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ORIGINAL STUDY

RAMD Analysis of Energy Sources for Water Pumping Application in Nigeria

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ABSTRACT

Energy supply is a key indicator of nation's development, hence, the need to shift attention towards its sustainability. In this study, a reliability, availability, maintainability and dependability-(RAMD)-based approach is utilized to determine subsystem components that impede sustainable water supply. Mathematical models using the Markovian birth-death process and transition diagrams are developed for each component/subsystem for the energy supply system. Chapman-Kolmogorov differential equations for each component are also formulated. The failure and repair time random variables are statistically independent and follow exponential distribution. Three different cases of energy supply system are considered. The components/subsystems are solar photovoltaic (PV), wind, diesel generator (DG), inverter, pump, and tank respectively. RAMD analysis result reveals that the subsystem pump is the most critical with minimum reliability of 0.548811636 after 10 months and availability of 0.92 for all cases. The results also reveal that at a period of 10 months, the reliability of the systems are 0.299778623 for case I, 0.284193481 for case II and 0.257385582 for case III respectively. Based on the numerical results, it can be inferred that case I is the best among other cases and subsystem pump is the most critical subsystem component. The findings of this work would be very useful for designers and maintenance engineers.

Keywords: Reliability, Availability, Maintainability, Dependability, Renewable energy, Water pumping system

1. Introduction

Reliable energy source is next to economic development of any nation, hence, RAMD (reliability, availability, maintainability, and dependability) [1] assessment of the system is extremely useful in identifying potential system redesigns to ensure a reliable energy supply. These amendments in system design is showcased by RAMD analysis, which would eventually lead to reliability enhancement [2]. RAMD analysis enables system designers to identify the most critical components or subsystems within the entire system that need an adequate maintenance strategy in order to improve their performance [3]. In order to ensure system reliability, professional engineers commonly use the RAMD analysis approach. Based on the above assertion, some researchers have carried out a few studies on RAMD analysis. Nuryanto et al. [4] did

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a study of RAMD analysis using an NKP fertilizer production line as a case study. The study aims to identify the most critical subsystem using RAMD analysis in the production line. Kumar et al. [5] established a RAMD mathematical framework for tube wells linked to subsurface irrigation pipelines. Gupta et al. [6], investigated the generator's performance in a steam turbine power plant using the RAMD technique. For each subsystem, mathematical models based on the Markovian birth-death process were developed. In addition, their study identified critical subsystem of the overall system plant. RAMD analysis of a cooling tower in a steam turbine was examined by Guptal et al. [7]. The cooling tower comprises six subsystems configured in series. obtaining the reliability metrics of an off-grid photovoltaic system and a comparison of four subsystems using RAMD methodology was done by Maihulla and Yusuf [8]. RAMD techniques were utilized for Computer Based Test (CBT) network system and tyre manufacturing rubber industry with five subsystems by Sanusi et al. [2] and Velmurugan et al. [9]. Application of RAMD in identifying the most critical component in a Sugar industry was conducted by Saini and Kumar [10]. Evaluation of a RAMD study in a series-parallel system was carried out by Danjuma et al. [11]. Maihulla et al. [12] used the recursive approach in assessing the RAMD analysis of a Reverse Osmosis (RO) machine with five subsystems. Their study also identified critical subsystem in the RO machine. Yusuf et al. [13] developed the RAMD mathematical analysis for a mirrored distributed system (Computer network topology) stationed in two locations. The system comprises of six series-parallel subsystems between the two locations. Using the Markovian process, the ordinary differential equations for each subsystem are obtained and then solved iteratively. Nurcahyo et al. [14], conducted RAMD analysis to determine the most crucial component of a cooling tower.

Using RAMD analysis, Gupta et al. developed a mathematical model for the steam turbine power plant's generator based on the Markovian birth-death process. Gupta et al. in references [15]. [16], investigated the reliability, availability, and maintainability of a grid-connected photovoltaic solar PV system with exponential distribution using a reliability block diagram (RBD).. The reliability assessment of the PV system considering the inverter thermal characteristics using fault tree theory was studied by [17]. Reliability, availability, and condition monitoring (RACM) of a grid-connected photovoltaic system with exponential probability distribution was investigated by the authors of [18]. Reliability of a large-scale photovoltaic system using fault tree approach was carried out in [19]. The long-term, reliability-based performance of a hybrid wind/solar power system, considering the reliability of the renewable energy source components, was investigated in [20]. A study, which examines the reliability of a photovoltaic system with the effect of $k - out - of - n$ components was conducted by [21]. The current study's objective is to determine which pumping system configuration is most suitable in terms of RAMD analysis and which subsystem component is the most critical. Each subsystem's RAMD is also determined.

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All the aforementioned studies require a lot of mathematical models, which are very complex in nature

All the aforementioned studies requires a lot of Mathematical models, which are very complex in nature. *The literature reveals that most of the work carried out so far focuses only on a particular system, without a comparative approach*. Hence, this study attempts to assess the RAMD of various energy sources, both conventional and non-conventional. The data required for the analysis of this work have been obtained from maintenance managers in the relevant industries in Nigeria.

2. Materials and methods

2.1. System description

Provision of water supply for agricultural and domestic purposes requires an energy source to power a submersible pump in order to achieve an output [22, 23]. In this study, renewable energy sources and the usual DG power sources are utilized for water pumping applications. The schematic block designs of the water pumping systems are given in Fig. 1 (Case I), Fig. 2 (Case II), and Fig. 3 (Case III), which demonstrate an efficient and simple design configuration to pump and distribute water.. The components used are solar panels, wind turbines, diesel generators, inverters, pump, and tank. All the subsystems otherwise referred to as components are arranged in a series configuration, with each subsystem having some internal redundancies as described by each component. The detailed descriptions of the subsystems are as follows:

2.1.1. Solar subsystem

There are two solar configurations that can supply the pump's energy requirements. The solar panel is made up of solar cells that convert sunlight into electricity, which is then used to power the submersible

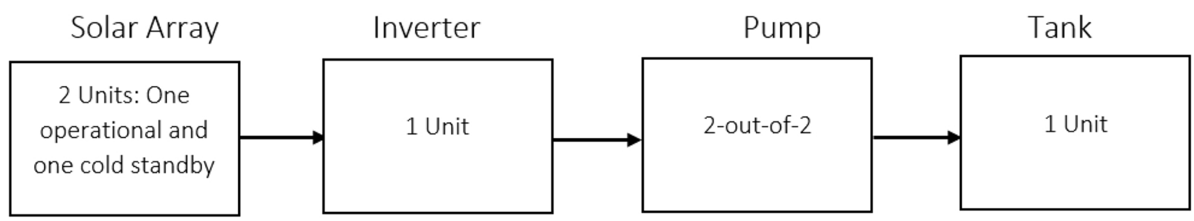

Fig. 1. Schematic block diagram for case I (PV source).

