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ORIGINAL RESEARCH

Tolerable random interruption duration based reliability estimation of stand alone hybrid renewable energy system by network reduction and sequential Monte Carlo simulation

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Abstract

This paper presents a novel tolerable random interruption duration (TRID) concept for estimation of reliability indices of stand-alone hybrid renewable energy system (SAHRES) during down time. This concept utilizes the ignorance of interruption duration if it is tolerable in event of failure. It uses a framework using network reduction technique and sequential Monte Carlo simulation (SMCS) suitable for present research whereas the solution in such cases is not feasible with analytical method. Thus reliability indices such as mean up time, mean down time, failure frequency, system failure rate, interruption duration and system unavailability are estimated using SMCS. Modelling aspects are considered for load, capacity, renewable energy system and TRID due to network outage. The impact of considering random tolerable interruption duration has been demonstrated on the reliability indices and case study is presented to show the effect of change of TRID on reliability indices. A sample SAHRES has been considered for the study.

1 | INTRODUCTION

Nowadays a small renewable energy system for example, photo voltaic panels, wind generator or small hydro system along with power conditioning equipments, battery, charge controller etc. for powering up the domestic and small business with no interconnection to grid is coming as an alternative to grid system in view of ecological concerns with economy termed as standalone system also providing viable solution to remote areas. Thus this stand alone hybrid renewable energy system (SAHRES) can be used for providing reliable power at reduced cost with independence from the grid to the meet the needs of consumer [1]. Thorough review of SAHRES presented as per configurations [1, 2], that discusses modern size optimization tactics for SAHRES. The potential of growth of hybrid renewable energy system (HRES) and evaluation at different geographical conditions in Moroccan affects the sizing issue as discussed in [3]. Raghuwanshi and Arya [4] presented present status of renewable energy system (RES) and suggestion for improvements to strengthen the power system with RES in India. Smart power control for SAHRES is addressed as key issue by Roselyn et al. [5]. Modelling of inverter and energy efficiency assessment of off grid system is analysed with distributed generation (DG) by Akpolat et al. [6]. Stability of RES integrated with power grid is

TABLE 1 Comparison of cited work and motivation for considering tolerable random interruption duration (TRID) for reliability assessment.

Sr. No.	Ref.	Research	Consideration of TRID
1	[11]	Design and economic analysis of SAHRES.	(x)
	[16]	Reliability analysis of distribution systems with photovoltaic generation with power flow simulator and a parallel Monte Carlo approach.	
2	[18]	Reliability evaluation of hybrid photovoltaic energy systems for rural electrification.	(x)
3	[19]	Reliability indices for stand-alone hybrid energy system.	(x)
4	[22]	Effects of distribution system reliability index distributions upon interruption cost/reliability worth estimates.	(x)
5	[23]	Probabilistic reliability indices evaluation of electrical distribution system.	(✓)
	[24]	Reliability indices for distribution systems using MCS.	(✓)
6	[25]	customer perceived reliability indices for active distribution systems.	(✓)
7	[26]	Hybrid stand alone energy systems optimization review.	(x)
	[27]	Recent advances for HRES.	
8	[28]	Reliability planning in transmission grid with RES.	(x)
	[29, 30]	Optimal design with hybrid DG.	
	[10]	Integration of RES for sustainable development.	
		Motivation-consideration of TRID for stand-alone hybrid renewable energy system reliability assessment.	

analysed by Harb and Tadeo [7]. Optimal sizing of a SAHRES is addressed in [8] and soft computing techniques are used to solve multi-objective optimization problem for HRES [9]. Integrated off-grid HRES optimization in view of sustainable development is executed [10].

Economic planning of HRES using a HOMER software is presented by Raghuwanshi and Arya [11]. Moreover a comparison of environmental aspects is presented for HRES and conventional system. Reliability analysis of distribution system including RES with use of MCS is presented [12–17]. This covers the adequacy assessment and economic analysis with RES integration.

Raghuwanshi and Arya [18, 19] diligently gave a road map for reliability evaluation of HRES for rural electrification and SAHRES for rural healthcare. L. Johnson [20] discussed maximum tolerable interruption duration concept for business impact analysis. Louit et al. [21] suggested a methodology for presenting optimal interval for down time repair in view of foremost maintenance actions required in distribution networks. Wojczynski and Billinton [22] gave interruption cost/reliability worth estimation analysis for distribution system. Systematic algorithms have been developed to demonstrate the effect of random repair time omission for MCS, this has been presented in [23, 24]. Systematic algorithms are used to demonstrate the random repair time omission with MCS for reliability assessment of distribution system and presented in [23–25]. Hybrid stand alone energy systems optimization review is presented in [26]. Most recent advances are addressed for HRES in [27]. Reliability planning in transmission grid with RES [28] and optimal design are discussed with hybrid DG in [29, 30]. Integration of RES for sustainable development is addressed in [10]. A tabular comparison is shown below in Table 1 for cited work and motivation of paper with consideration of random interruption duration concept for reliability assessment.

It is to be noted that a maiden attempt has been made in this paper to account random tolerable interruption duration for estimating reliability indices for stand-alone hybrid renewable energy system. None of the cited paper has consider this aspect as per Table 1. This is a novel contribution of this paper. For such cases reliability evaluation with analytical methods is not feasible therefore simulation based techniques such as Monte Carlo simulation is used [24]. Based on the discussion it is reflected that attempts are made for reliability indices evaluation for stand-alone hybrid RES but random interruption duration ignorance for reliability assessment for SAHRES is untouched which is taken as motivation to evaluate reliability indices using sequential Monte Carlo simulation based technique accounting TRID. The solution for such cases is not feasible with analytical method [24].

From the above discussion, it is revealed that the reliability assessment with SAHRES is becoming one of the important aspects to strengthen power system and the consideration of random interruption duration is important and needs more attention for reliability assessment and statistics. Therefore reliability assessment turns into an essential requirement along with economical considerations. This reliability assessment requires appropriate modelling of various components for example, PV generator, DC to DC converter, charge controller, battery, electronics switch as an integral part of SAHRES. This system when integrated with diesel generator with changeover switch known as SAHRES. It requires statistical data for reliability analysis and appropriate modelling. Also sometimes supply interruption is also not significant if it is tolerable in view of other alternative or emergency supply availability, and thus one can ignore the down time if interruption duration is tolerable. Thus this aspect of TRID in the reliability assessment becomes one of the important concerns and needs appropriate modelling of components and a detailed process to assess reliability analysis for SAHRES.

