Research Article

An analytical methodology for reliability assessment and failure analysis in distributed power system

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Abstract
Minimizing total system failure could improve the reliability of power network in order to optimize power system operation. In this way, reliability analysis has been proposed by researchers to tackle the mentioned problem. This paper investigates an analytical methodology for reliability assessment and failure analysis techniques in an actual distributed power system. We use reliability analysis to evaluate system design and gathering outage data in this paper. Modelling and simulation of our assumed system are implemented in electrical transient analyzer program (ETAP) software. The results of theoretical/practical reliability and failure analysis including mean time between failure, mean time to repair, availability, system average interruption frequency index, system average interruption duration index, consumer average interruption duration index, average service availability index, average service unavailability index, expected energy not supplied, expected interruption costs, and interrupted energy assessment rate are compared with the summary of reliability assessment simulation. The capability and effectiveness of reliability evaluation are demonstrated according to the simulation results through ETAP which obtained by applying it to this power system.

Keywords Reliability · Failure analysis · Power system · Distribution network

List of symbols

AC	Alternative current
DC	Direct current
Cust	Customer
f	Failure
h	Hour
i, j and k	Indices of elements
k	Kilo
n	Number of elements (i, k)
P.U.	Per unit
t	Time
kV	Kilo Volt
kWh	Kilo Watt hour
V	Volt
W	Watt
y	Year
$	Dollar
%	Per cent

1 Introduction

1.1 Background

According to opinion of most experts in the field of electrical engineering, overall, distributed power systems (DPSs) are considered under two general appearances: first, system security and second, system adequacy. The security of its power system includes reliability and availability [1]. Reliability assessment is considered as a primary importance in designing and planning in the DPSs to operate in an economical manner with minimal interruption of

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customer loads. System adequacy is related to total energy demand while system security is related to the dynamic response of the system, such as fault and failure [2]. Reliability analysis is relevant for any engineering system; some research findings confirm that the main objective for designing power and energy systems is reliable supply of load, under changing weather conditions, with the maximum reliability and minimum cost [3]. According to the Ref. [4], in studies of renewable energy for grid-connected system or stand-alone, reliability of different combination of renewable systems with different component specifications, configuration, available renewable sources, and load profile, can be solely assessed. The main objective of reliability evaluation in power systems is to provide qualitative analysis and indices in power supply performance for the operation and planning system. Besides, maintaining a high level of system security is one of the important aspects of power systems [5]. The structure of electric power systems can be changed considering environmental concerns, renewable energies, regulation of energy policy, economic issues, and consumer demands, for reliable, full efficiency, and secure electricity [6].

It is important to point out that the basic function of an electrical power system is to meet its customer's expectations while maintaining the acceptable levels of quality and continuity of supplies. In addition, the DPS is a vital link between the bulk power system and its customers. Transmission lines are required to transport the bulk electricity from the power stations to various locations to enhance supply reliability and achieve effective utilization of power system [7]. Unlike the reliability issue in the distribution system, the electricity deregulation is a new subject which changes the research orientation on the DPS.

1.2 Literature review

In the recent years, some researchers have proposed different methods to deal with the failure and reliability assessment in power networks and electric railway systems; for instance, in the Ref. [8], an improvement of reliability, predict temperature, and power output of the gas turbine by using time series is proposed. In the paper [9], a new reliability assessment model considering the Distributed Generation (DG) is presented. An analytical and practical approach to evaluate and analyze the reliability of network-connected PV systems is displayed in [10].

The authors of the paper [11] proposed reliability optimization method in automated distribution grids with probability customer interruption cost model in the presence of DG units. Authors in [12] presented the reliability analysis of electrical energy system. In the Ref. [13], an integrated incentive-based Demand Response (DR) and dynamic reconfiguration model is proposed, and in order to solve the proposed cost-reliability based framework, an Exchange Market Algorithm (EMA) was used. Authors of the references [14, 15] deal with risk management in metro structures; they presented a probabilistic approach of risk evaluation and economic assessment for solving transmission network expansion planning problems. Ref. [16] expanded some classification of load points by outage time from 4 types to 7 types and defined corresponding reliability parameters for different types. In the paper [17], reliability assessment of active distribution networks including islanding dynamics was presented, where the reliability analysis was performed by Non-Sequential Monte Carlo modelling, whereas the islanding process is assessed by a transient stability simulation with complete models of synchronous machine and its speed and voltage regulators. In [18], in order to model failure and reliability evaluation of power system substations, Stochastic Automata Networks (SANs) formalism is applied; authors in [19, 20] introduce new prediction models based on hybrid forecast engine for power market forecasting in power systems; and finally, the paper [21] proposed an integrated approach relies on cleverly cooperation of time rate-based Demand Response Program (DRP) and heterogeneous Distributed Energy Sources (DESs) deployment with goal to reliability-oriented planning of multiple Micro-Grids (MGs).