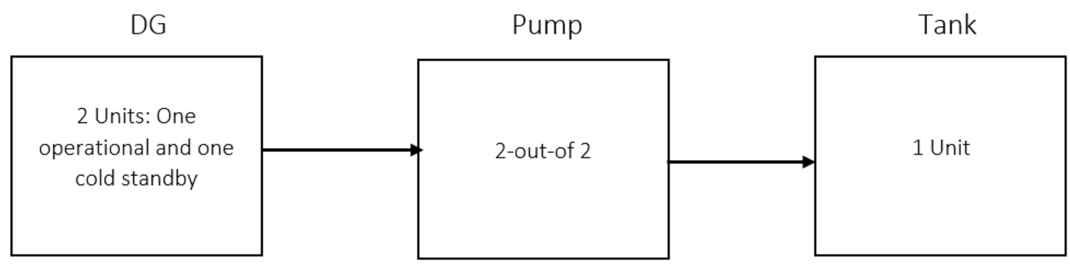

Fig. 2. Schematic block diagram for case II (DG source).

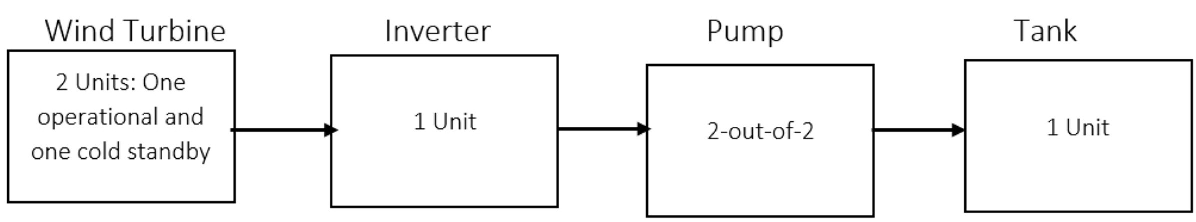

Fig. 3. Schematic block diagram for case II (Wind source).

pump for water delivery. If one configuration fails, the system will continue to function. The system will only fail if both configurations are shut down.

2.1.2. Wind subsystem

The energy requirements of the pump can be satisfied by either of the two wind system configurations. The submersible pump for water supply is driven by electricity generated by the wind system. The system will continue to function even if one configuration fails. The system will fail only if the two configurations shut down.

2.1.3. DG subsystem

There are two DG configurations, with each capable of delivering the energy needs of the pump. The DG is used to supply power directly to the submersible pump for water supply. If one configuration fails, the system will continue to function. The system will fail only if both configurations shut down.

2.1.4. Inverter subsystem

The inverter system converts direct current (DC) electricity into alternating current (AC), which is needed to power the submersible pumps. This converter ensures compatibility between the renewable energy source and the pumping system. The inverter subsystem is a single unit; therefore if it fails, the entire system fails.

2.1.5. Pump subsystem

Two specially designed pumps are buried underground in a water source, such as a borehole or well. They run on electricity generated by renewable energy sources or direct current (DG). These pumps draw water from a supply and transport it to a storage tank. Because the pumps are designed to work together, the system will fail if any of the pump units fails.

2.1.6. Tank subsystem

The tank subsystem is used to store water obtained from the water source. This water stored in the tank is needed for later use, either for agriculture or for domestic purposes. The amount of water storage depends on the capacity of the tank. The tank is a single system; in which if fails, the system will fail completely.

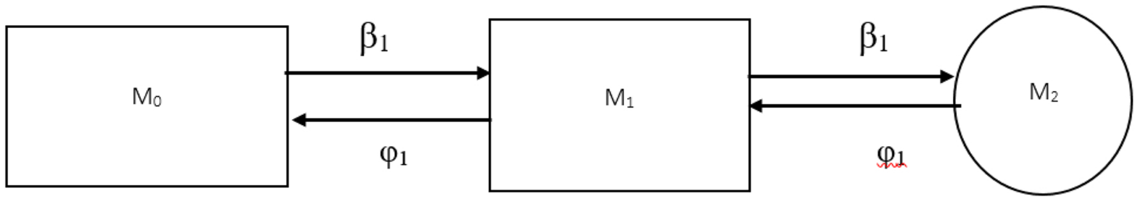

Fig. 4. Transition diagram of solar subsystem.

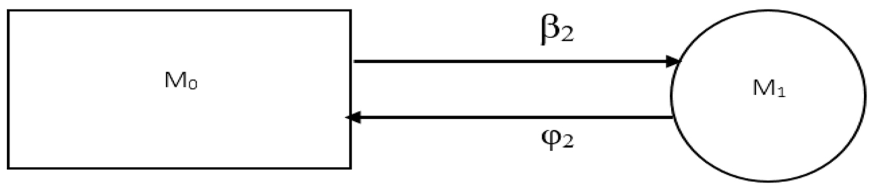

Fig. 5. Transition diagram of inverter subsystem.

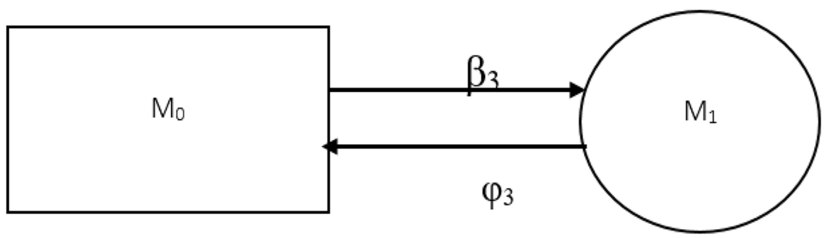

Fig. 6. Transition diagram of pump subsystem.