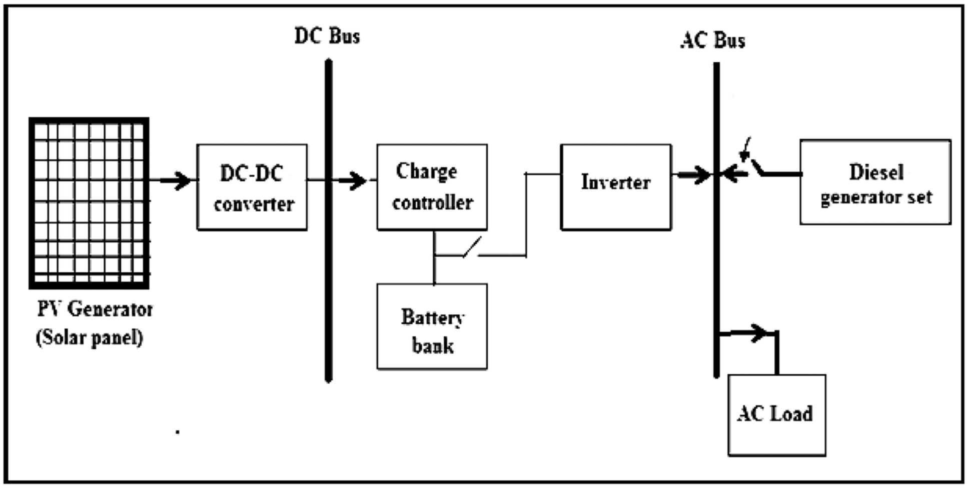

FIGURE 1 Stand alone hybrid renewable energy system.

Therefore the basic objectives of the paper as outcome will be:

(1) Reliability assessment of SAHRES using network reduction technique.
(2) Implementation of sequential Monte Carlo simulation (SMCS) algorithm with and without consideration of tolerable random interruption duration (TRID).
(3) Impact of changing the reliability indices with change in TRID.

The outline of the paper is as follows: Section 1: Introductory part. Section 2: Modelling aspects of SAHRES. Section 3: Presents SMCS algorithm for evaluation of reliability indices with and without consideration of tolerable random interruption duration. Section 4: Result and discussions. Section 5: Conclusion.

2 | RELIABILITY MODELLING OF STAND-ALONE HYBRID RENEWABLE ENERGY SYSTEM (SAHRES)

Following aspects are considered for reliability assessment for SAHRES given as follows:

1. Network modelling of SAHRES
2. Load model
3. Capacity model
4. Model for tolerable random interruption duration (TRID) due to network outage

2.1 | Network modelling of SAHRES

Stand alone renewable energy system (SARES) is integrated with diesel generator along with change-over switch arrangement then termed as stand alone hybrid renewable energy system [19] is shown in Figure 1 to supply A.C. load. Various components of SARES such as PV generator, DC–DC converter, battery charge controller, battery bank, electronic switch and inverter are represented in series fashion on reliability network diagram as failure of a single components leads to failure of system.

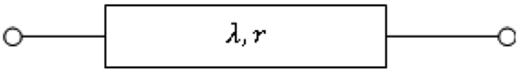

FIGURE 2 Reliability component model.

Diesel generator set (D-G) with changeover switch is integrated with SARES are represented on reliability network diagram in active parallel with SARES. Each components of SAHRES requires failure and repair rates and follows exponential density functions [19] as follows:

$$f_x(t) = \lambda e^{-\lambda t} \tag{1}$$

$$g_x(t) = \mu e^{-\mu t} \tag{2}$$

Comprehensive Markov modelling for unavailability is presented based on the time dependency.

$$U = (\lambda/(\lambda+\mu))(1-e^{-(\lambda+\mu)t})$$

And Markov model based unavailability of the component in long run [31] is given as:

$$U = \lambda/(\lambda+\mu) \tag{3}$$

Since $\mu \gg \lambda$

$$U = \frac{\lambda}{\mu} = \lambda r \text{ h/year} \tag{4}$$

Where $r = 1/\mu$ is repair time (h)
$\lambda =$ failure rate (/year)

Thus a single reliability component model is represented in Figure 2.

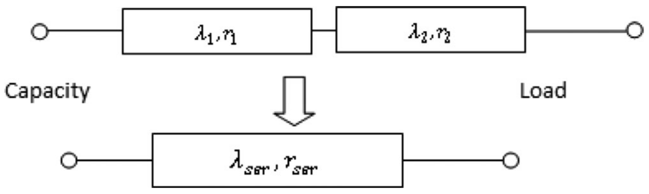

FIGURE 3 Series reliability network reduction model.

Based on the above components information the other reliability modelling aspects are considered given as follows for reliability evaluation using network reduction.

2.2 | Load and capacity model

One important aspect of reliability evaluation concerns about meeting the load by a supply system while the system is in operation. Depending on the type of system, such type of reliability evaluation requires probability of capacity of the system more than the load or probability of load exceeding the capacity. Important ingredients of such studies are suitable load model and capacity model. Then probability theory is applied to merge these two models to evaluate reliability or failure probability. Various loads may be encountered in practice. For electric equipment voltage may be a load (stress) depending on the magnitude of voltage applied the probability of failure may vary.

Load and capacity model may be assumed to be normally distributed.

$$f(l) = N\left(\bar{l}, \sigma_l^2\right)$$

$$f(c) = N\left(\bar{c}, \sigma_c^2\right)$$

$$p_s = 1 - p(l > c) = \emptyset(\beta)$$

where,

$$\beta = \frac{\bar{c} - \bar{l}}{\sqrt{\sigma_l^2 + \sigma_c^2}}$$

β is called safety factor ratio of reserve capacity to its standard deviation. For reliability planning it is an important parameter.

Time for which load exceeds the capacity

$$\mathrm{t} = \mathrm{T}_{\mathrm{up}} \cdot \left(1 - p_s\right)$$

T_{up} is up time due to network conditions. Hence net up time is

$$\mathrm{MUTN} = p_s \cdot \mathrm{T}_{\mathrm{up}} \tag{5}$$

2.3 | Series reduction formulae

The equivalent single component for series reliability network model is as shown in Figure 3 and reliability indices are evaluated as:

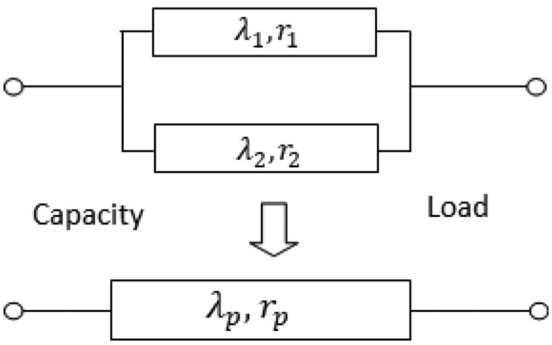

FIGURE 4 Parallel reliability network reduction model.

