Reliability and Safety Improvement of Emission-Free Ships: Systemic Reliability-Centered Maintenance

Mosayeb Afshari Igder, Mehdi Rafiei, Jalil Boudjadar, *Member, IEEE*, and Mohammad-Hassan Khooban, *Senior Member, IEEE*

***Abstract*— The power system of an all-electric ship (AES) establishes an independent microgrid using the distributed energy resources, energy storage devices, and power electronic converters. As a hybrid energy system (HES), the power system of an AES works as a unified system where each part can affect the reliability of the other parts. The systemic reliability centered maintenance (SRCM), which efficiently enhances the reliability and safety of the AES by identifying optimal maintenance tasks of the AES, is considered in this article to apply to the entire system. In order to calculate the reliability and optimal maintenance schedule, the Markov process and Enhanced JAYA (EJAYA) are utilized. A layer of protection analysis (LOPA), which is a risk management technique, is adopted to assess the safety of the system. A hybrid molten carbonate fuel cell, photovoltaic (PV), and lithium-ion battery are considered as energy sources of the AES. Based on two common standards, DNVGL-ST-0033 and DNVGL-ST-0373, the suggested maintenance planning method can be used in industrial applications. Eventually, in order to validate the proposed method, a model-in-the-loop real-time simulation using dSPACE is carried out. The obtained results show the applicability and efficiency of the proposed method for improving reliability and safety.**

***Index Terms*— All-electric ship (AES), layer of protection analysis (LOPA), reliability, safety, systemic reliability-centered maintenance (SRCM).**

I. Introduction

DUE to strong regulations on the increasing greenhouse gas emissions, ship industries are adopting new strategies to reduce emissions [1]–[4]. All-electric ships (AESs) are one of the most promising alternatives in this regard. The emission-free power generators and storage devices, such as fuel cells, photovoltaics (PVs), batteries, and supercapacitors, are used in these types of ships. Due to the novelty of this technology, no specific research has been done in the field of maintenance planning for the hybrid energy systems (HESs) of AESs. An efficient and optimal maintenance plan in this subject can noticeably improve the reliability and safety of the ship.

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Mosayeb Afshari Igder is with the Department of Electrical and Electronics Engineering, Shiraz University of Technology, Shiraz 84138, Iran (e-mail: m.afshari1990@gmail.com).

Mehdi Rafiei, Jalil Boudjadar, and Mohammad-Hassan Khooban are with the Department of Engineering, Aarhus University, 8200 Aarhus, Denmark (e-mail: rafiei@eng.au.dk; jalil@eng.au.dk; khooban@ieee.org).

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Hence, time-based maintenance that addresses the maintenance schedule by considering the failure rates and disregarding the condition of devices has been introduced [5], [6]. Alternatively, condition-based maintenance, which considers both importance and conditions of all equipment, has been used to approach the maintenance planning [7]–[10]. Reliability-centered maintenance (RCM), utilizing advantages of both time-based maintenance and condition-based maintenance, is one of the most appealing maintenance strategies providing the high reliability and low life cycle cost [11], [12]. Along with the maintenance plan, safety analysis plays an indispensable role in the AES. The safety analysis must be considered in studies to prevent or mitigate the potential hazard related to a failure cause in ship power systems. For this purpose, the failure mode and effect analysis (FMEA) of ship power systems needs to be identified to define the required safety integrity level (SIL) of the safety instrumented system (SIS) [13].

A. Literature Review

In recent years, some research projects have been conducted to examine the maintenance and safety analyses of the marine power system. In [14], the RCM, including the weighted aggregated product assessment and multicriteria decision-making, is used to obtain a maintenance plan for ship power systems. The hull maintenance approach is regarded to find the optimal maintenance plan for ship systems from an economic and environmental standpoint in [15]. The RCM analysis for the naval ship is investigated in [16]. The main goal of this article is to decrease the occurrence of equipment failure. Cicek *et al.* [17] utilize a risk-evaluation method for the preventive maintenance planning assessment based on the reliability of marine engine systems. In this article, the FMEA technique is used as a risk evaluation method. Liu and Frangopol [18] analyze the influence of the service life uncertainty on the lifetime maintenance planning of ship structure. The life-cycle cost formulation is applied for the probabilistic lifetime maintenance optimization. According to the abovementioned studies, most of the maintenance planning studies have not focused on AESs using HESs, and more importantly, none of them considers the impact of each component on the overall reliability, while here, by employing the systemic reliability-centered maintenance (SRCM), the influence of each component on the reliability of other parts and, consequently, the whole HES in an AES is modeled. Accordingly, a proper maintenance plan is chosen for this HES.

In [19], a HAZard and OPerability analysis technique using the experience of a team by comparing the consequence and frequency of the undesired events with analogous events in the past is employed to select a SIL. The safety layer matrix that utilizes the frequency, severity, and available independent protection layers (IPLs) to determine a SIL is represented in [20]. In [21], in order to guarantee the security and increase the safe operation of the ships, the HAZard and OPerability analysis method is utilized based on engineering and navigation subsystems. A finite discrete Markov model is suggested as a systematic technique in [22] to examine the safety of ships considering ships' failure, design, human errors, and environmental factors. In [23], a system theoretical process analysis is constructed to analyze the safety of a liquefied natural gas ship-to-ship transfer based on which accidents are regarded as control problems. So, these accidents are kept from happening by applying restrictions on the component behavior and interactions. The fuzzy cognitive-based method is used to model ship safety [24]. In this method, in order to transform input values and gain the intensity of interconnections, the fuzzy inference system and evidential reasoning are employed, respectively. In the abovementioned methods, not only the safety analysis is not considered for AESs using the HES but also they just evaluate the safety and do not improve the safety of marine vessels. Thus, there is a vivid gap in the literature for applying the SRCM to the AES in order to improve both reliability and safety.

B. Aims and Contributions

In this article, the SRCM that focuses on the entire HES is used to obtain appropriate maintenance tasks of the system's equipment in the AES. This systemic view of the RCM helps to consider the role of each piece of equipment on the entire energy system reliability and the impacts of each equipment's failures on the performance of other parts. To calculate the reliability and optimal maintenance schedule, the Markov process and Enhanced JAYA (EJAYA), considering the cost and reliability of the entire system as objectives of the optimization problem, are applied. Due to the utilization of the SRCM, the Markov model must consider the entire energy system states, which leads to new considerations and challenges. The layer of protection analysis (LOPA) that is a systematic and semiquantitative method is considered to evaluate the safety of the HES in the AES. In spite of the improvement of the reliability and cost, the proposed SRCM drastically improves the safety of the process by reducing the initiating cause frequency.