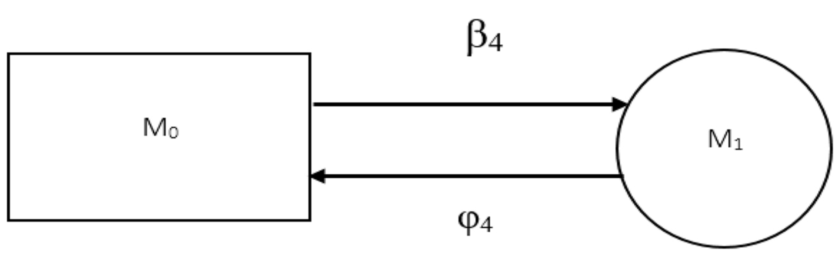

Fig. 7. Transition diagram of tank subsystem.

2.2. Assumptions

I. The failure rates and repair rates of each subsystem follow an exponential distribution.
II. There are no simultaneous subsystem failures.
III. Failure and repair rates for each subsystem are statistically independent.
IV. Repairmen and component replacements are always available, and repaired components are as good as new.
V. Standby system switchover devices are perfect.

2.3. Transition states of subsystem

Transition diagrams of all six subsystem components are shown in Figs. 4 to 9, and various failure and repair rates associated with these components are also presented in Table 1. From these figures (Figs. 4 to 9), E_0 is regarded as full operation for all subsystem components; E_1 is regarded as complete failure of the inverter, pump, and tank subsystems; and, order-wise, E_2 is regarded as complete failure of the solar, wind, and DG subsystems, respectively.

2.4. RAMD analysis

In this section, the mathematical models of various subsystems are developed. The Chapman-Kolmogorov differential equations are obtained using the Markov chain process. Figs. 4 to 9 depict the transition diagrams of various subsystem components. The RAMD analysis of the subsystem is explained in the subsection that follows.

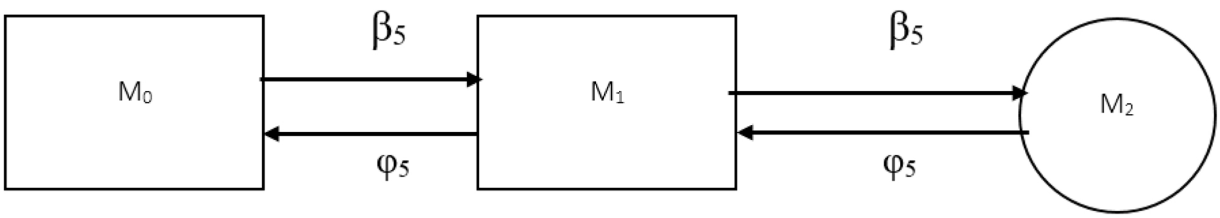

Fig. 8. Transition diagram of DG subsystem.

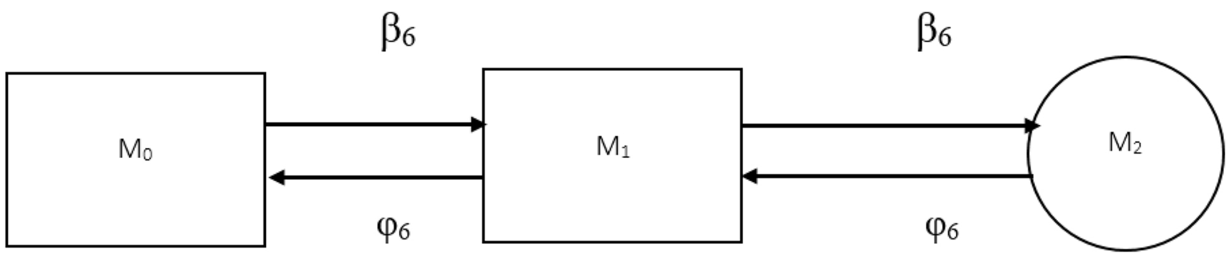

Fig. 9. Transition diagram of wind subsystem.

Table 1. Failure and repair rate of subsystem.

Component	Failure rate (β)	Repair rate (φ)
Solar panel	$\beta_1 = 0.010$	$\varphi_1 = 0.48$
Inverter	$\beta_2 = 0.020$	$\varphi_2 = 0.57$
Pump	$\beta_3 = 0.030$	$\varphi_3 = 0.69$
Tank	$\beta_4 = 0.040$	$\varphi_4 = 0.78$
DG	$\beta_5 = 0.090$	$\varphi_5 = 1.18$
Wind	$\beta_6 = 0.067$	$\varphi_6 = 0.90$

2.4.1. RAMD indices of solar subsystem

The solar subsystem consists of two units, one of which is operational and the other on cold standby. If both units fail, the system fails completely. The transition diagram and its Chapman- Kolmogorov differential equations are presented in [6]:

$$M_0'(t) = -\beta_1 M_0(t) + \varphi_1 M_1(t) \quad (1)$$

$$M_1'(t) = \beta_1 M_0(t) - (\beta_1 + \varphi_1) M_1(t) + \varphi_1 M_2(t) \quad (2)$$

$$M_2'(t) = \beta_1 M_1(t) - \varphi_1 M_2(t) \quad (3)$$

Under steady state, Eqs. (1) to (3) reduces to:

$$M_1(t) = \frac{\beta_1}{\varphi_1} M_0(t) \quad (4)$$

Substitute $M_1(t)$ in Eq. (4) into Eq. (2) under steady state, we have

$$M_2(t) = \left[\frac{\beta_1(\beta_1 + \varphi_1) - \beta_1\,\varphi_1}{\varphi_1^2}\right] M_0(t) \quad (5)$$

Using normalization condition, we have

$$M_0 + M_1 + M_2 = 1 \quad (6)$$

Substituting Eqs. (4) and (5) into Eq. (6), we have

$$M_0 = \frac{\varphi_1^2}{\varphi_1^2 + \beta_1\,\varphi_1 + \beta_1^2} \quad (7)$$

Availability of component is equal to the sum of probabilities at operational states. Therefore, the availability of the solar subsystem is given by [8]:

$$AV_{SP} = M_0 + M_1 = \frac{\varphi_1(\varphi_1 + \beta_1)}{\varphi_1^2 + \beta_1\,\varphi_1 + \beta_1^2} \quad (8)$$