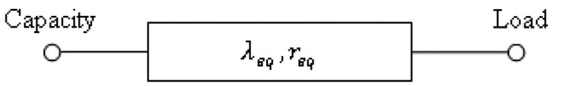

FIGURE 5 Equivalent hybrid renewable energy system reliability network model.

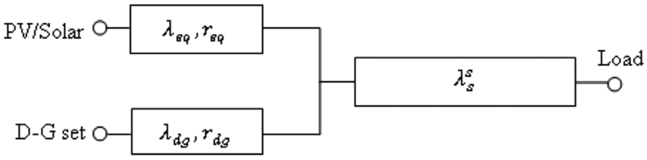

FIGURE 6 Hybrid renewable energy system reliability network model with switch and distributed generation set in standby mode.

$$\lambda_{\mathrm{ser}} = \sum \lambda_i \tag{6}$$

$$U_{\mathrm{ser}} = \sum \lambda_i \cdot r_i = \sum U_i \tag{7}$$

$$r_{\mathrm{ser}} = \frac{U_{\mathrm{ser}}}{\lambda_{\mathrm{ser}}} = \frac{\sum \lambda_i r_i}{\sum \lambda_i} \tag{8}$$

2.4 | Parallel reduction formulae

The equivalent single component for parallel reliability network model is as shown in Figure 4 and reliability indices are evaluated as

$$U_p = \lambda_1 r_1 \lambda_2 r_2 = \lambda_1 \lambda_2 r_1 r_2 / 8760 \tag{9}$$

If r_1 and r_2 are in h.

$$r_p = \frac{r_1 r_2}{r_1 + r_2} \tag{10}$$

$$\lambda_p = \frac{u_p}{r_p} = \lambda_1 \lambda_2 (r_1 + r_2)/8760 \tag{11}$$

Apply Equations (6) to (11) successively to reduce the hybrid renewable energy sources as a single component model shown in Figures 5 and 6.

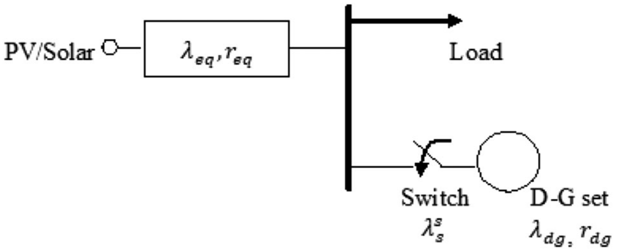

FIGURE 7 Hybrid renewable energy system reliability network model.

Modelling of switch if a diesel generator (DG) set is in standby

λ_s^s : failure rate of switch

s : insertion time of switch

Note: If PV/solar system is in active parallel then in λ_s^s, s will vanish.

2.5 | Representation of HRES

The HRES reliability network model is shown in Figure 7 as given below.

λ_{dg}, r_{dg} are the failure and repair rates of D-G set

2.6 | Modelling of tolerable random interruption duration

Some random interruption duration is always tolerable depending on the nature of load and alternative sources available in each consumer houses. If the load is irrigation load then also certain hours of load interruption duration may be tolerated. Assuming the tolerable random interruption duration [23] is normally distributed around some mean given as:

$$\Psi(to) = N(\bar{t}, {\sigma_t}^2) \tag{12}$$

A tolerable interruption duration sample may be generated.

3 | COMPUTATIONAL ALGORITHM FOR RELIABILITY ASSESSMENT FOR SAHRES USING SMCS WITH AND WITHOUT CONSIDERATION OF TRID

Step 1: Input data load model capacity model failure rate and repair time of each component of RES Interruption duration omission model: mean and variance.

Step 2: Obtain probability of success "ps" using load and capacity model using relation $\emptyset(\beta)$ disregarding network condition.

Step 3: Reduce the reliability network and obtain λ_{eq} and r_{eq}.

Step 4: Iteration count n=1.

Step 5: Generate samples for time to failure (UPT_i) and down time (DNT_i) using following relations:

$$UPT_i = -\frac{1}{\lambda_{eq}} \cdot \ln U_i \tag{13}$$

$$DNT_i = -r_{eq} \cdot \ln U_i' \tag{14}$$

U_i and U_i' are the random digits [0,1].

Step 6: Generate sample for tolerable random interruption duration from

$$\Psi_i = N_i(\bar{t}, {\sigma_t}^2).$$

Step 7: Obtain modified samples of up time and down time accounting load capacity model and tolerable interruption duration as follows: If

$$DNT_i \leq \Psi_i,$$

then

$$MDNT_i = 0$$

and

$$MUPT_i = p_s \bullet UPT_i + DNT_i,$$

otherwise

$$MDNT_i = DNT_i$$

and

$$MUPT_i = p_s \bullet UPT_i.$$

Step 8: Repeat step-5 to step-7 for NS times say 10,000. Step 9: Calculate modified mean up time and modified mean down time.

$$MMDNT = \frac{1}{NS}\sum_{i=1}^{NS} MDNT_i, \tag{15}$$

$$MMUPT = \frac{1}{NS}\sum_{i=1}^{NS} MUPT_i. \tag{16}$$

Step 10: Check for convergence calculate coefficient of variations 'α' for $MMUPT$ and $MMDNT$. If coefficient of variations for both is $\alpha \leq 0.04$, go to step-12.

Step 11: NS = NS+1000, and repeat from step-5.

Step 12: Calculate $MMUPT$ and $MMDNT$. Modified system failure rate

$$\hat{\lambda}_{sys} = \frac{1}{MMUPT} \text{ /year},$$

modified interruption duration

$$\hat{r}_{sys} = MMDNT \text{ h},$$

and modified system unavailability

$$\hat{U}_{sys} = \hat{\lambda}_{sys}\hat{r}_{sys}h \text{ /year}.$$

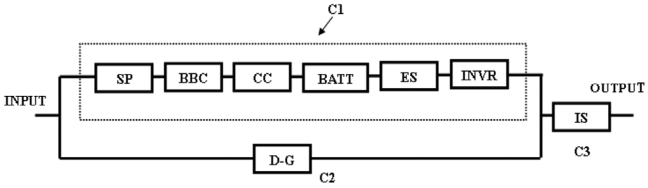

FIGURE 8 Reliability network for stand-alone hybrid renewable energy system with distributed generation set.