Hence, the main contributions of this article are expressed as follows:

1) implementation of the SRCM for the HES of a ship and development of the Markov diagram and the FMEA for this system to calculate the accurate maintenance tasks and improve the total reliability, safety, and cost of the proposed system;
2) applying the LOPA method to the ship's energy system to assess system safety.

The rest of this article is organized as follows. Section II presents the methodology used in the ship's hybrid energy, including the SRCM, Markov process, and LOPA. Section III describes the case study and implementation of the SRCM and Markov process on the HES of the AES. Section IV shows the numerical results of the case study. The conclusion is presented in Section V.

II. Methodology

A. Systemic Reliability-Centered Maintenance

RCM that is regarded as a corporate-level maintenance technique reaches the preventive scheduled maintenance plan. This results in acquiring an effective safety level for a device. Therefore, applying a certain maintenance plan for each system's component is the ultimate outcome.

The SRCM method, first introduced in [11], is implemented on the entire distance protection system. In this method, instead of dividing a device into its components and selecting the suitable maintenance task for each component, the entire system is divided into its equipment, and the selection of the most suitable maintenance tasks is done for each equipment. This systemic view leads to effectively consider the impact of each part on the system's reliability and also models the impacts of each part failure on the other parts. Due to the ship's HES as a unique system with a high impact on each other, herein, it is proposed to apply the SRCM method.

According to failures and failure sequences of each equipment, the proper maintenance plan is chosen in the first stage of the SRCM. Thus, for this purpose, the FMEA must be identified for all equipment at first. Subsequently, the appropriate maintenance plan is specified for each equipment based on the obtained FMEA and the RCM decision-making flowchart, which is portrayed in Fig. 1. Different maintenance plans, which can be chosen, are as follows:

1) scheduled on-condition task (SOT);
2) scheduled restoration task (SRT);
3) scheduled discard task (SDT);
4) scheduled failure-finding task (SFT);
5) redesign (ReD);
6) no scheduled task (NST);
7) combination of tasks (CoT).

By using the knowledge of multidisciplinary experts, suitable maintenance tasks are specified [25]. Next, the time period between the maintenance for all equipment is identified. The Markov process and optimization algorithms are used to take reliability and costs into account.

B. Markov Process

The Markov process that is a way to compute reliability is used in various studies for electrical systems [26], [27]. The first step in this approach is to identify all system states

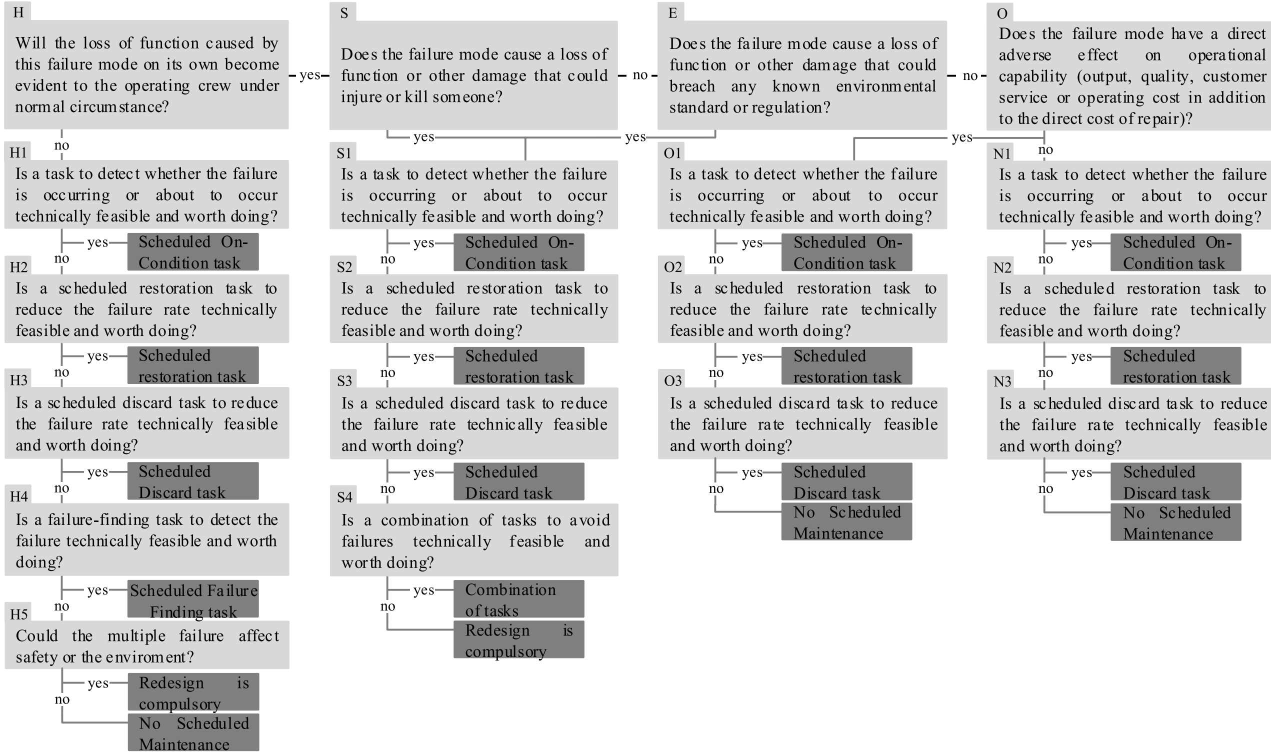

Fig. 1. Reliability-centered maintenance decision-making flowchart.

and routes between them. Afterward, transition coefficients of these routes are computed. The following equation is used to compute the coefficients of the transition from state A to state B:

$$d_{a-b} = \frac{\text{Times of transfer from state } A \text{ to state } B}{\text{Total time of being in state } A}. \quad (1)$$

The transition probability matrix (P) must be produced in order to compute the mean time to failure (MTTF), which indicates the system reliability index. The entry in mth row and nth column denotes the transition coefficient of the routes from state mth to state nth in the matrix P. To select entries of the main diagonal of matrix P, the summation of all entries of any row should be one. In order to generate the truncated probability matrix (Q), any rows and columns associated with nonfunctional states from matrix P should be eliminated. Afterward, the matrix M is computed as follows:

$$M = [I - Q]^{-1} \quad (2)$$

where I is an identity matrix. Herein, the evolutionary optimization algorithm is used to solve the maintenance problem due to the nonlinear characteristics of (2). If there are k states in the Markov model and l nonfunctional states, matrix M will be a matrix with dimension $(k-l) \times (k-l)$ and MTTF index with assuming that the system starts from the state i is computed as follows:

$$\text{MTTF}|_{\text{initial\_state}=i} = \sum_{j=1}^{k-l} m_{ij} \quad (3)$$

where m_{ij} is the entry of the ith row and jth column of the matrix M.