Maintainability is given by:

$$M(t) = 1 - e^{-\varphi t} \quad (9)$$

Therefore, the maintainability of the solar subsystem is given by [8]:

$$M_{SP}(t) = 1 - e^{-0.48t} \quad (10)$$

Dependability is given by [8]:

$$D = 1 - \left\{\left[\frac{1}{\frac{\varphi}{\beta} - 1}\right]\left[e^{-\ln\left(\frac{\frac{\varphi}{\beta}}{\frac{\varphi}{\beta}-1}\right)} - e^{-\left[\frac{\varphi}{\beta}\right]\ln\left(\frac{\frac{\varphi}{\beta}}{\frac{\varphi}{\beta}-1}\right)}\right]\right\} \quad (11)$$

Let $y_1 = \frac{\varphi_1}{\beta_1}$ = dependability ratio of solar subsystem, therefore, the solar subsystem dependability is given by [8]:

$$D_{SP} = 1 - \left\{\left[\frac{1}{y_1 - 1}\right]\left[e^{-\ln\left(\frac{y_1}{y_1-1}\right)} - e^{-y_1\ln\left(\frac{y_1}{y_1-1}\right)}\right]\right\} \quad (12)$$

The reliability of the solar subsystem is given by [8]:

$$R_{SP} = e^{-\beta_1 t}\ (1 + \beta_1 t) \tag{13}$$

2.4.2. RAMD indices of inverter subsystem

The inverter subsystem consists of only one operating unit. Failure of this unit will result in a complete system failure. The Chapman-Kolmogorov differential equations related to it are as follows [8]:

$$M_0'(t) = -\varphi_2 M_1(t) - \beta_2 M_0(t) \tag{14}$$

$$M_1'(t) = \beta_2 M_0(t) - \varphi_2 M_1(t) \tag{15}$$

Under steady state, Eqs. (14) and (15) reduces to:

$$M_1(t) = \frac{\beta_2}{\varphi_2} M_0(t) \tag{16}$$

Using normalization condition, we have

$$M_0 + M_1 = 1 \tag{17}$$

Substituting Eq. (16) into Eq. (17), we have

$$M_0 = \frac{\varphi_2}{\varphi_2 + \beta_2} \tag{18}$$

Therefore, the availability of the inverter subsystem is given by [8]:

$$AV_{INV} = M_0 = \frac{\varphi_2}{\varphi_2 + \beta_2} \tag{19}$$

The maintainability of the inverter subsystem is given by [8]:

$$M_{INV}(t) = 1 - e^{-0.57t} \tag{20}$$

The dependability of the inverter subsystem is given by [10]:

$$D_{INV} = 1 - \left\{\left[\frac{1}{y_2 - 1}\right]\left[e^{-\ln\left(\frac{y_2}{y_2-1}\right)} - e^{-y_2\ln\left(\frac{y_2}{y_2-1}\right)}\right]\right\} \tag{21}$$

Where $y_2 = \frac{\varphi_2}{\beta_2}$ = dependability ratio of inverter subsystem.

The reliability of the inverter subsystem is given by [10]:

$$R_{INV} = e^{-11\times10^{-6}t} \tag{22}$$

2.4.3. RAMD indices of pump subsystem

The pump subsystem consists of two units which must work at the same time for the system to be operational. Failure of either unit will cause a complete system failure. The Chapman-Kolmogorov differential equations associated with it are as follows [10]:

$$M_0'(t) = \varphi_3 M_1(t) - 2\beta_3 M_0(t) \tag{23}$$

$$M_1'(t) = 2\ \beta_3 M_0(t) - \varphi_3 M_1(t) \tag{24}$$

Under steady state, Eqs. (23) and (24) reduces to:

$$M_1(t) = \frac{2\beta_3}{\varphi_3} M_0(t) \tag{25}$$

Using normalization condition, we have

$$M_0 + M_1 = 1 \tag{26}$$

Substituting Eq. (16) into Eq. (17), we have

$$M_0 = \frac{\varphi_3}{\varphi_3 + 2\beta_3} \tag{27}$$

Therefore, the availability of the inverter subsystem is given by [10]:

$$AV_{PUM} = M_0 = \frac{\varphi_3}{\varphi_3 + 2\beta_3} \tag{28}$$

The maintainability of the inverter subsystem is given by [10]:

$$M_{PUM}(t) = 1 - e^{-0.69t} \tag{29}$$

The dependability of the pump subsystem is given by [10]:

$$D_{PUM} = 1 - \left\{\left[\frac{1}{y_3 - 1}\right]\left[e^{-\ln\left(\frac{y_3}{y_3-1}\right)} - e^{-y_3\ln\left(\frac{y_3}{y_3-1}\right)}\right]\right\} \tag{30}$$

Where $y_3 = \frac{\varphi_3}{\beta_3}$ = dependability ratio of pump subsystem.

The reliability of the inverter subsystem is given by [10]:

$$R_{PUM} = e^{-2\beta_3 t} \tag{31}$$

2.4.4. RAMD indices of tank subsystem

The tank subsystem consist of a single unit, which is operational. Failure of the unit will cause a complete system failure. The transition diagram and Chapman Kolmogorov differential equations associated with it are as follows [8]:

$$M_0'(t) = \varphi_4 M_1(t) - \beta_4 M_0(t) \tag{32}$$

$$M_1'(t) = \beta_4 M_0(t) - \varphi_4 M_1(t) \tag{33}$$

Under steady state, Eqs. (23) and (24) reduces to:

$$M_1(t) = \frac{\beta_4}{\varphi_4} M_0(t) \tag{34}$$

Using normalization condition, we have

$$M_0 + M_1 = 1 \tag{35}$$

Substituting Eq. (25) into Eq. (26), we have

$$M_0 = \frac{\varphi_4}{\varphi_4 + \beta_4} \tag{36}$$

Therefore, the availability of the tank subsystem is given by [8]:

$$AV_{TAN} = M_0 = \frac{\varphi_4}{\varphi_4 + \beta_4} \tag{37}$$

The maintainability of the tank subsystem is given by [10]:

$$M_{TAN}(t) = 1 - e^{-0.78t} \tag{38}$$

The dependability of the pump subsystem is given by [10]:

$$D_{TAN} = 1 - \left\{ \left[\frac{1}{y_4 - 1} \right] \left[e^{-\ln\left(\frac{y_4}{y_4 - 1}\right)} - e^{-y_4 \ln\left(\frac{y_4}{y_4 - 1}\right)} \right] \right\} \tag{39}$$

Where $y_4 = \frac{\varphi_4}{\beta_4}$ = dependability ratio of tank subsystem.