1.3 Motivation and main contribution

System average interruption frequency index (SAIFI) and System Average Interruption Duration Index (SAIDI) are typically used by utilities to statistically count the frequency and duration of customer load curtailments. In reliability evaluation at the planning stage, researchers typically use Expected Frequency of Load Curtailment (EFLC) and Loss of Load Expectation (LOLE). However, in this paper, we focus on the effectiveness of using ETAP for failure and reliability assessment. The results compromise large power system emanating from high voltage (H.V.), medium (M.V.), and low (L.V.) grid, equipment and loads. Besides, information which used for the assessment objective are in the form of single line diagrams of an actual DPS that starting from high voltage substation (HVS) and power transformer at the grid up to the loads. The results of theoretical and practical reliability and failure analysis such as MTBF, MTTR, Availability, SAIFI, SAIDI, CAIDI, ASAI, ASUI, ECOST, and IEAR are compared with the summary of reliability assessment simulation.

1.4 Paper structure

The rest of this paper is organized as follows: Sect. 2 introduces the fundamental theories of the proposed method.

Section 3 describes a case study analysis approach to our assumed actual DPS in detail. In Sect. 4, the results of reliability assessment are given; and finally, the conclusions are presented in Sect. 5.

2 Materials and method: reliability analysis

As mentioned in the literature review, several new methods have been presented to evaluate the failure and reliability of the DPSs in order to model and analyze cascading blackouts [22–24]. Availability and reliability are evaluated to determine the ability of components to accomplish an intended task [25, 26]. Authors in [1, 27] depicted some reliability and failure indices which were also cited for general application as follows:

2.1 Indices of distribution system reliability analysis

In order to evaluate the reliability and failure rate in power systems, the random variable is frequency time. Hence, the standard function which best fit can be the descriptive function as it has only time as the independent variable [25, 28]. Therefore, one of the critical factors for this function, which can be used, is known as the failure rate (λ). In addition, the reliability of the DPSs is usually measured in terms of several indices as defined below. According to [29], the failure rate (λ) is given by:

$$\lambda = \frac{Number\ of\ times\ which\ failure\ occured}{Number\ of\ unit - hours\ of\ operation} \tag{1}$$

The density function is given by:

$$f(t) = \lambda e^{-\lambda t} \tag{2}$$

The hazard rate is given as follows:

$$\lambda(t) = \frac{f(t)}{1 - f(t)} \tag{3}$$

The function of reliability distribution is given as follows:

$$R(t) = 1 - f(t) \tag{4}$$

Average failure rate at load point i, (λ) in (f/yr) is:

$$\lambda_i = \sum_{j \in N_e}^{n} \lambda_{i,j} \tag{5}$$

where $\lambda_{e,j}$ is the average failure rate of element j and N_e is the total number of the elements whose faults interrupt load point i. According to [27, 30], further reliability parameters are given by:

$$MTBF = \frac{Total\ system\ operating\ hours}{Number\ of\ failures} \tag{6}$$

$$MTTR = \frac{Total\ duration\ of\ outages}{Frequency\ of\ outage} \tag{7}$$

Here: (MTBF) is defined as the mean time between failure in (h), and (MTTR) is defined as the mean time to repair in (h). Availability of (A) in (p.u) is given by:

$$A = \frac{MTBF - MTTR}{MTBF} \tag{8}$$

The duration of annual outage at load point i, (U_i) in (h/y) is defined as:

$$U_i = \sum_{j \in N_e}^{n} \lambda_{i,j} r_{ij} \tag{9}$$

where r_{ij} is the duration of failure at load point i due to a failed element j. The duration of average outage at load point i, (r_i) in hour (h) is given as:

$$r_i = {}^{U_i}/_{\lambda_i} \tag{10}$$

The index of expected energy not supplied at load point i, ($EENS_i$) in (MWh/y) is given as:

$$EENS_i = P_i U_i \tag{11}$$

where P_i is defined as the average load of load point i. The index of expected interruption costs at load point i, ($ECOST_i$) in (k$/y) is defined as:

$$ECOST_i = P_i \sum_{j \in N_e}^{n} f\left(r_{ij}\right) \lambda_{ej} \tag{12}$$

where $f\left(r_{ij}\right)$ is the function of r.

