Reliability Analysis of Shore-to-Ship Fast Charging Systems

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***Abstract*- This paper presents a reliability assessment of Shore-to-Ship Sharging (S2SC) systems with focus on the two most common topologies of ac and dc charging. In the proposed reliability model, the Markov chain and reliability block diagrams are used to establish multi-state models of the system. In this regard, the state of system is defined as the maximum transferable charging power into the onboard batteries from shore which can be comprimised by the failure of the individual compoents. As the results of Markov chain analysis, the probability of the operation states and Mean Time to The First Failure (MTTFF) are calculated. Further, to clearify the impact of the failure of the individual compoents on the charigng mission, an application-specific failure threshold is defined. Subsequently, two relibility indices, namely, Loss of Charging Expectation (LOCE) and Derated Charging Expectation (DCE) are introduced and computed using the calculated prbability tables and the defined failure threshold. The results from conducting such analysis for two case studies with ac and dc S2SC systems, shows how the studied dc charging system is more reliable than its ac counterpart.**

INTRODUCTION

Shore-to-ship charging (S2SC) can contribute to the reduction of emissions from maritime transport by establishing a bridge between the propulsion systems of a vessel and the sustainable energies on land [1]. The battery-powered marine vessels, which are mostly short-distanced ships with a planned schedule, such as ferries, receive charging from shore during the docking period while unloading and loading [2]. Therefore, the S2SC process is constrained within a critical time, oftenless than 30 minutes. If a fault hindering the charging process happens, it causes inconvenience for the passengers and expensive fines for the ship operators by cancelling or postponing the ferry schedule [3]. Thus, the unavailability of the S2SC system can adversely affect the vessel operation and cause significant outage costs. Consequently, reliability assessment should be of significant importance in the preliminary design of such marine vessels.

Until now only few research-based studies on reliability evaluation of the marine power systems have been conducted. The available publications focus mainly on the shipboard power system topologies [4] or consider cold ironing (i.e. power from shore) in addition to onboard generators [5]. Despite the importance of the reliability analysis for the S2SC systems, dedicated studies on the main S2SC topologies are not available in the literature. However, since the S2SC systems mainly consist of the power electronics converters and battery energy storage systems, the reliability evaluation can be inspired by recent reasearch papers on modern power systems [6] and other electrified transportation systems like more electric aircrafts [7].

Additionally, in a S2SC system, the components are usually designed as modules to comply with the high power and energy requirements. Hence, in such systems, the failure of a single component may not end in the loss of charging missions, so-called, final failure of the system. Rather, the charging mission might be carried out, but at the expense of lower charging power. If the S2SC system of a ferry is not able to provide the nominal charging power due to component failures, extending the charging process would affect the daily schedule. Alternatively, if the remaining energy in the onboard batteries after the compromised charging process would be sufficient for next trips, the ferry could continue its operation within the determined schedule. Still, in the latter case, the ferry eventually needs to stop its operation or change its schedule until the faulty parts are repaired. To evaluate the reliability of a S2SC system in the system-level, it is proposed in this paper to define a failure threshold to classify the operation states into normal operation, derated operation and faulty operation. To do so, an application-specific charging curtailment threshold for a S2SC process is introduced by taking into account the energy profile of the onboard batteries and the design parameters of the system. Further, employing such failure threshold, the application-specific reliability indices are defined.

Regarding the reliability assessment methodology, the Markov chain models of the whole S2SC systems are established and analysed. In such models, states are the consequence of the failure of the critical units on the maximum transferable power from shore to the onboard batteires. Units are defined as a set of compenents in series, so unit failure rates are calculated by Reliability Block Diagram (RBD) using historical failure data from the handbooks and literature.

Using the proposed method, the two most common topologies of S2SC systems, ac and dc charging systems, supported by onshore batteries are compared in terms of reliability. Further, to compensate the uncertainity of the reliability data, especially for the shore to ship connection unit and the onshore batteries, a sensitivity analysis is conducted. The results show that the calculated MTTFF and LOCE for the dc S2SC system under study is 38% and 33% lower compared to the ac S2SC system. Thus, the dc S2SC system is more reliable than its counterpart, applying design and operational parameters in this paper.

