Introduction

Offshore cable systems are becoming significant components in the future power system in the wake of the energy transition [1] [2]. Offshore wind farms are growing so fast that very soon they will undoubtedly play an important role in the power supply reliability [3]. Export cables are key components of the offshore wind farms in transferring power to the shore. Submarine interconnectors are of critical means for increasing security and stability of the future power system with high penetration of renewable energy sources. The concept of offshore HVDC grid is going to facilitate offshore renewable energy trade between countries, implying more complex and critical role for the offshore cable connections [4]. As the penetration of submarine power cables is increasing, it steadily becomes more important to have a proper detailed model for the cables availability estimation, which considers significant influencing factors on the failure occurrence and the repair/maintenance operations.

Any failure in export cables, interconnectors and cable connections in an offshore grid will significantly disturb the power flow and considerably reduce the overall system security.

Submarine cables are subjected to different threats originated from environmental hazards, human activities and operational conditions. As reported in [5], most failures occurred on submarine cables have external causes such as falling objects, anchors, trawls, fishing gears, etc. Deviation of the cables mechanical protection from the design criteria and lack of proper communication channel with other mariners along the cables route are considered as main aspects for increasing the cables susceptibility to external failure causes [5] [6].

Besides, submarine cable repair and restoration of the cable system is a complex operation where many factors at different levels influence a fast and successful offshore operation.

Vessel availability, adverse weather conditions, failure location equipment and competence, local restrictions on marine activities, coordination between cable system operator/owner and repair contractor are of influencing factors [7]. Most of the factors can be considered during the planning and engineering phase depending on their significance levels and resolved through preparedness agreements and plans. However, the adverse weather remains as the most influencing factor for the offshore cable repair operations particularly in deep waters [5] [6]. Reviewing the literature, it is revealed that most the research work and papers have mainly focused on the reliability modelling of the converters, wind turbines [8] [9], while the availability models of submarine cables are kept simple and not detailed to consider the influencing factors. Considering the above mentioned facts, the main contribution of this paper is to propose a proper mode for the availability estimation of submarine cables taking account of the adverse weather condition and cable route survey/inspection/maintenance.

Proposed model

Markov process is used as a modelling approach in this paper [10]. It is assumed that a component has a number of states such as functioning, failed and maintenance. The component stays continuously in one of the states until a transition occurs that takes it to another state [11]. Transition rates between states are considered constant, and the probabilities of being in different states are calculated.

Figure 1 shows the detailed Markov process proposed for availability modeling of submarine cables. The model considers adverse weather conditions as the main influencing factor for the offshore repair operation and exposure of the cables as the main influencing factor in increasing cables vulnerability to external failure causes. Other aspects such as visibility of the cables to other mariners and electrothermal conditions of the cables can be incorporated in failure rates, which are in fact transition rates from functioning to failed states.

It is considered that time based route surveys/inspections are performed to detect any deviation in cables burial condition. It is further assumed that the inspection operations have 100% efficiency meaning that no burial issues remain undetected. In addition, the route maintenance is presumed to be performed on de-energized cables. It is worth mentioning that any failure will interrupt and seize the route survey/inspection operation and repair process will start thereafter. Once the repair is done (assuming with 100% efficiency), the halted operation will be restored. Two normal and adverse weather conditions are considered as influencing factors on weather dependent transition rates. Other factors such as preparedness and route restrictions can be incorporated in the transition rates from failed states.

The model consists of 5 working modes as stated in the following:

1. Operating/Protected (O/P), cables are functioning and the mechanical protection against external threats is in place as designed. This is a safe state of operation.
2. Operating/Exposed (O/E), cables are functioning, but as seabed conditions change over time along the cable route, it is not unlikely that the cable protection is partially or fully removed and no longer complying with the design criteria resulting in high vulnerability to external threats. This is considered as an unsafe state of operation.
3. Planned outage (PO), cable system is de-energized to take remedial actions on the cable route including re-trenching, rock dumping, etc. Since the system is de-energized, internal failures (operational threats) are assumed not to occur, however, the cables are still vulnerable to external threats.
4. Forced outage - Preparation for Repair (FO/P), a failure has occurred and the cable system is forced being de-energized. It includes all the pre-repair activities (failure location, pin pointing, etc), preparation works and planning.
5. Forced outage - Marine Repair Operation (FO/R), it includes the main repair activities as de-burial, jointing, re-laying and re-trenching operations.