The index of interrupted energy assessment rate at load point i, ($IEAR_i$) in ($/kWh) is defined as:

$$IEAR_i = \frac{ECOST_i}{EENS_i} \tag{13}$$

The index of Expected Energy Not Supplied of the system (EENS) in (MWh/y) is given as:

$$EENS = Total\ energy\ not\ supplied\ by\ the\ system = \sum EENS_i \tag{14}$$

The index of Expected interruption COST of the system (ECOST) in (k$/y) is given as:

$$ECOST = \sum ECOST_i \tag{15}$$

The index of interrupted energy assessment rate of the system (IEAR) in ($/kWh) is given as:

$$IEAR = \frac{ECOST}{EENS} \tag{16}$$

System average interruption duration index (SAIDI) in (h/cust.y) is given as:

$$SAIDI = \frac{Total\ duration\ in\ hours}{Number\ of\ customers\ supplied} = \frac{\sum U_i N_i}{\sum N_i} \quad (17)$$

System average interruption frequency index (SAIFI) in (f/cust.y) is given as:

$$SAIFI = \frac{Frequency\ of\ outages}{Number\ of\ customers\ supplied} = \frac{\sum \lambda_i N_i}{\sum N_i} \quad (18)$$

Consumer average interruption duration index (CAIDI) in (h/customer interruption) is given as:

$$CAIDI = \frac{Total\ duration\ in\ hours}{Number\ of\ customers\ affectd} = \frac{\sum U_i N_i}{\sum N_i \lambda_i} \quad (19)$$

Average service availability index (ASAI) and average service unavailability index (ASUI) in (p.u) are given as:

$$ASAI = \frac{Consumer\ hours\ service\ avilability}{Consumer\ hours\ service\ demand} \quad (20)$$

$$ASUI = 1 - ASAI \quad (21)$$

$$ASUI = \frac{Duration\ of\ outages\ in\ hours}{Total\ hours\ demanded} = \frac{\sum N_i * 8760 - \sum N_i U_i}{\sum N_i * 8760} \quad (22)$$

where in the Eq. (22), 8760 is defined as the number of hours in the calendar year. These information helps managers and utility experts at electric organizations to opt how to spend the money in order to improve reliability of the power systems by identifying the most effective reconfigurations and actions.

3 Study case of assumed DSP

According to the references [31, 32], our assumed DPS (power distribution network of Tehran metro) has supplied from three High Voltage Substations (HVS) and consists of 154 main feeders. All HVSs in this system comprise 63/20 kV and Gas Insulated Substation (GIS) type. Each station has two lighting and power substations (LPS). The LPSs supply electric power for equipment and loads. The LPS is located at each substation platform. Rectifier Substation (RS) converts AC to DC power to supply electric energy for traction motors of trains. Most of the stations have one RS. Each RS is capable to convert 20 kV (AC) to 750 V (DC) using diode rectifier's single line diagrams of the DPS in the form of ETAP are displayed in Fig. 1. As shown in Fig. 1, HVS are located on the top, LPS and loads at the middle, and RS and loads at the bottom.

4 Results of reliability analysis

Table 1 shows the number and failure rate of elements which used for reliability assessment. In Table 1, 225 is the total number of elements and 0.007 is the average amount of equipment failure rate (event per hour). Tables 2, 3 and 4 show the alteration of the number of outages, duration time, the indices of basic reliability, and indices of customer orientation over the course of the study (Between January and December, 2017) for each of the distribution feeders, power grid, lumped loads, and rectifiers.

The obtained results are the components outage rates that include scheduled, forced outages, and occurrences within the course of this study. In this study, we consider P_i = 10kW (the average load of load point i) for each of the elements and 5 $/kWh (sector interruption cost) in the numerical calculations; therefore, Table 5 shows the indices of computed annual cost between January and December, 2017. Due to the computation which followed from the statistical database, the behavior of the elements in terms of the duration time of outages, failure rate, average service availability, availability and expected interruption cost are shown in Figs. 2, 3, 4, 5 and 6. Finally, Table 6 shows the comparison between simulation results (SAIFI, SAIDI, CAIDI, ASAI, ASUI, EENS, ECOST, and IEAR) against the theoretical and practical values of the reliability analysis.