C. Layer of Protection Analysis

In order to figure out how an incident could contribute to a dangerous consequence, given that the IPL does not operate successfully, the LOPA is used. An IPL role is to prevent or reduce the potential consequence of an incident. Four IPLs, the process design, basic process control system (BPCS), alarms, and SIS, are used in the HES in the AES. The following equation represents the LOPA mathematically, in which the frequency of the undesired event is multiplied by the probabilities of each protection layer when it will not be able to operate:

$$\text{MEL}_i = F_i \times \text{PFD}_{i2} \times \cdots \times \text{PFD}_{il} \quad (4)$$

where MEL_i is a mitigated event likelihood (MEL). If the MEL is less than the maximum target likelihood, the number of IPLs is enough to meet the tolerable risk level. Otherwise, the other IPL should be added to reach the tolerable risk level. The maximum target likelihood varies from 10^{-8} to 10^{-2} based on the severity of the consequence of the failure mode. For example, if the severity is catastrophic, the maximum target likelihood is 10^{-8}. F_i is an initiating cause likelihood. An initiating event is a failure, which can result in dangerous occurrences if suitable IPLs are not regarded. How often failure can trigger off a hazardous consequence is called initiating cause likelihood. The frequency and consequence level descriptions are presented in [28]. PFD_{il} is a probability

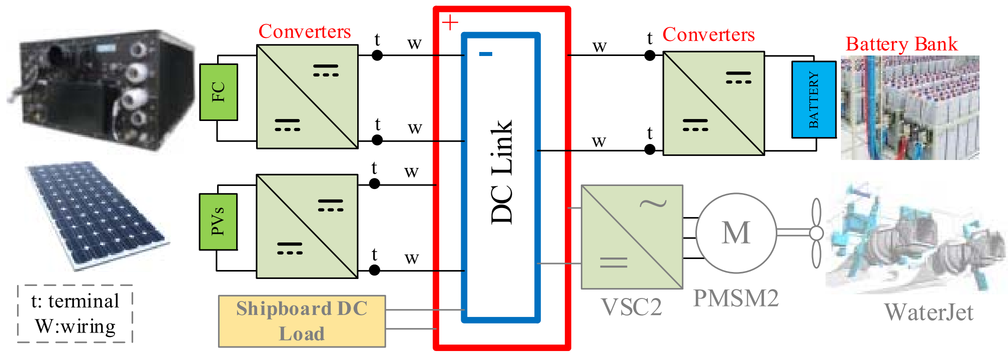

Fig. 2. HES circuit.

TABLE I
BOAT SPECIFICATIONS

Parameter	Value
Type	Passenger
Length (m)	20
Width (m)	8.2
Draft (m)	1.25
Displacement (t)	140
Fuel cells (kW)	3×100
Hydrogen tanks	6×125 kg at 500 bar
Photovoltaic (kWp)	2.7
Battery packs (kWh)	2×116
Electric propulsion motors (kW)	2×200

of failure on demand of the IPL i for the incident l. When the protection layer is asked to react against the undesired event but unable to show a reaction, the failure on demand happens. Based on the experience of the team, for example, the process design will act successfully once demanded 99 out of 100. It means that it fails to operate only one time for a hundred demands, then the PFD for process design will be 10^{-2}. The lower value of the PFD indicates that the IPL is more reliable. When a failure in the BPCS causes the initiating event, it cannot be considered as an IPL, so its PFD value will be one. The SIS is only used if other IPLs cannot decrease the MEL to less than the maximum target likelihood.

III. CASE STUDY AND IMPLEMENTATION

The HES in the AES comprises the molten carbonate fuel cell, PV, and lithium-ion battery. This system also has another component, such as a converter, terminal, and wiring, which has some specific failures. This HES is illustrated in Fig. 2.

A. Boat Specifications

In this work, the utilized boat is a bay tour ferry that transfers passengers for a one-day tour. The boat specifications using the HES are shown in Table I.

B. Failure Mode and Effect Analysis

As mentioned earlier, to apply the SRCM to the HES in the AES, first, the FMEA should be implemented to all equipment in the system. According to Fig. 2 and the experience of multidisciplinary experts in the construction and operation of the used equipment, all failure modes, and their effects on the entire equipment are indicated in Table II.

C. Systemic Reliability-Centered Maintenance

Based on the RCM decision-making flowchart, the proper maintenance plan must be chosen for all equipment after applying the FMEA to the HES and identifying all potential failure modes and their consequences. All information related to the failure modes and their consequences on the system is obtained from participants in hydrogen fuel cell and battery hybrid technology for marine application project [29]. The SRCM worksheet that is given in Table III indicates the outcomes of decisions made by experts in which “Y” and “N” are Yes and No to decision-making flowchart questions that are identified by their symbols [25]. According to Table III, to acquire an effective maintenance plan, the optimization parameters for the HES are expressed as follows:

1) schedule of the on-condition task for the fuel cells;
2) schedule of the failure-finding task for the fuel cells;
3) schedule of the on-condition task for the batteries;
4) schedule of the restoration task for the batteries;
5) schedule of the on-condition task for the PVs;
6) schedule of the restoration task for the PVs;
7) schedule of the on-condition task for the converters;
8) schedule of the on-condition task for the wiring/terminal;
9) schedule of the restoration task for the wiring/terminal.

D. Markov Process

After determining the type of maintenance tasks of the system’s equipment based on the SRCM method, to calculate the reliability of the system, the Markov diagram of the HES should be constructed (see Fig. 3). For this purpose, all the operation states and transition routes between them should be identified. The energy system has two general operation states, a normal operation state and a fault state that is known as a nonfunctional state, which are states 1 and 2 in the figure, respectively. In the next step, all the operation states of each piece of equipment are identified and created. Each type of equipment has one repair or replace state and one or more