The reliability of the inverter subsystem is given by [10]:

$$R_{TAN} = e^{-0.04t} \tag{40}$$

2.4.5. RAMD indices of DG subsystem

The DG subsystem consists of two units, one operating and the other on cold standby. Failure of both units results in complete system failure. The transition diagram and Chapman-Kolmogorov differential equations are as follows:

$$M_0'(t) = -\beta_5 M_0(t) + \varphi_5 M_1(t) \tag{41}$$

$$M_1'(t) = \beta_5 M_0(t) - (\beta_5 + \varphi_5) M_1(t) + \varphi_5 M_2(t) \tag{42}$$

$$M_2'(t) = \beta_5 M_1(t) - \varphi_5 M_2(t) \tag{43}$$

Under steady state, Eqs. (1) to (3) reduces to:

$$M_1(t) = \frac{\beta_5}{\varphi_5} M_0(t) \tag{44}$$

Substitute $M_1(t)$ in Eq. (4) into Eq. (2) under steady state, we have

$$M_2(t) = \left[\frac{\beta_5(\beta_5 + \varphi_5) - \beta_5 \varphi_5}{\varphi_5^2} \right] M_0(t) \tag{45}$$

Using normalization condition, we have

$$M_0 + M_1 + M_2 = 1 \tag{46}$$

Substituting Eqs. (4) and (5) into Eq. (6), we have

$$M_0 = \frac{\varphi_5^2}{\varphi_5^2 + \beta_5 \varphi_5 + \beta_5^2} \tag{47}$$

Availability of component is equal to the sum of probabilities at operational states. Therefore, the availability of the solar subsystem is given by:

$$AV_{DG} = M_0 + M_1 = \frac{\varphi_5(\varphi_5 + \beta_5)}{\varphi_5^2 + \beta_5 \varphi_5 + \beta_5^2} \tag{48}$$

Maintainability is given by:

$$M(t) = 1 - e^{-\varphi t} \tag{49}$$

Therefore, the maintainability of the solar subsystem is given by:

$$M_{DG}(t) = 1 - e^{-1.18t} \tag{50}$$

Dependability is given by:

$$D = 1 - \left\{ \left[\frac{1}{\frac{\varphi}{\beta} - 1} \right] \left[e^{-\ln\left(\frac{\frac{\varphi}{\beta}}{\frac{\varphi}{\beta} - 1}\right)} - e^{-\left[\frac{\varphi}{\beta}\right] \ln\left(\frac{\frac{\varphi}{\beta}}{\frac{\varphi}{\beta} - 1}\right)} \right] \right\} \tag{51}$$

Let $y_5 = \frac{\varphi_5}{\beta_5}$ = dependability ratio of solar subsystem, therefore, the solar subsystem dependability is given by:

$$D_{DG} = 1 - \left\{ \left[\frac{1}{y_5 - 1} \right] \left[e^{-\ln\left(\frac{y_5}{y_5 - 1}\right)} - e^{-y_5 \ln\left(\frac{y_5}{y_5 - 1}\right)} \right] \right\} \tag{52}$$

The reliability of the solar subsystem is given by:

$$R_{DG} = e^{-\beta_5 t} \; (1 + \beta_5 t) \tag{53}$$

2.4.6. RAMD indices of wind subsystem

The Wind subsystem consists of two units, one operating and the other in cold standby. Failure of both units causes complete system failure. The transition diagram and Chapman-Kolmogorov differential equations associated with it are as follows:

$$M_0'(t) = -\beta_6 M_0(t) + \varphi_6 M_1(t) \quad (54)$$

$$M_1'(t) = \beta_6 M_0(t) - (\beta_6 + \varphi_6) M_1(t) + \varphi_6 M_2(t) \quad (55)$$

$$M_2'(t) = \beta_6 M_1(t) - \varphi_6 M_2(t) \quad (56)$$

Under steady state, Eqs. (1) to (3) reduces to:

$$M_1(t) = \frac{\beta_6}{\varphi_6} M_0(t) \quad (57)$$

Substitute $M_1(t)$ in Eq. (4) into Eq. (2) under steady state, we have

$$M_2(t) = \left[\frac{\beta_6(\beta_6 + \varphi_6) - \beta_6\, \varphi_6}{\varphi_6^2}\right] M_0(t) \quad (58)$$

Using normalization condition, we have

$$M_0 + M_1 + M_2 = 1 \quad (59)$$

Substituting Eqs. (4) and (5) into Eq. (6), we have

$$M_0 = \frac{\varphi_6^2}{\varphi_6^2 + \beta_6\, \varphi_6 + \beta_6^2} \quad (60)$$

Availability of component is equal to the sum of probabilities at operational states. Therefore, the availability of the solar subsystem is given by:

$$AV_{WIN} = M_0 + M_1 = \frac{\varphi_6(\varphi_6 + \beta_6)}{\varphi_6^2 + \beta_6\, \varphi_6 + \beta_6^2} \quad (61)$$

Maintainability is given by:

$$M(t) = 1 - e^{-\varphi t} \quad (62)$$

Therefore, the maintainability of the solar subsystem is given by:

$$M_{WIN}(t) = 1 - e^{-0.9t} \quad (63)$$

Dependability is given by:

$$D = 1 - \left\{\left[\frac{1}{\frac{\varphi}{\beta} - 1}\right]\left[e^{-\ln\left(\frac{\frac{\varphi}{\beta}}{\frac{\varphi}{\beta}-1}\right)} - e^{-\left[\frac{\varphi}{\beta}\right]\ln\left(\frac{\frac{\varphi}{\beta}}{\frac{\varphi}{\beta}-1}\right)}\right]\right\} \quad (64)$$

Let $y_6 = \frac{\varphi_6}{\beta_6}$ = dependability ratio of solar subsystem, therefore, the solar subsystem dependability is given by:

$$D_{WIN} = 1 - \left\{\left[\frac{1}{y_6 - 1}\right]\left[e^{-\ln\left(\frac{y_6}{y_6-1}\right)} - e^{-y_6\ln\left(\frac{y_6}{y_6-1}\right)}\right]\right\} \quad (65)$$