Calculation of coefficient of variation is evaluated as:

$$\sigma_{\mathrm{UPTi}} = \sqrt{\frac{1}{NS}\sum_{i=1}^{NS}\left[MUPT_i - MMUPT\right]^2}. \tag{17}$$

Standard deviation for modified mean up time

$$\hat{s}_{UPT} = \frac{\sigma_{UPTi}}{\sqrt{NS}}$$

and coefficient of variation for modified mean up time

$$\alpha_{UPT} = \frac{\hat{s}_{UPT}}{MMUPT}$$

$$\sigma_{DNT} = \sqrt{\frac{1}{NS}\sum_{i=1}^{NS}\left[MDNT_i - MMDNT\right]^2}. \tag{18}$$

Standard deviation for modified mean down time

$$\hat{s}_{DT} = \frac{\sigma_{DT}}{\sqrt{NS}} \tag{19}$$

and coefficient of variation for modified mean down time

$$\alpha_{DT} = \frac{\hat{s}_{DT}}{MMDNT}. \tag{20}$$

4 | RESULTS AND DISCUSSION

A sample stand alone hybrid renewable energy system [19] is considered for the study with normally distributed capacity with mean 100 KW, 10% standard deviation and normally distributed load is considered with mean 80 KW with 10% standard deviation. The reliability network for SAHRES is considered and given in Figure 8. The reliability data is given in Table 2 and used for reliability assessment. Firstly as per Section 2, the network reduction technique is used to evaluate reliability indices of SAHRES with the reliability data given in Table 2. The Figure 8 represents reliability network diagram of the SAHRES with diesel generator set (D-G) [18]. The interpretation of block nomenclature is given in Table 2.

TABLE 2 Reliability data for stand-alone hybrid renewable energy system (SAHRES) components [18].

Sr. No.		SAHRES components	Failure rate (/year)	Repair time (h)
1	Series system block components (C1)	· Solar panel (SP)	0.05	30
2		· Buck-Boost converter (BBC)	0.037	50
3		· Charge controller (CC)	0.095	50
4		· Battery (BATT)	0.08	24
5		· Electronic switch (ES)	0.03	50
6		· Inverter (INVR)	0.01	10
7	C2	Diesel generator (D-G)	0.5	72
8	C3	Insertion switch (IS)	0.01	5

TABLE 3 Reliability indices obtained from network reduction technique for stand-alone hybrid renewable energy system.

Sr. No.	Reliability indices obtained by network reduction technique	Obtained value
1	Failure rate series system (/year)	0.302
2	Unavailability series system (h/year)	11.62
3	Repair time series system (h)	38.4768
4	Failure rate parallel system (/year)	0.00190
5	Unavailability parallel system (h/year)	0.0477
6	Repair time parallel system (h)	25.0761
7	Failure rate system (/year)	0.0119
8	Unavailability system (h/year)	0.0978
9	Repair time system (h)	8.2116

The C1 block reliability indices are assessed using Section 2.3 considering components in series from Sr. no. 1–6 as per Table 2 using relation (3) to (5). Failure rate series system (/year) is obtained as 0.302, unavailability series system (h/year) is obtained as 11.62 and repair time series system (h) is evaluated as 38.4768.

The parallel equivalent reliability indices using Section 2.4 with considering block C1 and C2 is evaluated as failure rate parallel system (/year) is obtained as 0.00190, unavailability parallel system (h/year) is obtained as 0.0477 and repair time parallel system (h) is evaluated as 25.0761.

The equivalent network reliability indices are evaluated with consideration of C1, C2, C3 blocks as given in Table 2 with use of Sections 2.1–2.5 for SAHRES. The equivalent system failure rate λ_{eq} (/year) is obtained as 0.0119. Moreover the system unavailability (h/year) is obtained as 0.0978 and equivalent repair time of the system r_{eq} (h) is evaluated as 8.2116. The results using network reduction technique is shown in Table 3.

TABLE 4 Tolerable random interruption duration (TRID) model for stand-alone hybrid renewable energy system reliability assessment.

Sr. No.	Cases	TRID distribution (h)	Range (h)
1	Case-I	Mean=10, S.D.=2.5	(0,20)
2	Case-II	Mean=12, S.D.=3.0	(0,24)
3	Case-III	Mean=14, S.D.=3.5	(0,28)
4	Case-IV	Mean=16, S.D.=4.0	(0,32)
5	Case-V	Mean=18, S.D.=4.5	(0,36)

The reliability as per step-2 given in computational algorithm in Section 3, disregarding network condition is evaluated as 0.94082 based on capacity and load model given for SAHRES.

The TRID model as per Table 4 is utilized for reliability indices evaluation using SMCS based algorithm developed in Section 3. Case-I to case-V are considered for the study with tolerable random interruption duration (TRID) model of a given normal distribution model with a given mean and standard deviation (S.D.).

Table 5 shows the reliability indices obtained using consideration of TRID for case-I to case-V and when random interruption duration is not tolerable then for this case reliability indices obtained and expressed as case-0. A comparison of reliability indices is presented as case study from case-0 to case-V mentioned in Table 5 for SAHRES. The SMCS is used for obtaining MMUPT for all cases and comparison of convergence curve for MMUPT versus NS is illustrated in Figure 9 and comparison of MMDNT versus NS is illustrated in Figure 10. The statistics is obtained for mean of modified up time (MMUPT) and mean of modified down time (MMDNT). If random interruption duration is not tolerable then the MMUPT (h) is

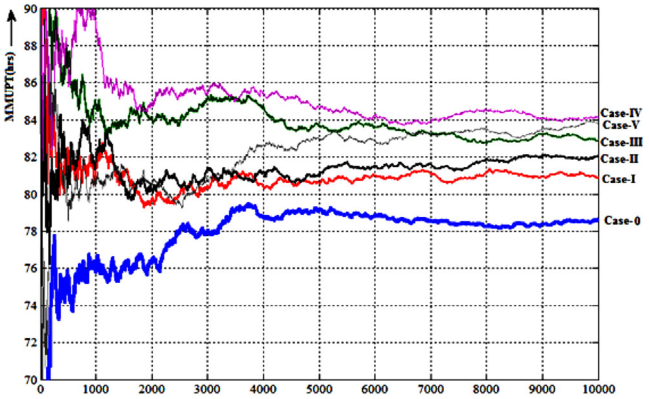

FIGURE 9 Comparison of mean of modified up time (MMUPT) versus NS for all cases.