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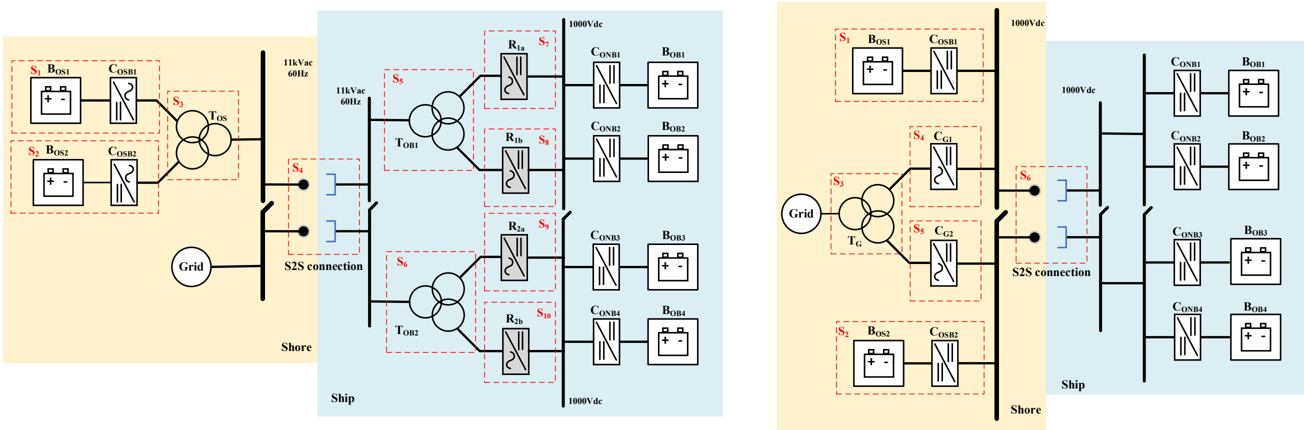

(a) (b)

Fig. 1. (a) The dc S2SC system and (b) the ac S2SC system

SHORE-TO-SHIP CHARGING SYSTEMS

The S2SC systems under study is described in the following as a basis for introducing the proposed application-specific reliability indices.

A. S2SC system description

The two most common S2SC solutions, 1) ac and 2) dc charging, are considered for the reliability assessment. The ac S2SC system, drawn in Fig. 1(a), has been the most common solution in which the charging energy is transferred as ac-current to the ship and converted into direct current by the onboard rectifiers [8]. In such configuration, which has been inspired by the S2S charging system used for MF Hadarøy at Sulesund, Norway, supplied by Norwegian Electric Systems (NES) [9], there is no dedicated transformer for the grid interface. Therefore, the shore-to-ship connection is high voltage, 11kVac. Further, the onshore batteries contribute to the charging by the dc-ac conversion stages and a transformer [8].

In Fig. 1 (b), the dc S2SC system for the same charging requirements is depicted. In this solution, the onboard transformers and rectifiers are avioded due to the supplied charging is in direct current. However, because of the high cost of medium voltage dc systems, the main dc bus is usually designed to be lower than 1500Vdc.

In the both single diagrams, the critical units which are vulnerable to failure independently from each other are marked and numbered. Therefore, the first step is the realization of the system configuration and identification of critical system.

B. Reliability characterization

In a S2SC system, the amount of the required charging power at each charging break is calculated online in the onboard power management system based on the operational factors. However, the planned charging profile can be used for design purposesWith a modular design as indicated in Fig. 1, the failure of one or a set of components in a S2SC system, may not lead to a final failure of the overall system. Thus, in the following a threshold to specify the derated operation states is defined. In the normal operation of a battery-powered passenger/car ferry, the onboard battery is discharged to supply propulsion loads during operation within trip time, t_{tr}, and recharged with charging power, P_{ch}, at docking within charging time, t_{ch}. For simplification, it is assumed that the discharged and charged energy of the onboard batteries remain constant in all the n trips. The energy equilibrium for the onboard batteries can be written as follows.