The model has further 34 states defined as:

- State 1 O/P, the cable system normally starts working in State 1, which is basically unknown to the system operator until a route survey/inspection is performed (transition to State 2). Failures may occur leading to a transition to State 14. In case of changes in cables burial condition, a transition is made to State 5.
- State 2 O/P, the cables are in the same condition as State 1, but to verify the protection soundness a route survey/inspection is undergoing. The route inspection frequency is decided by the cable system operator based on the seabed conditions and threats along the cable route. Route survey and inspection is known as an effective measure for avoiding third party damages on submarine cables [5]. Once the route survey is performed, the system returns to State 1. If a failure occurs, the survey operation is halted (since tracking the cables with no guiding tone or magnetic field will not be effectively possible) making a transition to State 3 for starting a repair process.
- State 3 FO/P, preparation for the repair is undergoing followed by State 4 for repair process.
- State 4 FO/R, marine repair process is undergoing. Once the repair is finished, it returns to State 2 wherein the failure had occurred.
- State 5 O/E, it is in fact unknown to a system operator that cables are exposed until being confirmed through a route survey/inspection making a transition to State 8.
- State 6 FO/P, preparation for the repair is undergoing followed by State 7 for repair process.

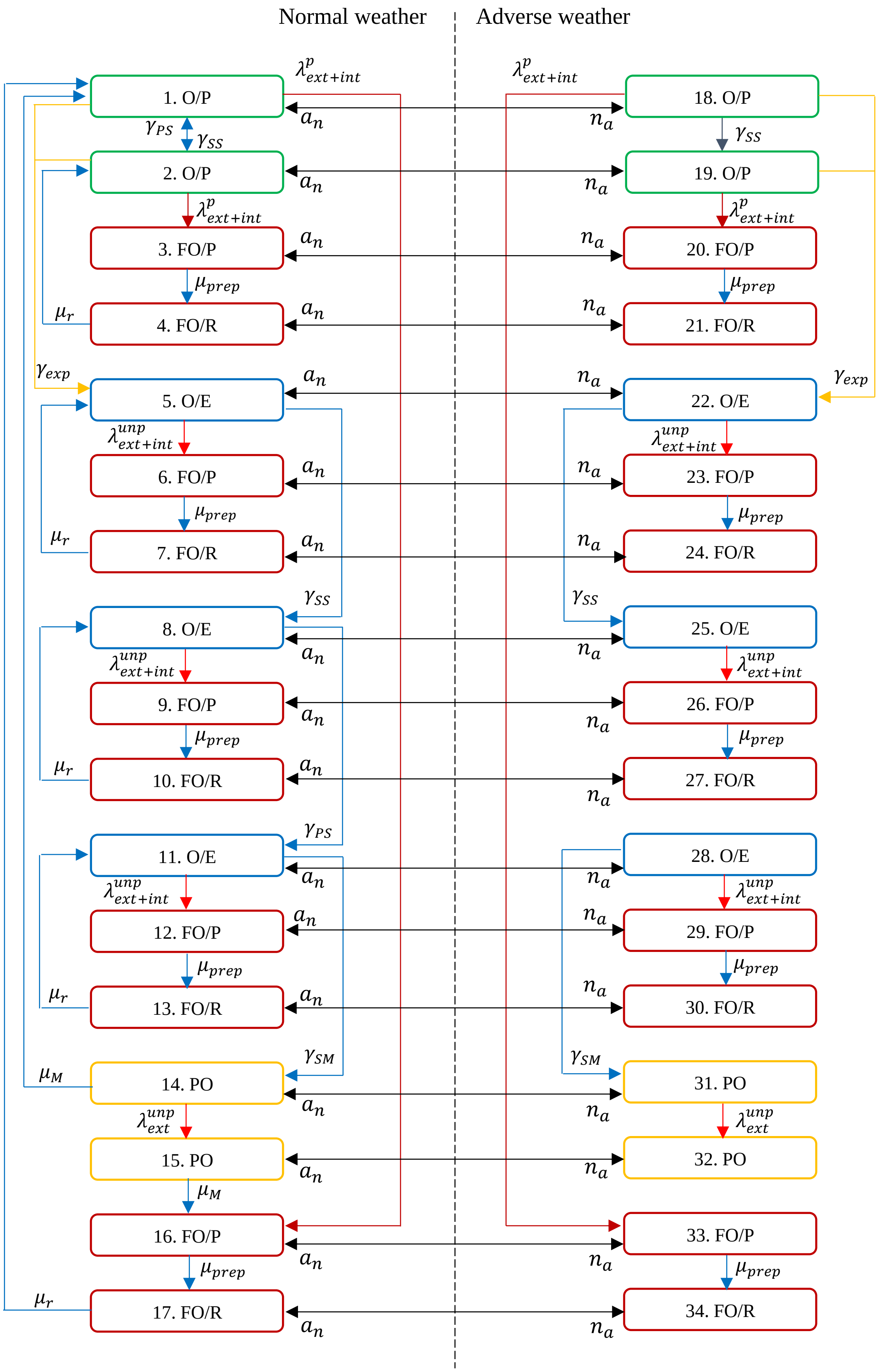

Figure 1 Detailed Markov model for availability assessment of submarine cables

- State 7 FO/R, marine repair process is undergoing. Once the repair is finished, it returns to State 5 wherein the failure had occurred.
- State 8 O/E, the cables are under route survey/inspection operation, but functioning, still exposed and undetected. Once the survey is completed, there is a transition to State 11.
- State 9 FO/P, the repair preparation is undergoing followed by State 10 for repair process.
- State 10 FO/R, marine repair process is undergoing. Once the repair is finished, it returns to State 8 wherein the failure had occurred.
- State 11 O/E, route survey/burial inspection is done, any deviations from design protection is now detected. Planning for doing remedial actions is in progress, once decided, there is a transition to State 14. In case of failure, a transition to State 12 takes place.
- State 12 FO/P, the repair preparation is undergoing followed by State 13 for repair process.
- State 13 FO/R, marine repair process is undergoing. Once the repair is finished, it returns to State 11 wherein the failure had occurred.