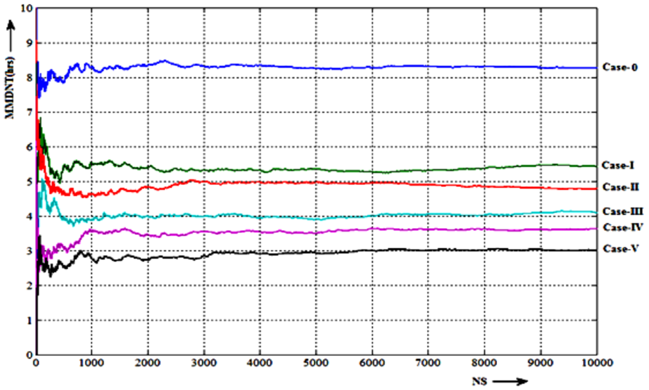

FIGURE 10 Comparison of mean of modified down time (MMDNT) versus NS for all cases.

TABLE 5 Reliability indices obtained with and without consideration of tolerable random interruption duration for stand-alone hybrid renewable energy system.

Sr. No.	Reliability indices	Case-0	Case-I	Case-II	Case-III	Case-IV	Case-V
1	MMUPT (h)	78.6318	80.8672	82.0424	82.8938	84.1325	83.7944
2	Median of MMUPT (h)	78.4292	80.8937	81.427	83.6324	84.5779	82.874
3	MMUPT range (h)	(3.9312, 80.7164)	(79.2319, 197.2661)	(44.5877, 104.6182)	(82.7301, 386.9889)	(81.6750, 158.8584)	(2.4746, 87.5148)
4	$\hat{s}_{UPT}$ (h)	0.7859	0.7907	0.7908	0.7764	0.7945	0.783
5	α_{UPT} (at Ns = 10,000)	0.01	0.0098	0.0096	0.0094	0.0094	0.0093
6	MMDNT (h)	8.2599	5.4274	4.78527	4.0907	3.6157	3.0103
7	Median of MMDNT (h)	8.2897	5.3388	4.8856	4.0145	3.5671	2.9364
8	MMDNT range (h)	(2.1653, 10.7569)	(0, 6.8434)	(2.7350, 10.9402)	(0, 8.3904)	(0, 7.4592)	(0, 3.4314)
9	$\hat{s}_{DNT}$ (h)	0.083	0.0929	0.0939	0.0916	0.0899	0.0863
10	α_{DNT} (at Ns = 10,000)	0.01	0.0171	0.0196	0.0224	0.0249	0.0287
11	Failure frequency	0.0115	0.0116	0.0115	0.0115	0.0114	0.0115
12	Modified system failure rate (/year)	0.0127	0.0124	0.0122	0.0121	0.0119	0.0119
13	Modified interruption duration (h)	8.2599	5.4274	4.6768	4.0907	3.6157	3.0103
14	Modified system unavailability	0.1049	0.0671	0.0571	0.0495	0.043	0.0358

Abbreviations: MMDNT, mean of modified down time; MMUPT, mean of modified up time.

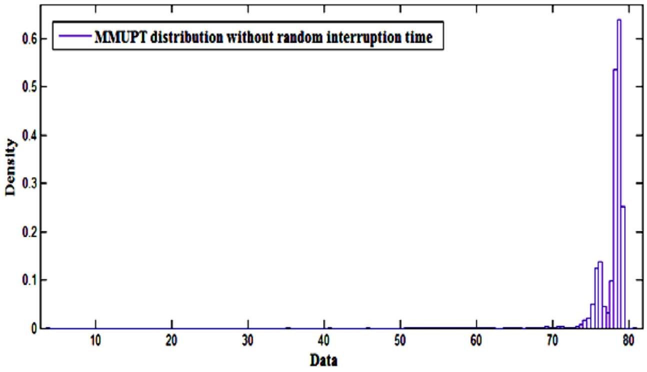

FIGURE 11 Comparison of mean of modified down time (MMDNT) versus NS for all cases.

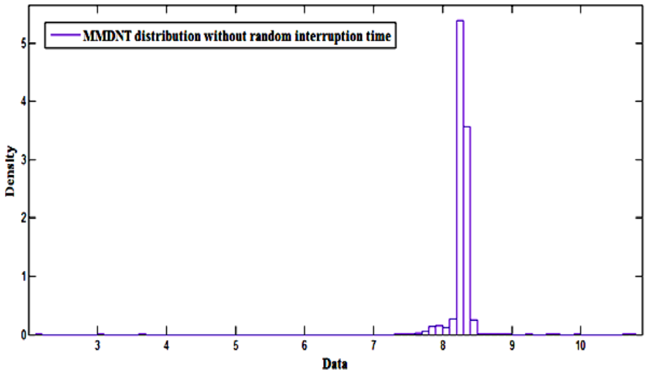

FIGURE 12 Mean of modified down time (MMDNT) distribution without random interruption time.

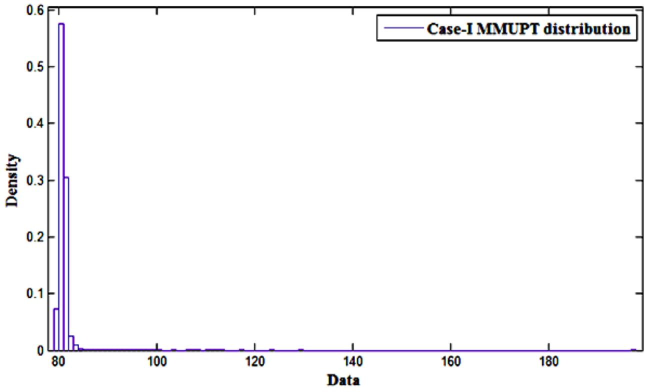

FIGURE 13 Case-I mean of modified up time (MMUPT) distribution.

obtained as 78.6318 whereas if TRID is increased from case-I to case-V then increasing trend of MMUPT is observed. The distribution curve without consideration of TRID is obtained for MMUPT and MMDNT are illustrated in Figure 11 and Figure 12 for case-0. The distribution curve with consideration of TRID obtained for MMUPT are illustrated in Figures 13–17. Moreover the distribution curve with consideration of TRID is obtained for MMDNT are illustrated in Figures 18–22.