The comparison between monthly values of availability and ASAI is shown in the Fig. 7. The figures for Availability fluctuated from 0.9538 in September to 0.9843 in October; in addition, the amount of ASAI fluctuated between 0.9531 in September and 0.9838 in October 2018. As can be seen from the results of numerical analysis, in 2017, the monthly outage rate picked at 32 h in July whereas the figure for April experienced the lowest level at 17. The figures for monthly ASAI (P.U.) and monthly Availability (P.U.) have a very similar trend in values to each other. Besides, Fig. 6 shows that the amount of expected interruption cost reached a peak of 20,299.75 $ in May.

By comparing the calculated values and simulation result of the reliability analysis report using the ETAP software, it can be concluded that the results are very close together, indicating the accuracy of the calculations. According to the obtained results, better estimation can be presented of how the system functions in reliability for controlling and planning in power systems. Also, detailed reliability analysis can reduce unwanted problems and minimize outages and blackouts and thus, improves

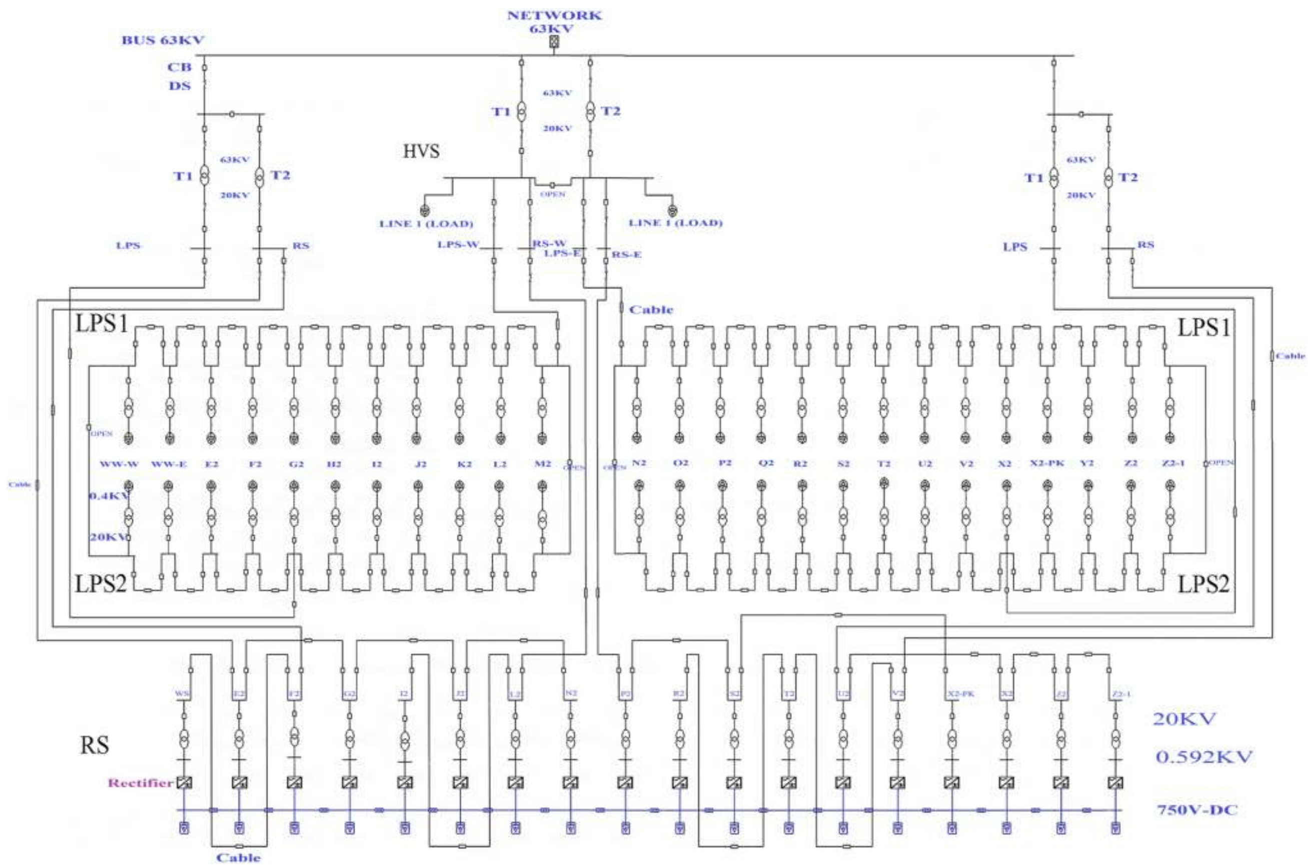

Fig. 1 Single-line diagram of the distributed power system

Table 1 The number and failure rate of elements

Element	Number	Failure rate (event/h)
Bus	154	0.001
Power grid	1	0.12
Lumped load	52	0.02
Rectifier	18	0.02
Total	225	0.007

power quality. In this study, the results show that the failure rate in the assumed distributed power system is too high.

5 Conclusion

In this paper, we described a case study of reliability calculations and failure analysis for an actual distributed power system. The results of theoretical reliability analysis of study including MTBF, MTTR, Availability, SAIFI, SAIDI, CAIDAI, ASAI, ASUI, EENS, ECOST and IEAR are compared with the summary of the reliability assessment simulation. Effectiveness of reliability evaluation is demonstrated according to the simulation. With the recent advancements in electrical engineering technology, efficient utilization of sources is now a need for reliable and secure DPS. In order to improve the reliability in power grids, the outages of distribution feeders occur on a daily basis owing to faults and suggestions made to minimize the system failure. Besides, in some places, sometimes, interruption of electricity occurred several times in a day which resulted in damage of elements and component. Hence, the reliability of the system has to be improved to keep valued customers satisfied.