TABLE II
FMEA OF THE SYSTEM

Equipment (Eq.)		Failure modes (F.M.)	Failure sequences
1. Fuel cell		a. Air closure	Cooling failure of the stack module, Fire/explosion, Unstable electrochemical reaction at the cathode
		b. Feed closure	Cooling failure of the stack module, Low power output in the stack module, Unstable electrochemical reaction at the anode
		c. H_2 BOG closure	Low electric voltage in the stack module
		d. Air increase	None
		e. Feed increase	Stack runaway
		f. H_2 BOG increase	Fire/explosion
		g. BPCS (basic process control system) failure	Stack runaway, Low electric voltage in the stack module, Fire/explosion, Low power output in the stack module
		h. Unheated stream flows (because of heat exchanger failure)	Electrolyte solidification of the molten carbonate, Low power output in the stack module
		i. Unstable electrochemical reaction	Low electric voltage in the stack module
		j. Air overflow (compressor failure)	None
		k. H_2 BOG overflow	Fire/explosion
		l. Feed overflow	Fire/explosion, Electrolyte volatilization of the molten carbonate
		m. Insufficient air flow	Unstable electrochemical reaction at the cathode, Fire/explosion
		n. Insufficient stream flows	Unstable electrochemical reaction in the stack module, Low power output in the stack module
		o. Psv-160/bv-160 blocked	Stack runaway, Fire/explosion
		p. Low electric current or voltage	Low power output in the stack module
		q. High electric current or voltage	Stack runaway
2. Battery	Anode and Cathode	a. Thickening of solid electrolyte interphase layer	Increased charge transfer resistance, Reduction of capacity, Reduction of power
		b. Particle fracture	Reduction of capacity, Reduction of power
		c. Reduced electrode porosity	Increased diffusion resistance, Reduction of capacity, Reduction of power
		d. Lithium plating and dendrite growth on anode surface	Short circuit
		e. Gas generation and bloating of cell casing	Reduction of capacity, Short-circuit
		f. Free copper particles or copper plating	Increased resistance, Reduction of power, Reduction of current density, Short-circuit
		g. Pitting corrosion of aluminum	Increased resistance, Reduction of power, Reduction of current density
	Separator	h. Hole in separator	High heat generation due to Joule heating, Bloating of cell casing, Drastic voltage reduction
		i. Closing of separator pores	Charge or discharge battery, Thermal runaway
	Lithium ions	j. Reduction in lithium ions	Reduction of capacity
		k. Thickening of solid electrolyte interphase layer	Reduction of capacity
	Electrolyte salt	l. Decrease in lithium salt concentration	Increased diffusion resistance
	Organic solvents	m. Gas generation and bloating of cell casing	Increased diffusion resistance, Thermal runaway
		n. Thickening of solid electrolyte interphase layer	Increased charge transfer resistance, Reduction of capacity, Reduction of power
	Casing	o. Internal short circuit between anode and cathode	High heat generation due to Joule heating, Bloating of cell casing, Drastic voltage reduction
3. PV		a. Interconnect, contact, or insulation failure	Arcing or open circuit
		b. Corrosion of cell metal (including hail impact, moisture, and delamination)	Open circuit, Reduced P_{pv}
		c. Severely cracked, fractured, mismatched cell (including hail impact)	Cell back-biasing, Overheating
		d. UV weathering	Material degradation
		e. Optical surface soiling	Temporary reduction of P_{pv} and I_{SC}
4. Convertors		a. Open circuit	Reduction of power
		b. Short circuit	Reduction of power, Fire
		c. Capacitor degradation	Decrease of power quality
		d. Inductor multiple-winding short	Decrease of power quality
		e. Current omission	Reduction of power
		f. Voltage omission	Reduction of power
5. Terminals and wiring		a. Chemical corrosion reaction	Arcing, Electric shock, Thermal runaway
		b. Thermal fatigue	Reduction of power
		c. Mechanical vibration fatigue	Reduction of power
		d. Connection problem	Reduction of power

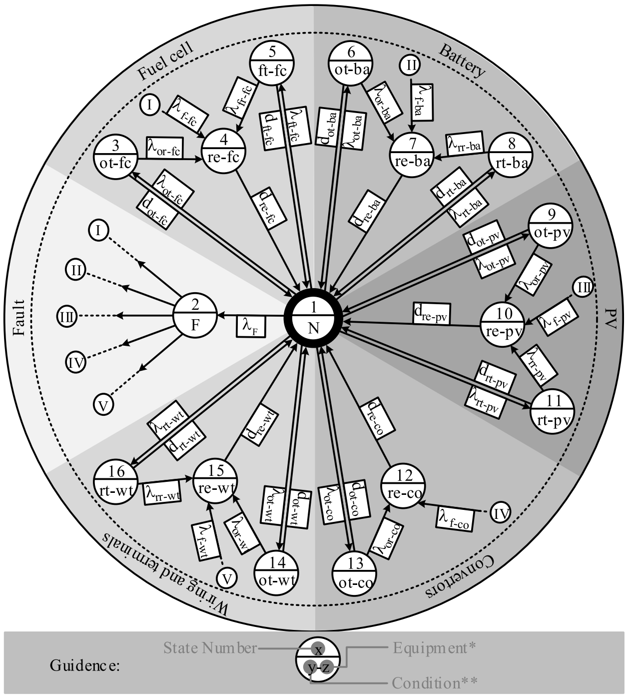

Fig. 3. Markov diagram of the HES. * fc: fuel cells. ba: Batteries. pv: PVs. co: converters. wt: wiring and terminals. ** N: normal operation state. F: total fault in the system. ot: on-condition task. rt: restoration task. ft: failure-finding task. re: repair or replace.

maintenance states based on the obtained results in Table III. Consider fuel cell as an example, and three operation states (states 3–5) are regarded. According to Table III, the fuel cell requires SOT and SFT tasks that are demonstrated with states 3 and 5 in the Markov diagram and one repair or replace state. This process is similarly applied to all other equipment to complete the Markov diagram. Then, all possible transition routes between these states are identified, and the coefficients of the transition related to them are calculated based on historical data and (1). Although the Markov diagram of the HES illustrates that each equipment has its specific maintenance and repair or replace states, the entire system has a unique normal operation and fault state. This structure effectively models the systemic behavior of the HES.

E. Optimization

According to chosen maintenance plans for each equipment and the drawn Markov diagram, the vector of optimization parameters is presented as follows:

$$X = \{\lambda_{ot-fc}, \lambda_{ft-fc}, \lambda_{ot-ba}, \lambda_{rt-ba}, \lambda_{ot-pv}, \lambda_{rt-pv}, \lambda_{ot-co}, \lambda_{ot-wt}, \lambda_{rt-wt}\}. \quad (5)$$

The objective functions of the optimization problem that are the maximizing reliability index (MTTF) and the minimizing costs are expressed as follows:

$$\begin{cases} F_1(X) = \max(\text{MTTF}) \\ F_2(X) = \min(\cos ts) = \min(\cos t_{\text{maintenance}} + \cos t_{\text{outage}}). \end{cases} \quad (6)$$