Further the median based on the sample obtained for MMUPT for cases-0, II, V is observed less than the MMUPT

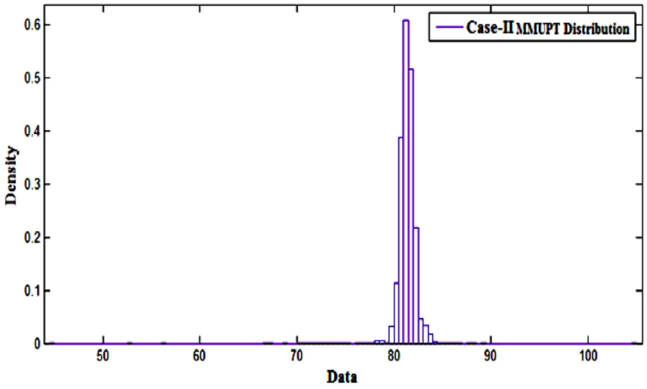

FIGURE 14 Case-II mean of modified up time (MMUPT) distribution.

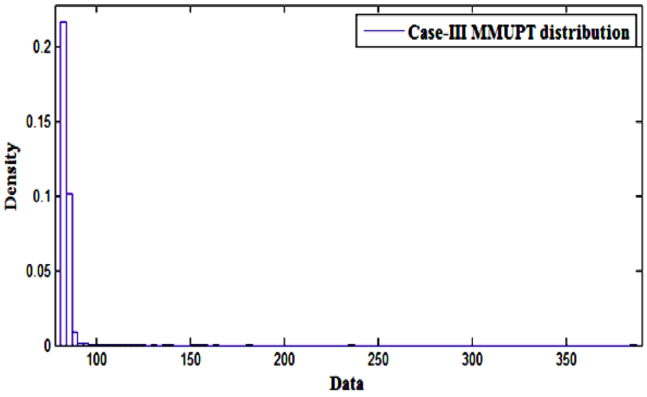

FIGURE 15 Case-III mean of modified up time (MMUPT) distribution.

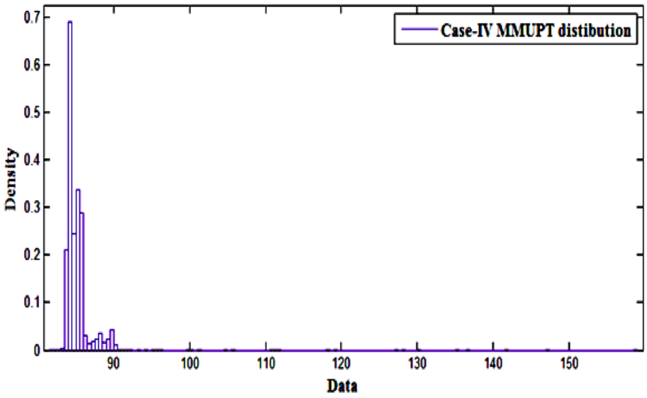

FIGURE 16 Case-IV mean of modified up time (MMUPT) distribution.

indicates that data for MMUPT is observed skewed right. Whereas for Cases-I, III, IV is observed more than the mean that indicates data for MMUPT is observed skewed left. Also MMUPT samples with minimum and maximum values are obtained for range in (h) and shown in Table 5. The $\hat{s}_{UPT}$ and α_{UPT} at NS=10,000 are obtained for all cases to observe estimate MMUPT.

If random interruption duration is not tolerable then the MMDNT (h) is obtained as 8.2599 given in case-0. Whereas if TRID is increased from case-I to case-V then decreasing trend

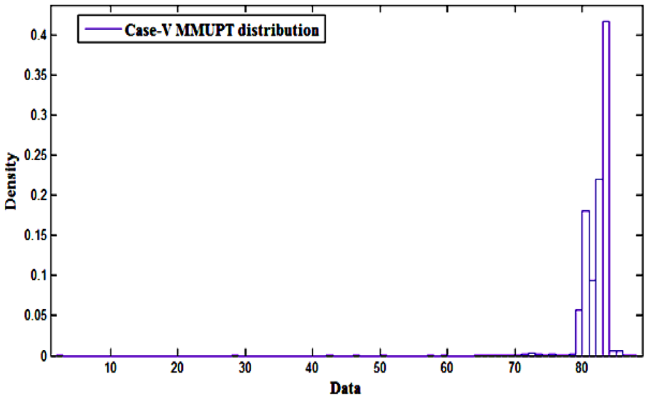

FIGURE 17 Case-V mean of modified up time (MMUPT) distribution.

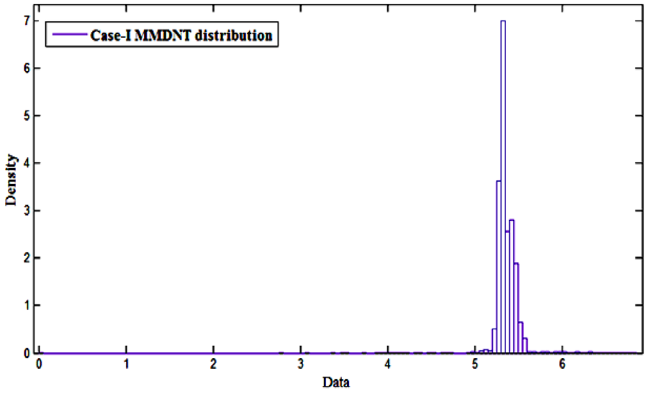

FIGURE 18 Case-I mean of modified down time (MMDNT) distribution.

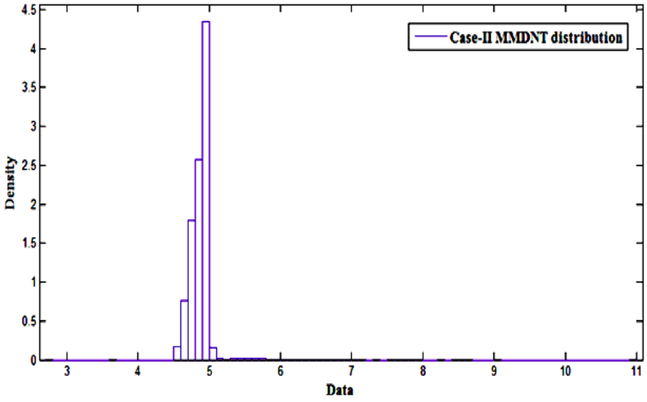

FIGURE 19 Case-II mean of modified down time (MMDNT) distribution.