The reliability of the solar subsystem is given by:

$$R_{WIN} = e^{-\beta_6 t}\,(1 + \beta_6 t) \quad (66)$$

2.4.7. RAMD indices of overall system

Since all components or subsystems are interconnected in series, the system fails if any component fails. Therefore, the RAMD indices are as follows:

For System Case I

The reliability of the system is given by:

$$R_{SYS1} = R_{SP} \times R_{INV} \times R_{PUM} \times R_{TAN} \quad (67)$$

$$R_{SYS1} = \left\{e^{-\beta_1 t}\,(1 + \beta_1 t)\right\} \times \left\{e^{-11\times 10^{-6} t}\right\} \times \left\{e^{-2\beta_3 t}\right\} \times \left\{e^{-0.04t}\right\} \quad (68)$$

The availability of the system is given by:

$$AV_{SYS1} = AV_{SP} \times AV_{INV} \times AV_{PUM} \times AV_{TAN} \quad (69)$$

$$AV_{SYS1} = \left\{\frac{\varphi_1(\varphi_1 + \beta_1)}{\varphi_1^2 + \beta_1\, \varphi_1 + \beta_1^2}\right\} \times \left\{\frac{\varphi_2}{\varphi_2 + \beta_2}\right\} \times \left\{\frac{\varphi_3}{\varphi_3 + 2\beta_3}\right\} \times \left\{\frac{\varphi_4}{\varphi_4 + \beta_4}\right\} \quad (70)$$

The maintainability of the system is given by:

$$M_{SYS1} = M_{SP}(t) \times M_{INV}(t) \times M_{PUM}(t) \times M_{TAN}(t) \quad (71)$$

$$M_{SYS1} = \left\{1 - e^{-0.48t}\right\} \times \left\{1 - e^{-0.57t}\right\} \times \left\{1 - e^{-0.69t}\right\} \times \left\{1 - e^{-0.78t}\right\} \quad (72)$$

The dependability of the system is given by:

$$D_{SYS1} = D_{SP} \times D_{INV} \times D_{PUM} \times D_{TAN} \quad (73)$$

$$\begin{aligned} D_{SYS1} = &\left\{1 - \left\{\left[\frac{1}{y_1 - 1}\right]\left[e^{-\ln\left(\frac{y_1}{y_1-1}\right)} - e^{-y_1\ln\left(\frac{y_1}{y_1-1}\right)}\right]\right\}\right\} \\ &\times \left\{1 - \left\{\left[\frac{1}{y_2 - 1}\right]\left[e^{-\ln\left(\frac{y_2}{y_2-1}\right)} - e^{-y_2\ln\left(\frac{y_2}{y_2-1}\right)}\right]\right\}\right\} \\ &\times \left\{1 - \left\{\left[\frac{1}{y_3 - 1}\right]\left[e^{-\ln\left(\frac{y_3}{y_3-1}\right)} - e^{-y_3\ln\left(\frac{y_3}{y_3-1}\right)}\right]\right\}\right\} \\ &\times \left\{1 - \left\{\left[\frac{1}{y_4 - 1}\right]\left[e^{-\ln\left(\frac{y_4}{y_4-1}\right)} - e^{-y_4\ln\left(\frac{y_4}{y_4-1}\right)}\right]\right\}\right\} \end{aligned} \quad (74)$$

For System Case II

The reliability of the system is given by:

$$R_{SYS2} = R_{DG} \times R_{PUM} \times R_{TAN} \quad (75)$$

$$R_{SYS2} = \left\{e^{-\beta_5 t}\,(1 + \beta_5 t)\right\} \times \left\{e^{-2\beta_3 t}\right\} \times \left\{e^{-0.04t}\right\} \quad (76)$$

The availability of the system is given by:

$$AV_{SYS2} = AV_{DG} \times AV_{PUM} \times AV_{TAN} \tag{77}$$

$$AV_{SYS2} = \left\{ \frac{\varphi_5 (\varphi_5 + \beta_5)}{\varphi_5^2 + \beta_5 \varphi_5 + \beta_5^2} \right\} \times \left\{ \frac{\varphi_3}{\varphi_3 + 2\beta_3} \right\} \times \left\{ \frac{\varphi_4}{\varphi_4 + \beta_4} \right\} \tag{78}$$

The maintainability of the system is given by:

$$M_{SYS2} = M_{DG}(t) \times M_{PUM}(t) \times M_{TAN}(t) \tag{79}$$

$$M_{SYS2} = \left\{1 - e^{-1.18t}\right\} \times \left\{1 - e^{-0.69t}\right\} \times \left\{1 - e^{-0.78t}\right\} \tag{80}$$

The dependability of the system is given by:

$$D_{SYS2} = D_{DG} \times D_{PUM} \times D_{TAN} \tag{81}$$

$$D_{SYS2} = \left\{1 - \left\{\left[\frac{1}{y_5 - 1}\right]\left[e^{-\ln\left(\frac{y_5}{y_5-1}\right)} - e^{-y_5 \ln\left(\frac{y_5}{y_5-1}\right)}\right]\right\}\right\} \times \left\{1 - \left\{\left[\frac{1}{y_3 - 1}\right]\left[e^{-\ln\left(\frac{y_3}{y_3-1}\right)} - e^{-y_3 \ln\left(\frac{y_3}{y_3-1}\right)}\right]\right\}\right\} \times \left\{1 - \left\{\left[\frac{1}{y_4 - 1}\right]\left[e^{-\ln\left(\frac{y_4}{y_4-1}\right)} - e^{-y_4 \ln\left(\frac{y_4}{y_4-1}\right)}\right]\right\}\right\} \tag{82}$$

For System Case III

The reliability of the system is given by:

$$R_{SYS3} = R_{WIN} \times R_{INV} \times R_{PUM} \times R_{TAN} \tag{83}$$

$$R_{SYS3} = \left\{e^{-\beta_6 t}\ (1 + \beta_6 t)\right\} \times \left\{e^{-11\times10^{-6}t}\right\} \times \left\{e^{-2\beta_3 t}\right\} \times \left\{e^{-0.04t}\right\} \tag{84}$$