$$(n-1)(P_{ch}t_{ch}) - nE_{tr} = (SoC_F - SoC_I)C_s \qquad (1)$$

in which E_{tr} and C_s are the discharged energy from the onboard batteries during the trips and the capacity of the onboard batteries. SoC_I and SoC_F are the initial and final value of equivalent SoC of the onboard batteries during one day of operation. Because of the safety and lifetime of the batteries, the SoC of the batteries should remain with the SoC_{Max} and SoC_{Min} which can be defined as 90% and 10%, for example. However, considering the optimum lifetime of the batteries, the operational parameters are usually designed in such a way that the SoC range within the operation do not reach the maximum and minimum values. Rather, the state of the charge of the onboard batteries start at SoC_U at the beginning of the trip and end up in SoC_L at the end of a trip.

$$SoC_{Min} \leq SoC_L < SoC_U \leq SoC_{Max} \qquad (2)$$

Given the trip and docking times as well as propulsion power being constant during one day of operation, the final SoC at the end of the day can vary depending on the charging power, as shown in Fig. 2. In case of the reduced charging power, the ferry can continue operating as long as the SoC does not reach the minimum value. Therefore, in order to calculate the failure threshold, the minimum charging power by which the ferry can continue operation until the failed components are repaired should be identified. In this regard, it is assumed that the failure happens before the first charging interval and the charging mission should be carried out for one full day of operation

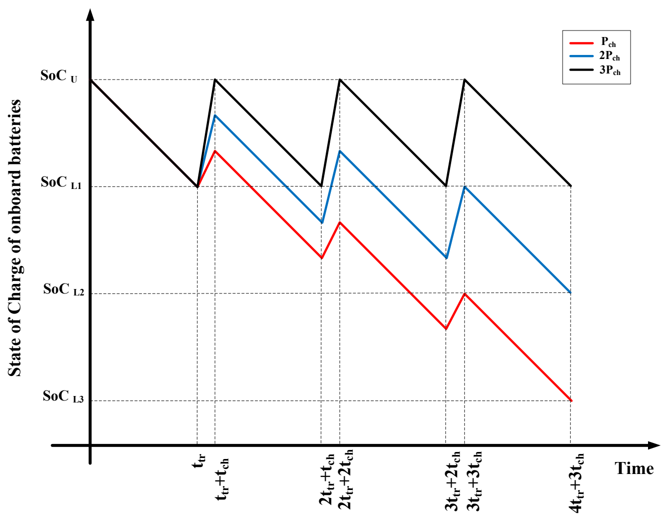

Fig. 2. An example of the energy profile of onboard batteries

without any impact on the ferry schedule. Thus, by considering the final SoC to be equal to SoC_{Min}, based on (1), the minimum allowable charging power is calculated in (3).

$$P_{ch}^{Th} = \frac{(SoC_{Min} - SoC_I)C_s + nE_{tr}}{(n-1)t_{ch}} \tag{3}$$

Hence, the operation states are categorized into three classes; 1) normal operation with the nominal charging power, 2) derated operation with charging power more than the threshold and lower than the nominal value and 3) final failure operation with charging power less than the threshold and the major maintenance is required. Inspired by the probabilistic indices used for the power system such as Loss of Load Expectation (LOLE) in which the probability of not being able to supply the forecasted peak load within a year is calculated [6], three application-specific indices are defined for S2SC. The first is Loss of Charging Expected (LOCE), which indicates the number of failed charging breaks per year and is obtained as follows.

$$LOCE = 365 \sum_{j=1}^{n} \Pr\left(P_{ch} < P_{ch}^{Th}\right) \tag{4}$$

In this equation, P_{ch} and n are the charging power capacity of the system in a charging break and n is the number of the charging breaks per day. Pr(.) is the probability of supply charging power which is calculated through the reliability analysis. The second index is labelled as Derated Charging Expected (DCE), and indicates the number of charging breaks when the charging has been compromised due to faults.

$$DCE = 365 \sum_{j=1}^{n} \Pr\left(P_{ch}^{Th} < P_{ch} < P_{req-i}\right) \tag{5}$$

In which $P_{req-i,j}$ is the required charging power at i^th day of the year in j^th charging break. Mean Time To the First Failure (MTTFF) is also considered as a reliability index which can be calculated based on the Markov chain of the system and is explained in the next section.