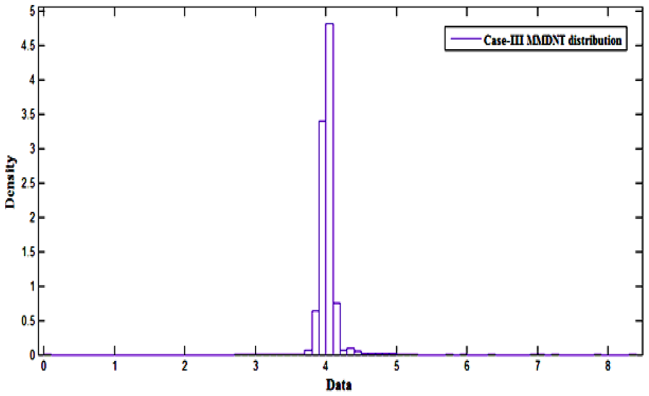

FIGURE 20 Case-III mean of modified down time (MMDNT) distribution.

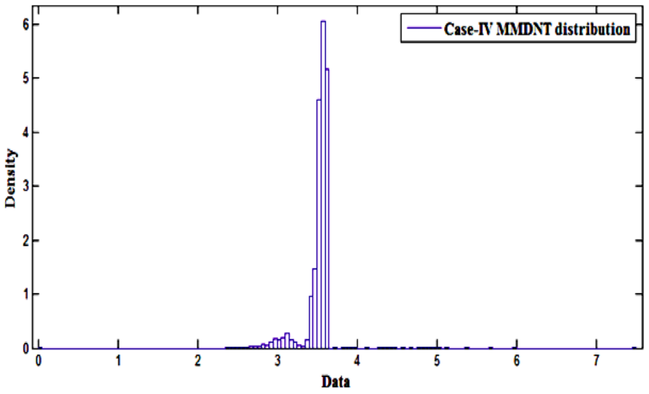

FIGURE 21 Case-IV mean of modified down time (MMDNT) distribution.

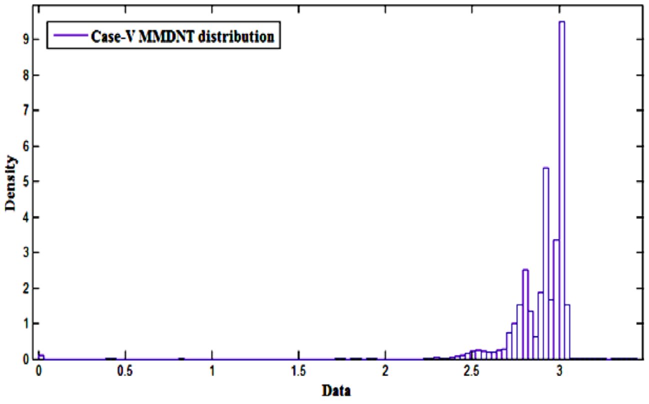

FIGURE 22 Comparison of mean of modified up time (MMUPT) with and without consideration of tolerable random interruption duration.

of MMDNT is observed from case-I to case-V. Moreover the median based on the sample obtained for MMDNT for cases-I, III, IV and V is observed less than the MMDNT indicates that data for MMDNT is observed skewed right. Whereas for Case-0, II is observed more than the mean that indicates data for MMDNT is observed skewed left. Also MMDNT samples with minimum and maximum values are obtained for range in (h) and shown in Table 5 for all cases. The $\hat{s}_{UPT}$ and α_{UPT} at $NS = 10{,}000$ are obtained for all cases to observe estimate MMUPT.

Comparison of MMUPT with and without consideration of TRID is shown in Figure 23. Further the comparison of MMDNT with and without consideration of TRID is shown in Figure 24.

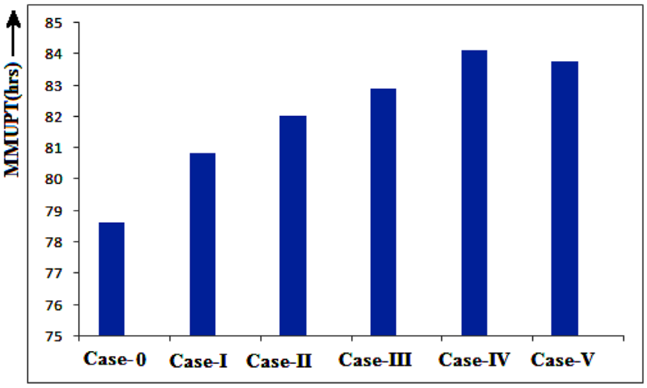

FIGURE 23 Case-V mean of modified down time (MMDNT) distribution.

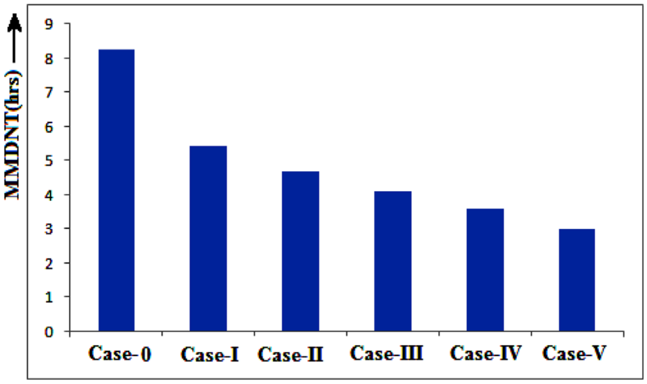

FIGURE 24 Comparison of modified failure frequency with and without consideration of tolerable random interruption duration.

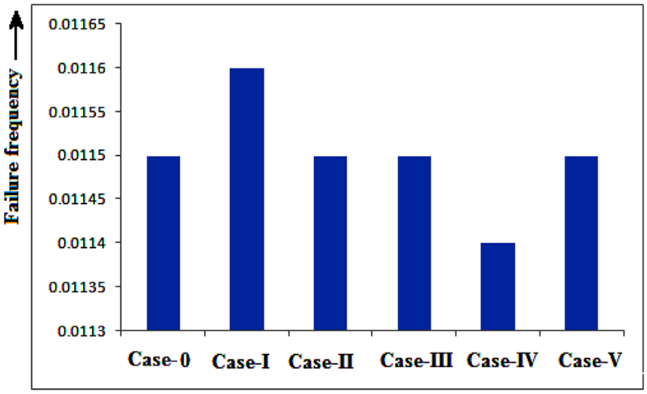

FIGURE 25 Comparison of modified system failure rate with and without consideration of tolerable random interruption duration.