TABLE III

SRCM Worksheet of the System

Eq.	F.M.	Consequence evaluation				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default tasks			Selected tasks
		H	S	E	O				H4	H5	S4	
1	a	N				Y						SOT
	b	Y	N	N	Y	Y						SOT
	c	Y	N	N	Y	Y						SOT
	d	N				N	N	N	N	N		NST
	e	Y	N	Y		Y						SOT
	f	Y	Y			Y						SOT
	g	Y	Y			Y						SOT
	h	Y	N	N	Y	Y						SOT
	i	N				N	N	N	Y			SFT
	j	N				N	N	N	N	N		SOT
	k	Y	Y			Y						SOT
	l	Y	Y			Y						SOT
	m	N				Y						SOT
	n	Y	N	N	Y	Y						SOT
	o	Y	Y			Y						SOT
	p	Y	N	N	Y	Y						SOT
	q	Y	N	Y		Y						SOT
2	a	N				N	Y					SRT
	b	N				N	Y					SRT
	c	N				N	Y					SRT
	d	Y	Y			N	Y					SRT
	e	Y	N	N	Y	Y						SOT
	f	N				N	Y					SRT
	g	N				N	Y					SRT
	h	Y	Y			Y						SOT
	i	N				Y						SOT
	j	N				N	Y					SRT
	k	N				N	Y					SRT
	l	N				N	Y					SRT
	m	Y	N	N	Y	N	Y					SRT
	n	N				N	Y					SRT
	o	Y	Y			Y						SOT
3	a	Y	N	N	Y	Y						SOT
	b	Y	N	N	Y	N	Y					SRT
	c	Y	N	N	Y	N	Y					SRT
	d	N				N	Y					SRT
	e	Y	N	N	Y	N	Y					SRT
4	a	Y	N	N	Y	Y						SOT
	b	Y	Y				Y					SOT
	c	Y	N	N	Y	Y						SOT
	d	Y	N	N	Y	Y						SOT
	e	Y	N	N	Y	Y						SOT
	f	Y	N	N	Y	Y						SOT
5	a	Y	Y			N	N	N			N	NST
	b	Y	N	N	Y	N	Y					SRT
	c	Y	N	N	Y	N	Y					SRT
	d	N					Y					SOT

Thus, the problem is a two-objective (MTTF and cost) optimization. To address this multiobjective problem, the EJAYA [30] is used.

IV. Advantages of the Suggested Method

The purpose of this study is to develop suitable maintenance plans for a zero-emission ship using the HES to improve both reliability and safety. In the modeling of the suggested method, considerations have been made that have a noticeable role in its practical application.

1) The proposed SRCM concentrates on the whole energy system by determining the role of each equipment on

TABLE IV
CLASSES OF THE SIMULATOR FOR THE MACHINERY OPERATION AND LIQUID CARGO HANDLING BASED ON DNVGL-ST-0033 STANDARD [32]

Classes	Descriptions
Class A	A full mission simulator with capability to simulate "all machinery operations in engine control room and machinery spaces, by the use of the simulated operational panels in machinery spaces/ a complete liquid cargo handling system including all auxiliary systems and an online stability and stress calculation system."
Class B	A multi task simulator with capability to simulate "several machinery operations in engine control room and machinery spaces, but with limited use of the simulated operational panels in machinery spaces/ a complete liquid cargo handling system including auxiliary systems."
Class C	A limited task simulator with capability to simulate "some machinery operations in engine control room for procedural training/ the processes in a liquid cargo handling system."
Class S	A special tasks simulator with capability to simulate operation and/or maintenance of "particular machinery equipment, and/or defined engineering scenarios/ particular cargo handling equipment, and/or defined cargo handling scenarios."

the entire energy system reliability and the influence of each equipment's failures on the performance of other parts.

2) The proposed LOPA, which is regarded as a systematic strategy to examine the importance of potentially accidental scenarios in HES, can analyze the safety of the system with a conservative view.
3) The proposed method can be implemented for different configurations of the zero-emission ship, with different energy sources and ship typologies.

V. STANDARD ACCEPTANCE

For the purpose of the industrial application of the suggested maintenance planning approach, some prerequisite standards should be fulfilled. A Norwegian company called the DNV GL has allocated a research section to advance some regulations, standards, and services related to maritime, energy, oil, and gas industries. According to the notion of the suggested approach, employed hardware, and DNV GL information, the suggested maintenance planning approach should get by with two standards to be able to attend the marine industry. DNVGL-ST-0033 (Maritime simulator systems) [31] and DNVGL-ST-0373 (hardware-in-the-loop) [32] are regarded as mentioned standards. There are some regards to these two-mentioned standards related to the suggested method as follows.

A. DNVGL-ST-0033

This standard offers one specific means of performing the acceptance of the related maritime administration for the maritime simulator systems that are utilized for compulsory simulator-based training to show competency needed for the Standards of Training, Certification, and Watch keeping (STCW). According to the mentioned descriptions associated with the standard in Table IV (selected parts of the standard for "machinery operation" and "liquid cargo handling"), the suggested technique is classified as a simulator related to class S one which should be able to simulate a pragmatic environment for the selected STCW competence requirement mentioned in DNVGL-ST-0033.

In order to receive the standard acceptance according to the considered equipment and the class S simulator, first, the relationships between the subsystems and the machinery systems' dynamic behavior and its indispensable parameters should be duplicated in the simulation model. Then, all the elements must be simulated. Finally, the simulation design must contain equipment required for the fault rearranging and inserting during service at a suitable time.

B. DNVGL-ST-0373

The hardware-in-the-loop scrutiny that appraises the object system to offer unbiased evidence of the appropriate performance of the suggested system based on functional requirements suggests a standard document to the third-party certification related to the hardware-in-the-loop testing. This document is: 1) test package document of the hardware-in-the-loop (records mentioned in the DNVGL-ST-0373 text) and 2) report associated with the hardware-in-the-loop (records mentioned in the DNVGL-ST-0373 text).

VI. NUMERICAL RESULTS

In this section, the proposed method is applied to the HES in the all-electric ferry boat, the performance of the proposed method is evaluated on real-world data, and these data are gained from participants in hydrogen fuel cell and battery hybrid technology for marine application project [29]. According to the explanation mentioned in Section V, in order to implement the proposed maintenance planning method in industrial application, it is required to validate the performance of the proposed method by means of the hardware-in-the-loop method (DNVGL-ST-0373). Thus, real-time emulator-based dSPACE hardware is applied to validate the performance of the suggested method. The hardware-in-the-loop application of the suggested method is carried out using a real-time simulator (RTS), wherein both the Markov model and energy system are inserted in a single RTS. The whole system comprising the suggested Markov model is performed by means of the dSPACE Control Desk for the corroboration of hardware-in-the-loop, as demonstrated in Fig. 4(a). The modeling platform for the dSPACE is MATLAB/Simulink. The model-to-data workflow of the power system model under test is presented in Fig. 4(b). To make the Simulink model of the entire system comprising the proposed method well-suited with the dSPACE, the model is further modified and compiled with the assistance of MATLAB and the dSPACE Control Desk library. After modifying, the whole system model is divided into three subsystems as master, slave, and console for Control Desk simulation.