Table 2 Summary report of frequency and duration of outages feeders, power grid, lumped loads and rectifiers between January and December, 2017

Month	Scheduled outage (SO)		Forced outage (FO)		Total outage (TO)	
	Freq.	Duration (h)	Freq.	Duration (h)	Freq.	Duration (h)
Jan	10	17	4	11	14	28
Feb	9	19	3	3	12	22
Mar	8	16	4	8	12	24
Apr	8	17	0	0	8	17
May	10	16	5	11	15	27
June	9	12	5	15	14	27
July	11	26	3	6	14	32
Aug	7	18	1	3	8	21
Sep	6	19	4	12	11	31
Oct	8	19	1	4	9	23
Nov	9	24	2	6	11	30
Dec	10	20	0	0	10	20
Total	105	223	32	79	138	302

Table 3 Computed basic reliability indices on feeders, power grid, lumped loads, and rectifiers between January and December, 2017

Month	Freq.	Outage (h)	Total (h)	Failure rate (event/h)	MTBF (h)	MTTR (h)	Availability (P.U.)
Jan	14	28	740	0.007	52.8571	2	0.9621
Feb	12	22	676	0.008	56.3333	1.8333	0.9675
Mar	12	24	740	0.006	61.6666	2	0.9675
Apr	8	17	724	0.006	90.5000	2.1250	0.9765
May	15	27	740	0.008	49.3333	1.8000	0.9634
June	14	27	724	0.007	51.7142	1.9285	0.9632
July	14	32	740	0.007	52.8571	2.2857	0.9583
Aug	8	21	748	0.008	93.5	2.625	0.9688
Sep	11	31	716	0.006	65.0909	3	0.9538
Oct	9	23	748	0.007	83.1111	2.5555	0.9843
Nov	11	30	716	0.007	56.0909	2.7272	0.9589
Dec	10	20	748	0.007	74.8	2	0.9732
Total	138	302	8760	0.007	58.8741	2.2266	0.9642

Table 4 Computed customer orientation indices between January and December, 2017

Month	Freq.	Outage (h)	Hours	Customer	SAIFI	SAIDI	CAIDI	ASAI	ASUI
Jan	14	28	740	225	0.06222	0.1244	2	0.9615	0.0385
Feb	12	22	676	225	0.05333	0.0977	1.8333	0.9660	0.034
Mar	12	24	740	225	0.05333	0.1066	2	0.9660	0.034
Apr	8	17	724	225	0.03555	0.0755	2.125	0.9758	0.0242
May	15	27	740	225	0.0666	0.1200	1.8	0.9620	0.038
June	14	27	724	225	0.0622	0.1200	1.928	0.9619	0.0381
July	14	32	740	225	0.0622	0.1422	2.2857	0.9575	0.0425
Aug	8	21	748	225	0.035	0.0933	2.625	0.9680	0.032
Sep	11	31	716	225	0.0488	0.1377	2.8181	0.9531	0.0469
Oct	9	23	748	225	0.0400	0.1022	2.5555	0.9838	0.0162
Nov	11	30	716	225	0.0488	0.1333	2.7272	0.9581	0.0419
Dec	10	20	748	225	0.0444	0.0888	2	0.9730	0.027
Total	138	302	8760	225	0.0496	0.1125	2.2456	0.9632	0.0358