- State 14 PO, planned outage is effective and remedial actions are in progress. Once done, there is a transition back to State 1. During the route maintenance, an external failure may occur leading to a transition to State 15.
- State 15 PO, the cable system is under maintenance outage, however, an external failure has occurred, since the cable system is out of service, the failure will not be detected until the maintenance is over; the system operator attempts to re-energize the system. Once the fault is confirmed, there is a transition to State 16 instead of returning to State 1.
- State 16 FO/P, the repair preparation is undergoing followed by State 17 for repair process.
- State 17 FO/R, marine repair process is undergoing. Once the repair is finished, it returns to State 1.
- States 18-34, adopting the approach presented in [12] for considering weather dependent activities, all the states from 1 through 17 have twins under adverse weather condition, which may have different transition rates or even no transition compared to their corresponding states under normal weather condition. The states 19, 21, 24, 25, 27, 30, 31, 32 and 34 have no transition for performing marine surveys, route maintenance and repair operation. In the model shown in Figure 1, it is presumed that the failure rates are weather independent. However, if there is supporting statistics/knowledge on weather dependency of the threats exposure (weather dependent fishing activity, vessel incidents, emergency anchoring, cargo droppings, etc), it can be considered in the failure rates under adverse weather condition.

Model parameters

Departure rates in the proposed Markov model are associated with threats and different aspects of cables vulnerability. In the following, considerations on calculation/estimation of the departure rates are discussed:

1. Normal to Adverse weather (n_a) and Adverse to Normal weather transition rates (a_n)
   The rate of departure from normal weather to adverse weather can be estimated using the meteorological ocean data and weather statistics. Adverse weather is mainly limiting the marine operations for installations, repair and re-trenching being associated with the repair vessel limits in terms of wind speed and significant wave height. Considering these

constraints and historical weather data of the intended location, chronological variation of weather can be obtained through which an average weather duration is calculated for a specified period of time as shown in Figure 2, where S and N represent average adverse and normal weather durations, respectively [12] [13]; the transition rates are calculated as $n_a = \frac{1}{N}$, $a_n = \frac{1}{S}$.