Reliability Assessment Methodology

Reliability of a system is calculated as the probability of operation of the system for a time interval under a specified operating condition [10]. The reliability analysis flowchart is drawn in Fig. 3. The first block in such flowchart is the S2SC system design and configuration in which the S2SC system the reliability-critical units are identified and the reliability indices are characterised as menitoned in the previous secion. Here, the heirarcy of the S2SC system is assumed to start from parts for which, their failure rate and repair rate are extracted form the handbooks and literature. Then, the next level of heirarchy is assumed to be the components which can be composed of a set of parts, such as power converters or only one part, e.g., transformers. Subsequently, units are defined to be made of components connected in series. The failure rate of the compoenents are obtained by RBD method from the part reliability data.

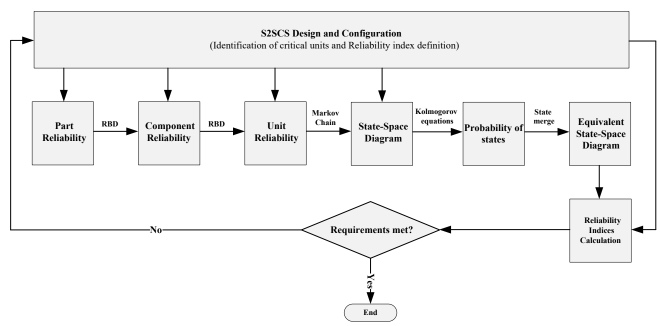

Fig. 3. Reliability analysis flowchart of S2SC system

Next, the state-space diagram for S2SC systems in terms of the maximum charging power by using Markov chain analysis is established. By using the failure and repair rates of the units, the transition rates between different failure modes can be obtained. Moreover, the maximum number of components which can fail in a row and the system can continue operating is assumed to be three. Further, it is assumed that after failure of a set of components the overloading of other components is avoided through local and high-level controllers. To calculate the probability of the states, the Kolmogorov equation in steady state is used [11]:

$$PA = 0 \tag{6}$$

where P is the matrix of probability of states and A is the matrix of transition rates in which a_{ij} ($i \neq j$) is the transition rate from state i to state j.

$$P = [P_1 \; P_2 \ldots P_n] \tag{7}$$

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \quad (8)$$

$$\text{s.t.} \qquad a_{ii} = -\sum_{\substack{j=0 \\ j\neq i}}^{n} a_{ij}$$

In order to determine the state probability, only (n-1) row of the equations in (3) with the following equation are considered.

$$\sum_{i=1}^{n} P_i = 1 \quad (9)$$

Then, employing the state-merge method, the states with the same maximum charging power merge into an equivalent state [12]. Further, using the failure threshold the reliability indices, LOCE and DCE are calculated by the probability table of the states [11]. Apart from such indices, the Mean Time to the First Failure (MTTFF) is calculated by setting up the reduced transition matrix after assigning the final failure states, states with charging capacity less than the threshold, as absorbing states and solving the differential equations for calculation of the state probabilities. The MTTFF can be obtained as following in which P_i is the time-dependent probability of state i and j is the number of non-final failure states [11].

$$MTTFF = \int_0^{\infty} \left(\sum_{i=1}^{j} P_i(t)\right) dt \quad (10)$$

Case Studies and Results

In this section, the proposed reliability assessment is carried out for two case studies with the power system topologies depicted in Fig. 1. The critical units are identified in the same figure. To calculate the reliability requirements and indices the operational parmeters of the S2SC systems under study is given as listed in Table I.

TABLE I
S2SC OPERATIONAL PARAMETERS

Parameter	Value
Number of trips per day (n)	14
Nominal S2SC power	5MW
Charging power from the grid\onshore batteries	3MW\2MW
Averaged charging time (t_{ch}) \sailing time	4 min\25min
Discharged energy from onboard batteries during one trip (E_{tr})	333kWh
Onboard battery SoC safety range ($SoC_{Min} – SoC_{Max}$)	10%-90%
Nominal onboard batteries SoC range during one trip ($SoC_L – SoC_U$)	70%-80%

Based on (2), the charging power threshold by using the operational parameters of the S2SC systems listed in Table I is calculated to be equal to 3MW. In the next step, the failure rates of the units are obtained by RBD method. The unit failure rates and repair rates for two S2SC systems are listed in Table II and Table III [7], [13], [14] and [5]. Note that apart from the technology and material used for a S2S connection unit, the operational conditions, such as the weather conditions, location and the number of connections per day have a significant impact on the reliability of such system. However, the uncertainty of reliability data, especially the S2S connection is compensated by presenting the sensitivity analysis of the results on the inputs.