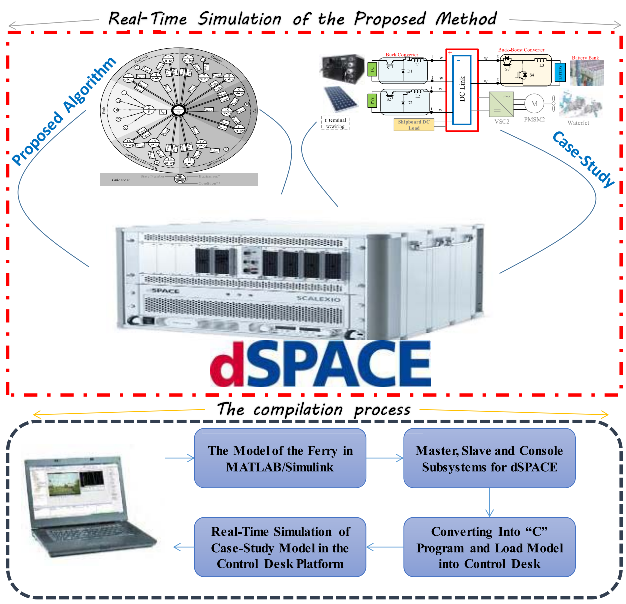

Fig. 4. Real-time setup-based dSPACE hardware.

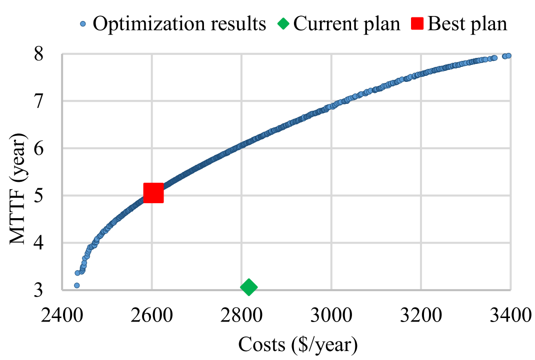

Fig. 5. Pareto line of the HES maintenance optimization.

In the master subsystem, the energy system model excluding the Markov model and the system circuit is maintained. The Markov model is maintained in the slave subsystem, and the visual output devices are maintained in the console subsystem. After compilation, the whole model comprising all three subsystems is transferred to the dSPACE server for converting to the equivalent "C" code of the model under test. Before the simulation, the solver time step is remained in fixed step mode, meaning that the time step in a real-time system is prespecified. Eventually, the general real-time setup is shown in Fig. 4. The coefficients of the Markov diagram should be calculated first. For this purpose, the historical maintenance data of the equipment are used. Then, the current MTTF index, utilizing the Markov equations, is computed. Afterward, the current cost values, including the outage cost and maintenance cost, are calculated in the form of the annual average.

In the following, the optimal maintenance plan is obtained by using the evolutionary optimization algorithm. For this purpose, the EJAYA is applied, and the obtained result is shown in Fig. 5. As seen from this figure, because of being two objectives problem, the results are in the form of the Pareto, and the horizontal and vertical axes indicate the cost and reliability index objectives, respectively. This figure comprises Pareto points, current operating point, and selected optimal point. The optimal point is chosen based on the expected reliability of the operator.

TABLE V
OBJECTIVE FUNCTIONS AND OPTIMIZATION PARAMETERS FOR CURRENT AND OPTIMAL SITUATION OF THE SYSTEM

Parameters	Current plan	Operating point 1	Operating point 2	Operating point 3	**Modified Plan**
λ_{ot-fc} (1/year)	0.33	0.75	0.23	0.61	**0.66**
λ_{ft-fc} (1/year)	0.33	0.8	0.37	0.61	**0.66**
λ_{ot-ba} (1/year)	0.33	0.84	0.54	0.7	**0.66**
λ_{rt-ba} (1/year)	0.5	0.99	1	0.99	**1**
λ_{ot-pv} (1/year)	0.33	0.62	0.37	0.51	**0.5**
λ_{rt-pv} (1/year)	0.5	0.85	0.48	0.68	**0.66**
λ_{ot-co} (1/year)	0.25	0.38	0.2	0.3	**0.33**
λ_{ot-wt} (1/year)	0.33	0.52	0.3	0.39	**0.4**
λ_{rt-wt} (1/year)	0.5	0.53	0.2	0.4	**0.4**
Total cost ($/year)	2816.1	2816.5	2432.8	2603.7	**2637.2**
MTTF (year)	3.1	6.1	3.1	5.1	**5.0**

A. Reliability Assessment

To examine the proposed method, the system's current operating condition is compared with three operating points in the Pareto point set, which are as follows.

1) *Operating Point 1:* Operating point with the nearest cost to the current operating condition.
2) *Operating Point 2:* Operating point with the nearest reliability to the current operating condition.
3) *Operating Point 3:* Ultimate optimal point (a compromise between the cost and reliability).

The operating point 1 is selected for the purpose to check whether the proposed method can guarantee the highest reliability or not once the same cost is spent. The operating point 2 in which the reliability value is the same for both the current method and selecting point is chosen to check whether the proposed method can provide this reliability at a lower cost or not.

Optimization results, including optimization parameters and objective values (reliability index and total cost), are presented in Table V. According to the obtained optimal decimal values of the maintenance schedule and irrationality and impossibility of applying them precisely, they must be replaced with modified ones [25], and consequently, the corresponding cost and reliability should be calculated. Based on Table V, the related analyses can be expressed as follows.

It can be seen in the column of the operating point 1 that the proposed method can identify a maintenance plan with the same cost as the current state and double improvement in the reliability. Also, operating point 2 that is a maintenance plan with the same reliability as the current plan indicates a 15% decline in the annual cost. Ultimately, the optimal maintenance plan proposed by the suggested method (modified plan) contributes to the 65% improvement in the reliability and 7% improvement in the annual cost of the system.