Table 5 Computed annual cost indices between January and December, 2017

Month	Average interrupting rate (f/y)	Average outage duration (h)	Annual outage duration (h/y)	P (kW)	EENS (MWh/y)	ECOST ($/y)	IEAR ($/kWh)
Jan	13.9995	28	391.986	10	3.91986	19,599.3	5
Feb	11.9992	22	263.9824	10	2.63982	13,199.1	5
Mar	11.9992	24	287.9808	10	2.87980	14,399	5
Apr	7.9987	17	135.9779	10	1.35977	6798.85	5
May	14.985	27	404.595	10	4.04595	20,299.75	5
June	13.995	27	377.865	10	3.77865	18,893.25	5
July	13.995	32	447.84	10	4.4784	22,392	5
Aug	7.875	21	165.375	10	1.65375	8268.75	5
Sep	10.98	31	340.38	10	3.4038	17,019	5
Oct	9	23	207	10	2.07	10,350	5
Nov	10.98	30	329.4	10	3.294	16,470	5
Dec	9.99	20	199.8	10	1.998	9990	5
Total	137.7966	302	3552.1821	10	35.52182	177,679	5

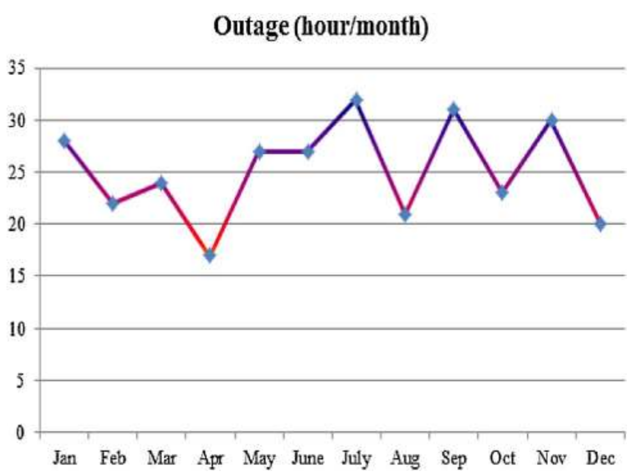

Fig. 2 Bar chart of monthly outage rate (hours per mount) in Year 2017

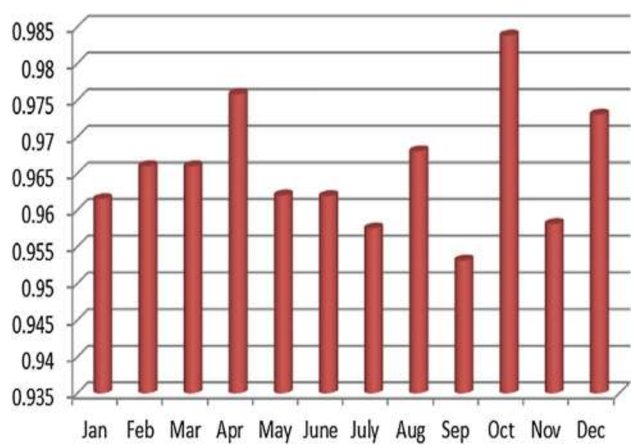

Fig. 4 Bar chart of monthly average service availability (P.U.) in Year 2017