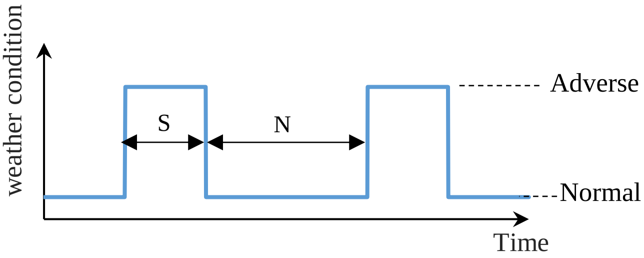

Figure 2 Average weather duration profile *[12] [13]*

2. $\lambda^{p}_{ext+int}$ [failure/year]
   Total internal and external failure rates $(= \lambda^{p}_{ext} + \lambda_{int})$ for the protected cables based on design criteria. External threats and preventive barriers, which are considered to prevent development of a threat to an unwanted event (failure), determine the external failure rate of cables. Electrothermal aging of the insulation, fatigue aging of the radial water barrier and threats such as over voltages and overloading determine the internal failure rate of cables . Proper models are required for probabilistic evaluation of internal and external failure mechanisms [14] [15] [16]. Statistical data from service experience (such as [6], [5], [17], [18], [19], [20] and [21]) can also be used for estimation of failure rates, however, it must be treated carefully if the data is representative for the conditions of the study.
3. γ_{exp} (exposure/year)
   It describes at what rate the cable protection and burial is removed resulting in cables exposure. The rate of being exposed depends on factors such as seabed conditions, sand waves, currents, etc, that can be experimentally estimated based on data from route surveys.
4. $\lambda^{unp}_{ext+int}$ (failure/year)
   Total internal and external failure rates $(= \lambda^{unp}_{ext} + \lambda_{int})$ for unprotected cables. The general approach as explained for the protected cables can be used here considering that the cables are not protected and thus more vulnerable.
5. γ_{SS} Route survey frequency (Survey/year)
   It is associated with the route survey/inspection schedule considering all the preparation and planning times for starting a marine survey. It is the cable system operator's internal policy that determines how often the route inspection and survey should be performed depending on the threats exposure to the cables along the route.
6. γ_{PS} Route survey rate (Operation/year)
   It is associated with the time to perform a marine survey/inspection operation. It can be estimated using the route characteristics and experience from similar previous operations.
7. γ_{SM} Route maintenance frequency (maintenance/year)
   It is associated with the time planned for taking route remedial actions. Power system operational conditions (form technical and reliability point of view) and energy market status are of influencing factors in determining when maintenance actions must be taken.

8. μ_M Maintenance rate (operation/year)
   It is associated with the time to perform remedial actions including re-trenching, rock dumping, etc. An expert knowledge can be used for the estimation considering the route-specific factors such as narrow passages, sharp turns, concentration of other cables in the area, seabed conditions, etc.
9. μ_{prep} Repair preparation rate (repair/year)
   It describes preparation level of an operator when encountering a cable failure. Prepared repair methodologies and processes, having an agreement with service providers and procedures to follow when a failure occurs are of significant factors [7].
10. μ_r Marine repair rate (operation/year)
    The repair process that is associated with the time required for performing a cable repair on-board vessel. It considers the active repair time excluding any logistics, preparations and waiting for weather window. Route/technology restrictions and service experience can be used as a basis for estimation of the repair rate.

Implementation

The differential equation governing the state probabilities is expressed with $\frac{d\bar{p}}{dt} = \bar{p}.\bar{T}$ [11], where $\bar{p}$ is the vector consisting of state probabilities, $\bar{T}$ is transition matrix of the Markov process presented in Figure 1. The equation is solved with an assumption that the system is initially in the O/P state such as initial probability vector $p_0 = [1\ 0\ 0\ 0\ ...\ 0]$. The transition matrix ($\bar{T}$) is an order of 34x34, its elements denoted with $m_{i,j}$ are:

$m_{i,j} =$ departure rate from State *i* to State j, for $i \neq j$.

$m_{i,j} = 0$ if no transition exists between State *i* and State j, for $i \neq j$.

$m_{i,i} = -\sum_{j=1}^{34} m_{i,j}$

Once the equations are solved, asymptotic availability (A), unavailability due to forced outage (U_{FO}) and planned outage (U_{PO}) can be calculated using equations $A = \lim_{t\to\infty} \sum_{i=O/P,O/E\ states}(p_i)$, $U_{FO} = \lim_{t\to\infty} \sum_{i=\mathrm{FO/P,FO/R}\ states}(p_i)$ and $U_{PO} = \lim_{t\to\infty} \sum_{i=PO\ states}(p_i)$.
Considering the O/P states as a safe and the O/E states as an unsafe operational conditions from the cables protection viewpoint, the probabilities of such situations can be calculated with $A_{safe} = \lim_{t\to\infty} \sum_{i=O/P\ states}(p_i)$ and $A_{unsafe} = \lim_{t\to\infty} \sum_{i=O/E\ states}(p_i)$.
In order to calculate mean time to failure (MTTF), the reliability function $R(t)$ is first obtained through which the MTTF is calculated as $\int_0^\infty R(t)dt$. The reliability function is basically defined for non-repairable systems that is the probability of an item operating for a given time interval without failure [10]. It is therefore the same as availability function when the failure states (FO/P and FO/R) are assumed as absorbing states ($\mu_{prep} = 0, \mu_r = 0$) meaning no transitions occur from those states [11]. Mean down time (MDT) is calculated with an initial condition set to one of the failed states while the return state is considered as an absorbing state. For example, for the case with State 16 as an initial state and State 1 as an absorbing state, the MDT is calculated with $\int_0^\infty (p_{16} + p_{17} + p_{33} + p_{34})dt$. Using the same fashion, mean time to maintenance (MTTM) is calculated with $\int_0^\infty (p_{14} + p_{15} + p_{31} + p_{32})dt$ for State 14 as an initial state and State 1 together with State 16 as absorbing states.