TABLE II
AC S2SC SYSTEM DESIGN PARAMETERS AND UNIT RELIABILITIES

Units	Components	Parts	Failure Rate ($occ.y^{-1}$)	Repair Rate ($r.y^{-1}$)
Onshore battery bank (S_1, S_2)	Onshore Battery Converters (C_{OSB1}, C_{OSB2})	6*IGBT+ dc cap+ ac filter	1.15	182.5
	Onshore Batteries (B_{OS1}, B_{OS2})	-		
Onshore transformer (S_3)	Three-winding transformer (T_{OS})	-	0.05	219
S2S connection (S_4)	Fully automatic plug system	-	0.02	121
Onboard transformer (S_5, S_6)	Three-winding transformer (T_{OB1}, T_{OB2})	-	0.05	219
Onboard rectifier (S_7-S_{10})	Three-phase diode rectifier (R_{1a}, R_{1a}, R_{2a}, R_{2b})	12*diode+ dc cap	0.017	365

TABLE III
DC S2SC SYSTEM DESIGN PARAMETERS AND UNIT RELIABILITIES

Units	Components	Parts	Failure Rate ($occ.y^{-1}$)	Repair Rate ($r.y^{-1}$)
Onshore battery bank (S_1, S_2)	Onshore Battery Converters (C_{OSB1}, C_{OSB2})	2*IGBT+ 2*diode+ dc cap	1.11	182.5
	Onshore Batteries (B_{OS1}, B_{OS2})	-		
Grid transformer (S_3)	Grid-side Transformer (T_G)	-	0.05	219
Grid-interface converter (S_4, S_5)	Grid-side Converters (C_{G1}, C_{G2})	6*IGBT+ dc cap+ ac filter	0.057	365
S2S connection (S_6)	Fully automatic plug system	-	0.02	121

In the next step, the state-space model of the system by considering the failure of the critical units in terms of the charging power capcity is established. After applying the Kolmogorov equation and the state merge technique, the equivalent state spaces are obtained. Due to the page limitation, only the equivalent state spece of the case studies are shown in Fig. 4 and Fig. 5. Note than the states with the zero charging power which are considered as final failure states are only showed with the critical failed units.

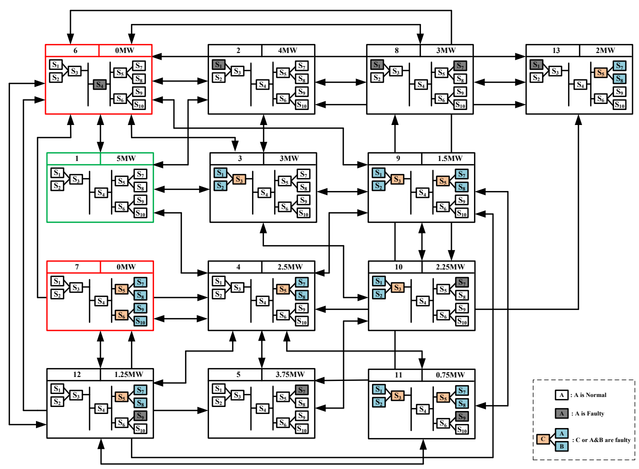

Fig. 4. State-space diagram for the ac S2S charging system

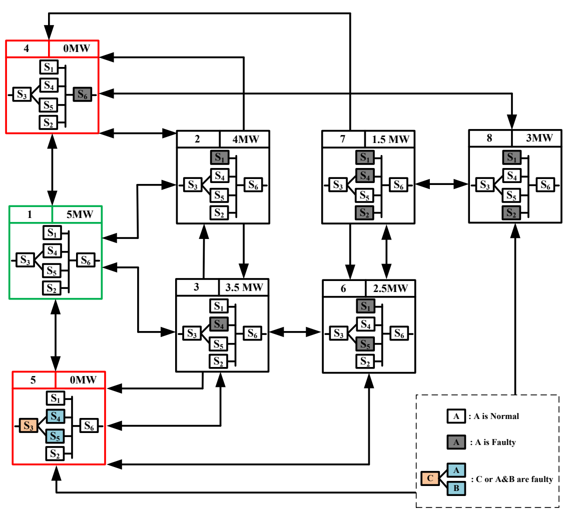

Fig. 5. State-space diagram for the dc S2S charging system

The calculated reliability indices for the both solutions are listed in Table IV.