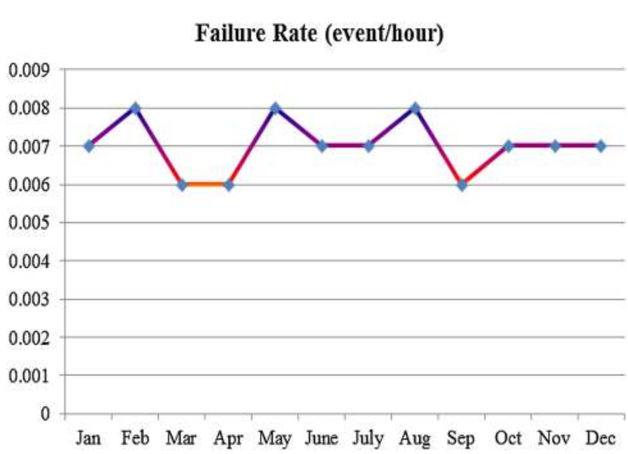

Fig. 3 Bar chart of monthly failure rate (event per hours) in Year 2017

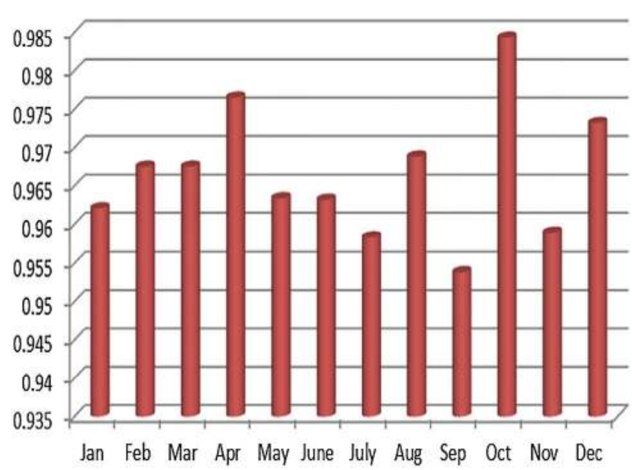

Fig. 5 Bar chart of monthly availability (P.U.) in Year 2017

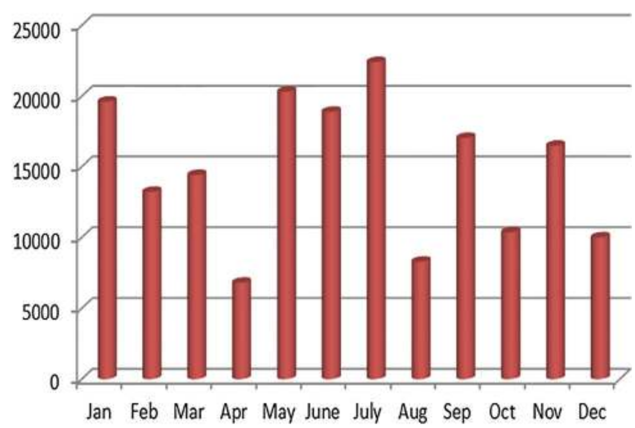

Fig. 6 Bar chart of expected interruption cost ($ per mount) in Year 2017

Table 6 Comparison between simulation and the theoretical values of the reliability analysis

ID type	Simulation results	Theoretical values
SAIFI	0.0497 (f/cust.y)	0.0496 (f/cust.y)
SAIDI	0.1126 (h/cust.y)	0.1125 (h/cust.y)
CAIDI	2.2456 (h/cust. intrpt)	2.2456 (h/cust. intrpt)
ASAI	0.9633 (p.u)	0.9632 (p.u)
ASUI	0.0357 (p.u)	0.0358 (p.u)
EENS	35.22182 (MWh/y)	35.2218 (MWh/y)
ECOST	177,651.6 ($/y)	177,679 ($/y)
IEAR	4.98 ($/kWh)	5 ($/kWh)

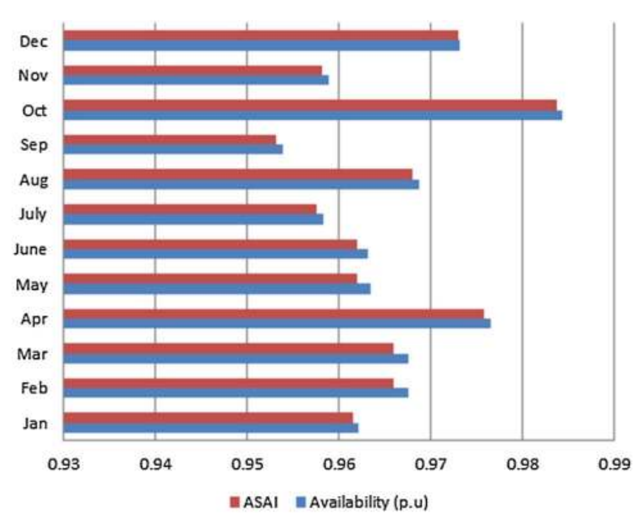

Fig. 7 Comparison between availability and ASAI in Year 2017

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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