Modified failure frequency is nearly observed same due to increase of MMUPT and decrease of MMDNT for almost all cases I to V comparing to case-0. Comparison of modified system failure frequency with and without consideration of TRID is shown in Figure 25.

Modified system failure rate (/year) is observed decreasing tendency comparing to case-0 with respect to increasing TRID from case-I to case-V and comparison is shown in Figure 26.

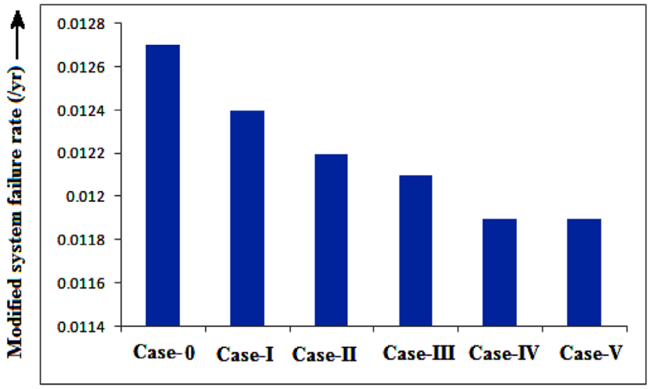

FIGURE 26 Comparison of modified system unavailability with and without consideration of tolerable random interruption duration.

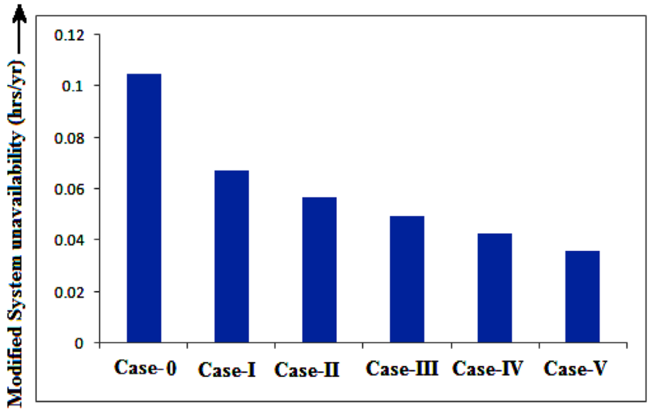

FIGURE 27 Comparison of modified system unavailability with and without consideration of tolerable random interruption duration.

Whereas modified interruption duration (h) is also observed to be decreasing trend comparing to case-0 with respect to increasing TRID from case-I to case-V. Same decreasing tradition is observed for modified system unavailability comparing to case-0 and presented as bar chart for comparison of modified system unavailability for all cases as shown in Figure 27.

Case-0 represents without TRID duration consideration. Case-I to Case-V represents with the consideration of TRID as per Table 5.

5 | CONCLUSION

Impact of tolerable random interruption duration on reliability indices for stand-alone hybrid renewable energy system (SAHRES) has been investigated. Improvement in reliability indices is obtained. This amounts that one may tolerate higher repair time and failure rate. This in fact will result in less maintenance costs on corrective and preventive maintenance. This in fact, cost optimization is our future agenda of research. With this objective an algorithm has been developed using SMCS which utilizes the reliability data as obtained from network reduction technique for evaluation of reliability indices as

MMUPT, MMDNT, modified system failure frequency, modified system failure rate and modified unavailability statistics. Moreover a case study has been presented to show the impact of variation of TRID on reliability indices for SAHRES from case-0 to case-V, it is observed that there is improvement in reliability indices with increase of TRID. This developed algorithm demonstrates the analysis with and without consideration of TRID for SAHRES. That can be utilized effectively for reliability improvement and planning for SAHRES.

NOMENCLATURE

σ_{DNT}	Coefficient of variation for MMDNT
σ_{UPTi}	Coefficient of variation for MMUPT
D-G	Diesel generator set
DG	Distributed generation
UPTi	DNTi ith up down time sample respectively
$\lambda_{\text{ser}}, \lambda_p$	Equivalent single component failure rate of series and parallel systems
r_{ser}, r_p	Equivalent single component repair time of series and parallel systems
U_{ser}, U_p	Equivalent single component unavailability of series and parallel systems
λ_{sw}	Failure rate of switch
λ_{dg}, r_{dg}	Failure rate, repair time of D-G set
HRES	Hybrid renewable energy system
MMUPT	MMDNT Modified MUPT, MUDNT
$\hat{r}_{sys}$	Modified interruption duration
$\hat{\lambda}_{sys}$	Modified system failure rate
$\hat{U}_{sys}$	Modified system unavailability
MUPT	MUDNT Mean UPT and DNT.
$N(\bar{c}, \sigma_c^2)$	Normally distributed capacity model of mean $\bar{c}$ and standard deviation σ_c
$N(\bar{l}, \sigma_l^2)$	Normally distributed load model of mean $\bar{l}$ and standard deviation σ_l
Ψ	Normally distributed tolerable random interruption duration of mean $\bar{t}$ and standard deviation σ_{t}
p_s	Probability of success
RES	Renewable energy system
SMCS	Sequential monte carlo simulation
SAHRES	Stand-alone hybrid renewable energy system
λ_{eq}, r_{eq}	System equivalent Failure rate and repair time
TRID	Tolerable random interruption duration
"Tup"	Up time due to network conditions

AUTHOR CONTRIBUTIONS

Atul S. Koshti: Conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing - original draft, writing - review and editing. Aanchal Verma: Conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing - original draft. Rajesh Arya: Investigation, methodology, resources, software, supervision, validation, visualization, writing - original draft, writing - review and editing. Chandrima Roy: Methodology, resources, software, supervision, validation, visualization, writing - original draft, writing - review and editing. Liladhar Arya: Resources, software, supervision, validation, visualization, writing - original draft, writing - review and editing. Sharat Chandra Choube: Investigation, methodology, resources, software, supervision, validation, visualization, writing - original draft, writing - review and editing. Baseem Khan: Conceptualization, data curation, formal analysis, investigation, resources, software, supervision, validation, visualization, writing - original draft, writing - review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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