The availability of the system is given by:

$$AV_{SYS3} = AV_{WIN} \times AV_{INV} \times AV_{PUM} \times AV_{TAN} \tag{85}$$

$$AV_{SYS3} = \left\{ \frac{\varphi_6 (\varphi_6 + \beta_6)}{\varphi_6^2 + \beta_6 \varphi_6 + \beta_6^2} \right\} \times \left\{ \frac{\varphi_2}{\varphi_2 + \beta_2} \right\} \times \left\{ \frac{\varphi_3}{\varphi_3 + 2\beta_3} \right\} \times \left\{ \frac{\varphi_4}{\varphi_4 + \beta_4} \right\} \tag{86}$$

The maintainability of the system is given by:

$$M_{SYS3} = M_{WIN}(t) \times M_{INV}(t) \times M_{PUM}(t) \times M_{TAN}(t) \tag{87}$$

$$M_{SYS3} = \left\{1 - e^{-0.9t}\right\} \times \left\{1 - e^{-0.0057t}\right\} \times \left\{1 - e^{-0.69t}\right\} \times \left\{1 - e^{-0.78t}\right\} \tag{88}$$

The dependability of the system is given by:

$$D_{SYS3} = D_{WIN} \times D_{INV} \times D_{PUM} \times D_{TAN} \tag{89}$$

$$D_{SYS3} = \left\{1 - \left\{\left[\frac{1}{y_6 - 1}\right]\left[e^{-\ln\left(\frac{y_6}{y_6-1}\right)} - e^{-y_6 \ln\left(\frac{y_6}{y_6-1}\right)}\right]\right\}\right\} \times \left\{1 - \left\{\left[\frac{1}{y_2 - 1}\right]\left[e^{-\ln\left(\frac{y_2}{y_2-1}\right)} - e^{-y_2 \ln\left(\frac{y_2}{y_2-1}\right)}\right]\right\}\right\} \times \left\{1 - \left\{\left[\frac{1}{y_3 - 1}\right]\left[e^{-\ln\left(\frac{y_3}{y_3-1}\right)} - e^{-y_3 \ln\left(\frac{y_3}{y_3-1}\right)}\right]\right\}\right\} \times \left\{1 - \left\{\left[\frac{1}{y_4 - 1}\right]\left[e^{-\ln\left(\frac{y_4}{y_4-1}\right)} - e^{-y_4 \ln\left(\frac{y_4}{y_4-1}\right)}\right]\right\}\right\} \tag{90}$$

3. Results and discussion

To obtain the reliability metric of different subsystems and system, an empirical comparative study was conducted on some energy sources configured in series, various subsystems were assigned with some numerical values, as shown in Table 1. Tables 2 to 4 and Figs. 10 to 12 present the reliability of various subsystems and system over time for different cases. These Tables and show that reliability decreases with the passage of time for the various subsystems and systems for all cases. This decrease in reliability is due to aging, wear and tear of components which leads to component failure or overall system degradation. In addition, the reliability of the system is less than the reliability of each subsystems for all cases; this is because of the serial configuration of each components subsystems. According to the numerical values in these tables at a period of 10 months, the reliability of the systems are 0.299778623 for case I, 0.284193481 for case II and 0.257385582 for case III respectively. This is a poor reliability value, which should be investigated. It is observed from the results in Tables 2 to 4 that subsystem pump has the least reliability value compared to other subsystems in all cases considered. Thus, it can be inferred that subsystem pump is behind the low reliability value of the systems and calls for adequate preventive maintenance in order to mitigate failure occurrence of the subsystem and enhance its reliability, which will enhance the reliability of the system.

Tables 5 to 7 and Figs. 13 to 15 reveal the availability of various subsystems and system for all cases. The results depict that the availability of the systems for various cases is less than the availability of each subsystem; this is also due to the serial configuration of each subsystem. According to the numerical values in these tables, the availability of the systems is

Table 2. Variation of subsystem reliability with time for Case I.

	Reliability for Case I				
Time (Month)	R_{SP}	R_{INV}	R_{PUM}	R_{TAN}	R_{SYS1}
2	0.999058244	0.960789439	0.886920437	0.923116346	0.785887049
4	0.998117374	0.923116346	0.786627861	0.852143789	0.617618454
6	0.997177391	0.886920437	0.697676326	0.786627861	0.485378345
8	0.996238293	0.852143789	0.618783392	0.726149037	0.381452555
10	0.995300079	0.818730753	0.548811636	0.670320046	0.299778623
12	0.994362749	0.786627861	0.486752256	0.618783392	0.235592138
14	0.993426302	0.755783741	0.431710523	0.571209064	0.185148810
16	0.992490736	0.726149037	0.382892886	0.527292424	0.145506052
18	0.991556052	0.697676326	0.339595526	0.486752256	0.114351322
20	0.990622248	0.670320046	0.301194212	0.449328964	0.089867223

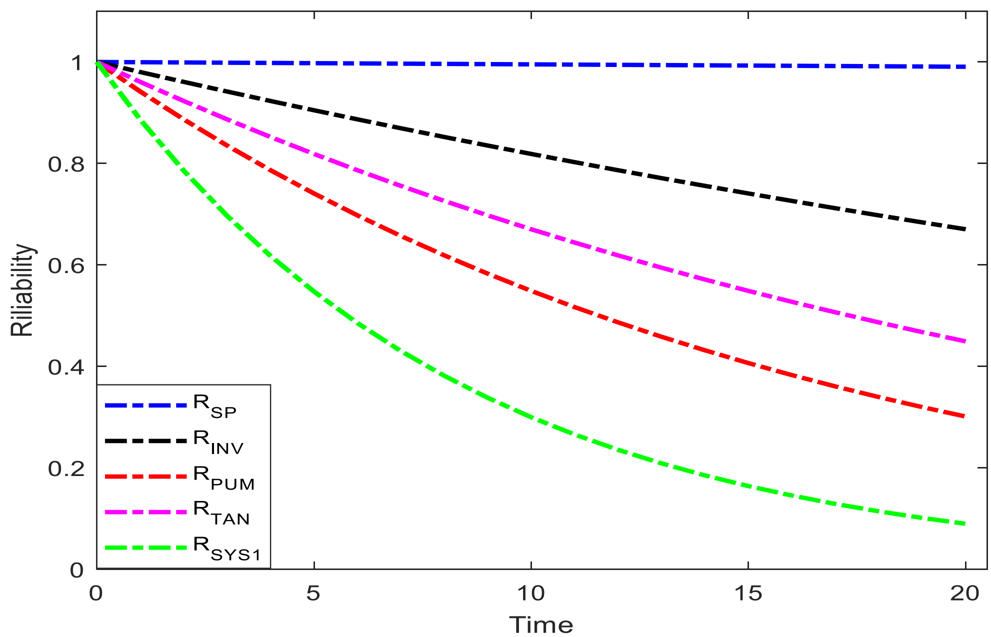

Fig. 10. Variation of subsystem reliability with time for case I.