TABLE IV
RELIABILITY COM PARISON BETWEEN AC AND DC SOLUTIONS

Reliability index	ac S2SC system	dc S2SC system
LOCE (charging break/yr)	2.98	2.02
DCE (charging break /yr)	64.63	62.95
MTTFF (yr)	9.77	13.49

It is obvious from the results shown in Table V that it is expected to lose approximately 3 and 2 charging breaks per year for the ac and dc solutions respectively. In other words, the dc charging system with the applied parameters in this paper, is more reliable than the ac solution by 33%. Moreover, the derated operation is more likely in the ac system because the expected derated charging in the ac solution is more than that for the dc charging by 1.68 charging breaks per year. It can be explained by the redundancy in the onboard transformer and rectifiers. Further, by comparing the calculated MTTFFs, it can be concluded that it takes in average 13.5 and 9.77 years for the dc and ac charging to not be able to carry out the charging mission due to the failure. All in all, the dc S2S charging system under study is resulted to be more reliable than its ac counterpart given based on the proposed reliability assessment method and applied parameters.

Since the S2S connection unit plays a key role in the S2SC system, its reliability data have a significant impact on the overall reliability. Further, the uncertainty of existing reliability data and the various technologies pose the need for a sensitivity analysis of the results regarding such unit failure and repair rate. In the following the sensititvity of the calculated reliability indices upon the ±50% change in the considered failure rate and repair rate of the S2S conneciton is analyzed in Fig. 6.

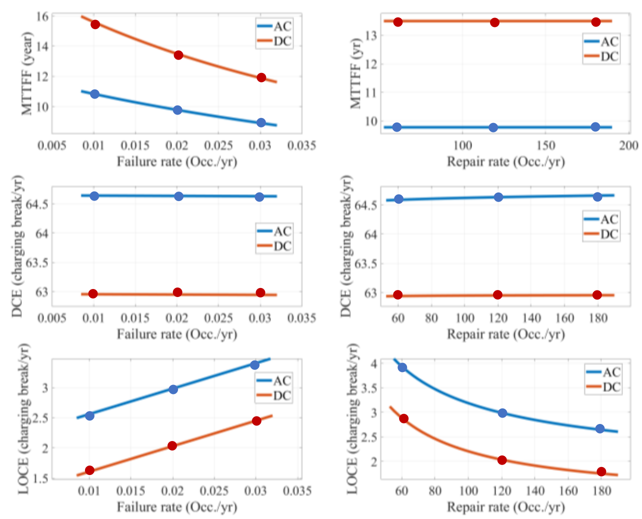

Fig. 6. Sensitivity analysis in terms of ±50% change in the S2S connection

(a) failure rate and (b) repair rate.

By considering the impact of the S2S connection failure and repair rate on the reliability in Fig. 6, the hereby remarks can be made. The MTTFF of the system is higly dependant on the failure rate of S2S connection such that by −50% and +50% chagne of such parameter, the MTTFF changes by +15.6% and −12% for the dc charging system as well as +10.3% and −9% for the ac charging solution. Although the impact of the change of the S2S failure rate on the DCE can be neglecterd, +50% chagne of S2S connection can increase the LOCE of the ac and dc charging solutions by approximately 0.5 charging breaks per year. Furthermore, Even though the impact of the repair rate of the S2S connection on the MTTFF and DCE is negligible, the 50% increase of this parameter can increase the LOCE of the both solutions by 0.4 charging per year.

Next, the sensitivity of the reliability data of the onshore battery units, which are composed by the battery packs and battery converters, on the calculated reliability indices are studied in the Fig. 7.