TABLE VI
COMPARISON OF THE PROPOSED SRCM WITH THE CONVENTIONAL RCM

Parameters	Current plan	RCM	Modified RCM	SRCM	**Modified SRCM**
λ_{ot-fc} (1/year)	0.33	0.51	0.5	0.61	**0.66**
λ_{ft-fc} (1/year)	0.33	0.38	0.4	0.61	**0.66**
λ_{ot-ba} (1/year)	0.33	0.68	0.66	0.7	**0.66**
λ_{rt-ba}(1/year)	0.5	0.71	0.66	0.99	**1**
λ_{ot-pv}(1/year)	0.33	0.29	0.33	0.51	**0.5**
λ_{rt-pv} (1/year)	0.5	0.68	0.66	0.68	**0.66**
λ_{ot-co} (1/year)	0.25	0.22	0.2	0.3	**0.33**
λ_{ot-wt} (1/year)	0.33	0.3	0.33	0.39	**0.4**
λ_{rt-wt} (1/year)	0.5	0.43	0.4	0.4	**0.4**
Total cost ($/year)	2816.1	2593.1	2580.8	2603.7	**2637.2**
MTTF (year)	3.1	4.2	4.3	5.1	**5.0**

TABLE VII
OPTIMIZATION ALGORITHMS' PERFORMANCE

Objective	Current plan	PSO	DE	ISCA	**EJAYA**
Total cost ($/year)	2816.1	2693.5	2681.9	2642.3	**2603.7**
MTTF (year)	3.1	4.8	4.8	5	**5.1**

In order to evaluate the effectiveness of the proposed SRCM in comparison to the conventional RCM method, the related results of optimal maintenance planning by both methods are presented in Table VI. In the RCM method, the Markov diagrams have been developed for each piece of equipment (e.g., fuel cells, batteries, and PV), and the optimal maintenance plans have been extracted for each of them regardless of their impacts on each other. Based on the presented results in Table VI, it can be seen that the SRCM method leads to a higher level of reliability. This better result is obtained by the consideration of the effects of different equipment on each other with the presented systemic view.

Furthermore, the efficacy of the suggested optimization algorithm is appraised. To this end, the suggested EJAYA is superseded by several other renowned evolutionary optimization algorithms comprising particle swarm optimization (PSO) [33], differential evolution (DE), and improved sine cosine algorithm (ISCA) [34]. As seen from Table VII, the suggested EJAYA results in the highest reliability index and lowest cost among all other optimization methods, which shows the efficacy of the suggested EJAYA.

According to the obtained results of new maintenance schedules, maintenance times are increased for some equipment, which means that these pieces of equipment have a high impact on reliability. On the other hand, the maintenance times of some equipment are decreased, indicating that these pieces of equipment have less effect on reliability. As a result, it can be seen that the proposed method (SRCM) in this article in comparison with the RCM, which only concentrates on a single device, not only models the impact of all the equipment effectively but also improves the reliability and cost of the entire system by optimizing the maintenance schedule.

B. Safety Assessment

LOPA that is implemented to examine the safety issue of the HES in the ferry boat has the following specific procedure.

1) Determine the cause and consequence of the incident and categorize the severity.
2) Appraise the frequency likelihood of each cause.
3) Identify IPLs for each cause and consequence set.
4) Assign the PFD for each IPL.
5) Compute the MLE for each cause and consequence set using (4).
6) Compare MLE to the maximum target likelihood to check whether the risk is in an acceptable zone or not.

All cause and consequence sets are illustrated in Table II. Table VIII comprises the severity of all consequences and their maximum target likelihood, the IPLs with their PFD, the initiation likelihood for both with the SRCM and without the SRCM, and MEL with the SRCM and without the SRCM to indicate the LOPA. After identifying the severity of the consequence, suitable IPLs that are shown with the symbol are determined by multidisciplinary experts to prevent or mitigate the consequence of the undesired event. The experts use all IPLs when the severity of the consequence is catastrophic. Otherwise, they use the process design and alarms to address the problem inherently. Furthermore, there is not any IPL for minor consequences because of the no injury and negligible impact on the environment, so the risk is at an acceptable level.

For the illustration, some of the cause and consequence sets' LOPA are considered. For Equipment 2 (Eq. 2) and Failure Mode f (F.M.f), free copper particles or copper plating in the battery lead to a catastrophic consequence, such as short circuit, consequently fire and explosion. The LOPA team determined four IPLs to prevent or reduce the consequence. The initiation likelihood without using the SRCM for this failure mode is 10^{-2}. The MEL for this cause and consequence set is computed, and its value is 10^{-8} that equals the maximum target likelihood of 10^{-8} for a catastrophic event. Although the obtained risk meets the tolerable risk level suggesting that there are enough IPLs, it is highly recommended that this MEL should be less than the maximum target likelihood. The SRCM that reduces the initiation cause likelihood can improve the safety of the system. In this example, initiation cause likelihood declines from 10^{-2} to 10^{-3}; consequently, MEL decreases from 10^{-8} to 10^{-9} that is now in the acceptable risk level. Another example is when there is a failure in the BPCS that also contributes to fire and explosion and is classified as a catastrophic event. Since the failure is in the BPCS, the LOPA team cannot use the BPCS as an IPL. The calculated MEL for this cause and the consequence set is 10^{-7}, which is more than the maximum target likelihood of 10^{-8}. As a result, the team needs to consider another IPL to bring this risk level to an acceptable zone. However, by applying the SRCM to the HES, the initiation cause of this failure falls from 10^{-2} to 10^{-3}, subsequently a decrease in MEL from 10^{-7} to 10^{-8}. Thus, this example again indicates how SRCM can enhance the safety level of the HES.

As it can be seen from Table VIII, risk levels related to many cause and consequence sets with catastrophic severity are declined by applying the SRCM to the system. Thus, SRCM is a practical option to reduce risk inherently. Also, the whole system risk level (WSRL) is computed by multiplying all MELs. The obtained result (with SRCM WSRL is 10^{-221} and