Performance

To evaluate the performance of the proposed model, the equations are implemented in MATLAB and run with the parameters shown in Table 1 as a base case. Table 2 shows the results.

Table 1 Model parameters-base case

Model Parameters	$\lambda^{p}_{ext+int}$	$\lambda^{unp}_{ext+int}$	a_n	n_a	γ_{exp}	γ_{SS}	γ_{PS}	γ_{SM}	μ_M	μ_{prep}	μ_r
event/year	0.008	0.095	10	90	0.25	0.5	18.25	6.1	26.1	8.7	17.4

Table 2 Simulation results for the base case

A, %	U_{FO}, %	U_{PO}, %	A_{safe}, %	A_{unsafe}, %	MTTF, years	MDT, days
98.48	0.74	0.77	63.18	35.30	27.6	67.4

Sensitivity study is a useful means to see how outputs vary with an input parameter. As an example, Figure 3 to the left shows how the MTTF and the MDT varies with increasing the adverse weather duration. It is obvious why the MDT is increasing with adverse weather condition duration, since it delays the marine repair operation. However, it may be less straight that why MTTF is decreasing that is in fact because the cables stay longer in exposed and thus more vulnerable states when the weather adverse condition is longer. Figure 3 to the right shows the sensitivity of the overall availability, safe and unsafe operational conditions to the route survey/inspection frequency. As can be seen, increasing the time interval between the route surveys leads to an increase in the unsafe operation, while the overall availability remains almost constant. As far as the survey interval is less than the cables exposure time, safe operation probability is higher than that of unsafe condition. Nevertheless, more frequent surveys means higher cost to the cable system operator. In order to optimize the route survey scheduling, an overall cost function as an objective to minimize should be defined combined with the probabilities of the different relevant states obtained from the availability model.

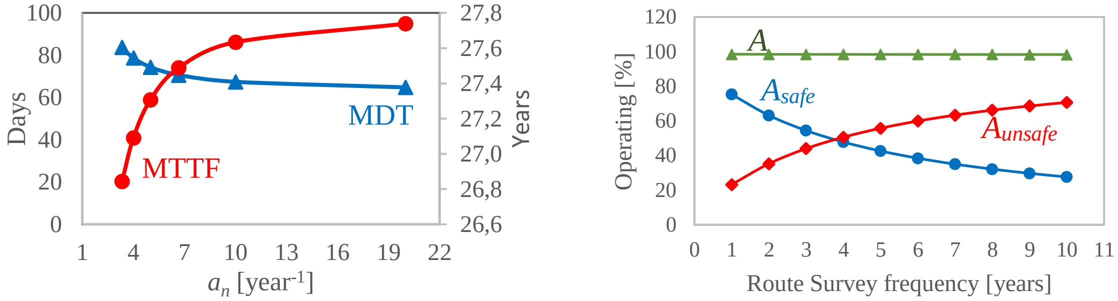

Figure 3 Left) sensitivity of MDT and MTTF to the adverse weather condition. Right) Sensitivity of the availability, safe and unsafe operation probabilities to the route survey/inspection frequency.

CONCLUSION

Availability study of the submarine cable systems is becoming steadily important as their penetration in the power system is growing as submarine interconnectors, export cables from offshore windfarm and offshore cable grids. A detailed conceptual availability model based on Markov process is presented in this paper. The influence factors of adverse weather condition, cable route survey/inspection and maintenance scheduling are considered in the reliability indices such as overall availability, forced outage, planned outage as well as MTTF and MDT. Besides, a sensitivity study on the significance of the influencing factors can be practically performed with the proposed model, which can assists the cable operators for an efficient future planning. The details introduced in the model enable the cable operators to have an estimation of different states probabilities that can be used for further analysis. For example, the costs of the route survey/inspection, maintenance and repair operations can be included for the optimization of the route survey frequency. To this purpose, it is necessary to have the probabilities of being in states wherein the route surveys, maintenance and cable repair operations are undergoing, which are of the proposed model outputs.

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