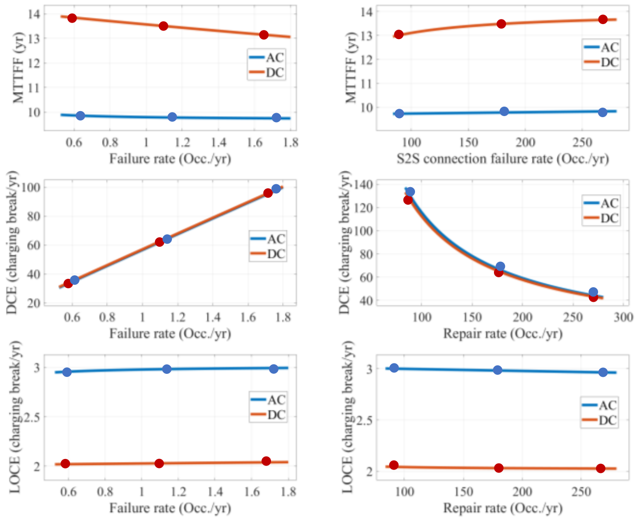

Fig. 7. Sensitivity analysis in terms of ±50% change in the onshore battery unit (a) failure rate and (b) repair rate.

It can be observed that the change in the failure and repair rate of the onshore battery units can affect the DCE. By increasing the failure rate the DCE of the both systems increases linearly. However, the impact of the change of such parameters on the LOCE is negligable.

In the end, the effect of a ±50% change in the repair rate of the transformer, rectfiers and the grid-side converters on the calculated reliability is anlyzed in the following.

According to the results depicted in Fig. 8, it can be concluded that the repair rate of the transformer can affect the LOCE. By increasign the repair rate of the transformers by 50%, the LOCE increases by 0.8 and 0.3 for the ac and dc solutions respecitvely. It can be explained by the fact that there are more transformers employed in the ac system. Additinally, the change of the repair rate of the rectifier for the ac solution and the grid-side converters for the dc solution can change the DCE. It is worth mentioning that the impact of the change in the repair rate on the DCE is 0.36 and 0.47 charging breaks per year for the 50% increase in the repair rate. Such difference can be explained by the fact that the nominal power of each rectifier and grid-side converters are 1.25MW and 1.5MW.

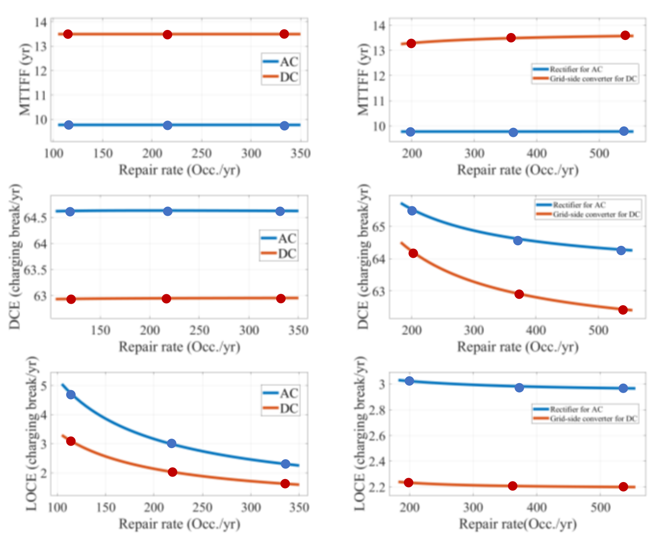

Fig. 8. Sensitivity analysis in terms of ±50% change in transformer repair rate and (b) converter repair rate.

CONCLUSION

In this paper, a reliability assessment analysis based on the failure of the critical components is carried out for two most common S2SC solutions, ac and dc charging. Such analysis is based on the Markov chain of the whole system. The failure rate of the critical units is calculated by the using RBD method for the included compoents. The Failure rate of the power electronics components is obtained by summing the failure rate of critcal parts inside the converters, e.g., IGBTs, diodes and capacitors. Such data is extracted from the reliability handbooks which are based on the historical data of failures. In the end, the state space model of the whole system is established in terms of the charging power capability and analyzed by the Markov chain method. Further, to address the multi-state nature of the S2SC systems, the application specific failure threshold and reliability indices such as LOCE and DCE are introduced.

Applying the proposed relability evaluation method for two case studies with ac and dc charging, it resulted that the dc solution under study is more reliable than the ac solution. The expected lost charging breaks for the dc solution is reduced by 33% compared to the ac system. Further the mean time to the first failure (loss of chargign break) is reduced by 27.5% for the dc S2SC system compared to the ac system. In the end, the sensitivity analysis for the failure rates and repair rates of the different units are given to compensate the uncertainity of the available reliability data.

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