TABLE VIII
LOPA RESULTS OF THE HES

Eq.	F. M.	Severity*/ Maximum target likelihood	IPL PDF: Process Design 1E-2	IPL PDF: BPCS 1E-1	IPL PDF: Alarms 1E-1	IPL PDF: SIS 1E-2	Initiation likelihood Before Using SRCM (1/year)	**Initiation likelihood After Using SRCM (1/year)**	MEL Before Using SRCM (1/year)	**MEL After Using SRCM (1/year)**
1	a	CA/1E-8	✓	✓	✓	✓	1E-2	**1E-2**	1E-8	**1E-8**
	b	MO/1E-4	✓		✓		1E-2	**1E-2**	1E-5	**1E-5**
	c	MO/1E-4	✓		✓		1E-2	**1E-3**	1E-5	**1E-6**
	d	MI					1E-2	**1E-2**	-	**-**
	e	MO/1E-4	✓		✓		1E-2	**1E-2**	1E-5	**1E-5**
	f	CA/1E-8	✓	✓	✓	✓	1E-2	**1E-3**	1E-8	**1E-9**
	g	CA/1E-8	✓		✓	✓	1E-2	**1E-3**	1E-7	**1E-8**
	h	MO/1E-4	✓	✓	✓		1E-1	**1E-1**	1E-5	**1E-5**
	i	MO/1E-4	✓		✓		1E-2	**1E-2**	1E-5	**1E-5**
	j	MI					1E-1	**1E-1**	-	**-**
	k	CA/1E-8	✓	✓	✓	✓	1E-3	**1E-3**	1E-9	**1E-9**
	l	CA/1E-8	✓	✓	✓	✓	1E-2	**1E-2**	1E-8	**1E-8**
	m	CA/1E-8	✓	✓	✓	✓	1E-3	**1E-3**	1E-9	**1E-9**
	n	MO/1E-4	✓		✓		1E-3	**1E-3**	1E-6	**1E-6**
	o	CA/1E-8	✓	✓	✓	✓	1E-3	**1E-3**	1E-9	**1E-9**
	p	MO/1E-4	✓		✓		1E-2	**1E-2**	1E-5	**1E-5**
	q	MO/1E-4	✓		✓		1E-2	**1E-2**	1E-5	**1E-5**
2	a	MI					1E-1	**1E-1**	-	**-**
	b	MI					1E-2	**1E-2**	-	**-**
	c	MI					1E-2	**1E-2**	-	**-**
	d	CA/1E-8	✓	✓	✓	✓	1E-2	**1E-2**	1E-8	**1E-8**
	e	CA/1E-8	✓	✓	✓	✓	1E-2	**1E-3**	1E-8	**1E-9**
	f	CA/1E-8	✓	✓	✓	✓	1E-2	**1E-3**	1E-8	**1E-9**
	g	MO/1E-4	✓				1E-3	**1E-3**	1E-5	**1E-5**
	h	CA/1E-8	✓	✓	✓	✓	1E-3	**1E-3**	1E-9	**1E-9**
	i	CA/1E-8	✓	✓	✓	✓	1E-3	**1E-3**	1E-9	**1E-9**
	j	MI					1E-1	**1E-1**	-	**-**
	k	MI					1E-1	**1E-1**	-	**-**
	l	MI					1E-1	**1E-1**	-	**-**
	m	CA/1E-8	✓	✓	✓	✓	1E-2	**1E-3**	1E-8	**1E-9**
	n	MI					1E-1	**1E-1**	-	**-**
	o	CA/1E-8	✓	✓	✓	✓	1E-2	**1E-2**	1E-8	**1E-8**
3	a	MO/1E-4	✓		✓		1E-2	**1E-2**	1E-5	**1E-5**
	b	MI					1E-2	**1E-2**	-	**-**
	c	MO/1E-4	✓		✓		1E-2	**1E-3**	1E-5	**1E-6**
	d	MI					1E-3	**1E-3**	-	**-**
	e	MI					1E-1	**1E-1**	-	**-**
4	a	MO/1E-4	✓		✓		1E-2	**1E-2**	1E-5	**1E-5**
	b	CA/1E-8	✓	✓	✓	✓	1E-2	**1E-3**	1E-8	**1E-9**
	c	MI					1E-3	**1E-3**	-	**-**
	d	MI					1E-3	**1E-3**	-	**-**
	e	MO/1E-4	✓		✓		1E-2	**1E-2**	1E-5	**1E-5**
	f	MO/1E-4	✓		✓		1E-2	**1E-2**	1E-5	**1E-5**
5	a	CA/1E-8	✓	✓	✓	✓	1E-2	**1E-2**	1E-8	**1E-8**
	b	MO/1E-4	✓		✓		1E-2	**1E-2**	1E-5	**1E-5**
	c	MO/1E-4	✓		✓		1E-2	**1E-2**	1E-5	**1E-5**
	d	MI					1E-3	**1E-3**	-	**-**

* CA: Catastrophic, MO: Moderate, MI: Minor

without SRCM WSRL is 10^{-213}) demonstrates that the HES when uses the SRCM operates in a safer condition.

VII. CONCLUSION

In this article, a new maintenance strategy called SRCM based on which instead of considering a piece of equipment, the entire HES is considered to increase the reliability and safety levels and cost-effectiveness of the HES in the AES is proposed. The Markov process and EJAYA are proposed and adapted as tools to obtain reliability and optimize maintenance plan schedules. Moreover, the LOPA is investigated to analyze the safety of the system in the AES, which makes it possible for the HES users to observe the risks of their system, utilized IPLs, and where extra risk reduction is required to gain acceptable risk. The effectiveness of the proposed maintenance strategy is extensively assessed using real-world data of the HES. The suggested SRCM improves not only the reliability and cost but also the safety of the system, which makes it a completely applicable method to be used in the industrial environments. Future studies could be spent on utilizing other clean energy sources, such as wind power, and investigating their reliability and safety aspects when considered as power electric suppliers in AESs. Moreover, evaluating the propulsion system's reliability and safety in addition to energy suppliers could be another topic for future attempts to delve.

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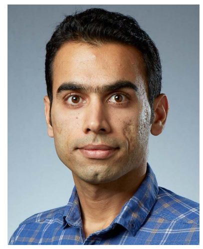
Mosayeb Afshari Igder was born in 1990. He received the M.S degree in electrical engineering from the Shiraz University of Technology, Shiraz, Iran, in 2016.

He has had a research collaboration with the Department of Electrical and Electronics Engineering, Shiraz University of Technology, since 2016. His research interests include power system operation, renewable energy, and marine power systems.



Mehdi Rafiei received the B.S. degree in electrical engineering from Yazd University, Yazd, Iran, in 2013, and the M.S. degree in power electrical engineering from the Shiraz University of Technology, Shiraz, Iran, in 2015.

He is currently a Research Assistant with Aarhus University, Aarhus, Denmark. His research interests include power systems, machine learning, energy management, and safety assessment.

Jalil Boudjadar (Member, IEEE) received the Ph.D. degree from the University of Toulouse, Toulouse, France, in December 2012.

He has been doing research for four years at different prestigious universities in Canada and Sweden. He is currently an Assistant Professor with the Department of Engineering, Aarhus University, Aarhus, Denmark. He is also a member of the DIGIT Research Centre, Aarhus University. His research is about the design, safety, and performance of embedded systems and control. He is also doing intensive research on energy-related performance and safety control for shipboard systems.

Mohammad-Hassan Khooban (Senior Member, IEEE) received the Ph.D. degree in power systems and electronics from the Shiraz University of Technology, Shiraz, Iran, in 2017.

From 2016 to 2017, he was a Research Assistant with Aalborg University, Aalborg, Denmark, where he conducted research on advanced control of microgrids and marine power systems. From 2017 to 2018, he was a Post-Doctoral Associate with Aalborg University. From 2019 to 2020, he was a Post-Doctoral Fellow with Aarhus University, Aarhus, Denmark, where he is currently an Assistant Professor and the Director of the Power Circuits and Systems Laboratory. He has authored or coauthored more than 170 publications on journals and international conferences and one book chapter. He holds one patent. His current research interests include control theory and application, power electronics, and its applications in power systems, industrial electronics, and renewable energy systems.

Dr. Khooban is also a Guest Editor/Associate Editor of the *Complexity* journal and the IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS. He also serves extensively as a reviewer for various IEEE/IET transactions and journals on power electronics, circuits, and control engineering.