Table 3. Variation of subsystem reliability with time for case II.

	Reliability for Case II			
Time (Month)	R_{DG}	R_{PUM}	R_{TAN}	R_{SYS2}
2	0.949689680	0.886920437	0.923116346	0.777540147
4	0.901910489	0.786627861	0.852143789	0.604568680
6	0.856535084	0.697676326	0.786627861	0.470076421
8	0.813442530	0.618783392	0.726149037	0.365503289
10	0.772517976	0.548811636	0.670320046	0.284193481
12	0.733652350	0.486752256	0.618783392	0.220971841
14	0.696742066	0.431710523	0.571209064	0.171814478
16	0.661688750	0.382892886	0.527292424	0.133592655
18	0.628398977	0.339595526	0.486752256	0.103873652
20	0.596784024	0.301194212	0.449328964	0.080765935

0.845097737 for case I, 0.747051082 for case II, and 0.841118171 for case III respectively. It is observed from the results in the tables that subsystem pump has the lowest availability value compared to other subsystems in all cases considered. Thus, it can be said that subsystem pump is behind the low availability value of the systems and calls for adequate preventive maintenance in order to mitigate failure occurrence

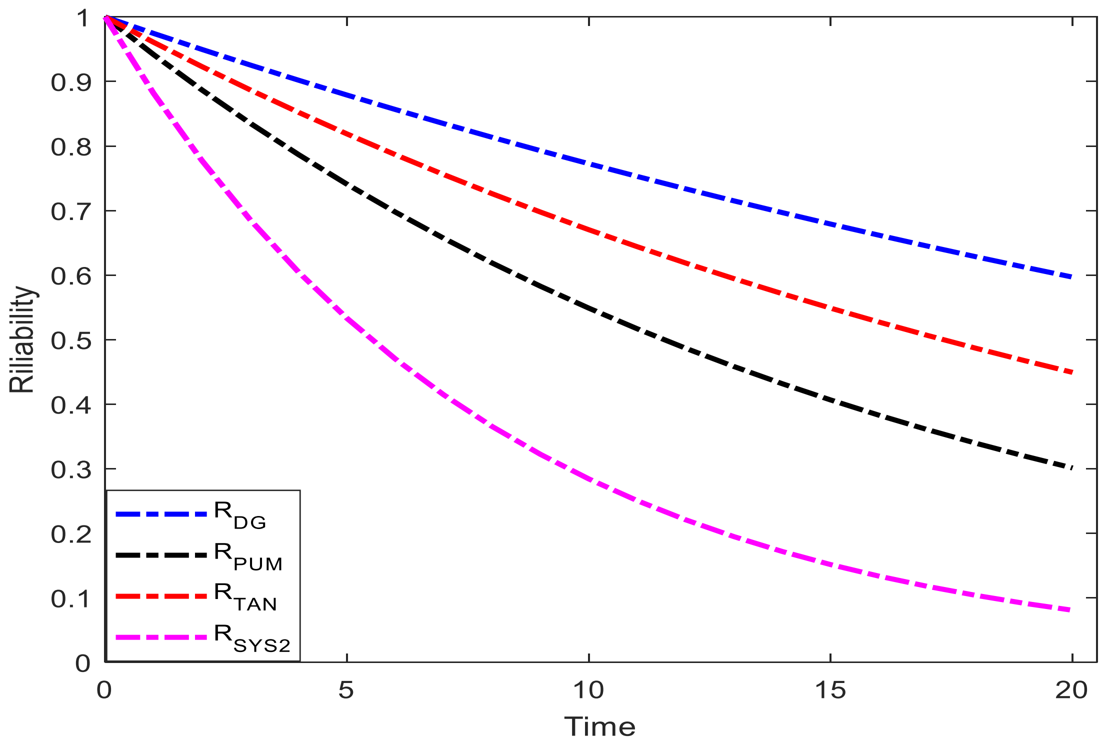

Fig. 11. Variation of subsystem reliability with time for case II.

Table 4. Variation of subsystem reliability with time for Case III.

	Reliability for Case III				
Time (Month)	R_{WIN}	R_{INV}	R_{PUM}	R_{TAN}	R_{SYS3}
2	0.969052974	0.960789439	0.886920437	0.923116346	0.762284068
4	0.939063666	0.923116346	0.786627861	0.852143789	0.581077000
6	0.910002438	0.886920437	0.697676326	0.786627861	0.442945740
8	0.881840569	0.852143789	0.618783392	0.726149037	0.337650480
10	0.854550226	0.818730753	0.548811636	0.670320046	0.257385582
12	0.828104438	0.786627861	0.486752256	0.618783392	0.196200928
14	0.802477068	0.755783741	0.431710523	0.571209064	0.149560842
16	0.777642789	0.726149037	0.382892886	0.527292424	0.114007847
18	0.753577058	0.697676326	0.339595526	0.486752256	0.086906365
20	0.730256089	0.670320046	0.301194212	0.449328964	0.066247338

Table 5. Availability of case I system.

Availability for Case I				
AV_{SP}	AV_{INV}	AV_{PUM}	AV_{TAN}	AV_{SYS1}
0.999575011	0.966101695	0.920000000	0.951219512	0.845097737

Table 6. Availability of case II system.

Availability for Case II			
AV_{DG}	AV_{PUM}	AV_{TAN}	AV_{SYS2}
0.853653680	0.920000000	0.951219512	0.747051082

of this subsystem and enhance its availability, which will enhance the availability of the system.

Tables 8 to 10 and Figs. 16 to 18 depict the maintainability of various subsystems and systems for different cases with time variations. After 10 days, according to the numerical values in these tables, the maintainability of the systems is 0.987051081 for case I, 0.998575399 for case II and 0.995118846 for case III respectively. For various cases, it is observed that subsystem solar, pump and inverter have the lowest maintainability value for cases I–III respectively. This low maintainability value is mainly due to low repair rate of these subsystems compared to other subsystem components as shown

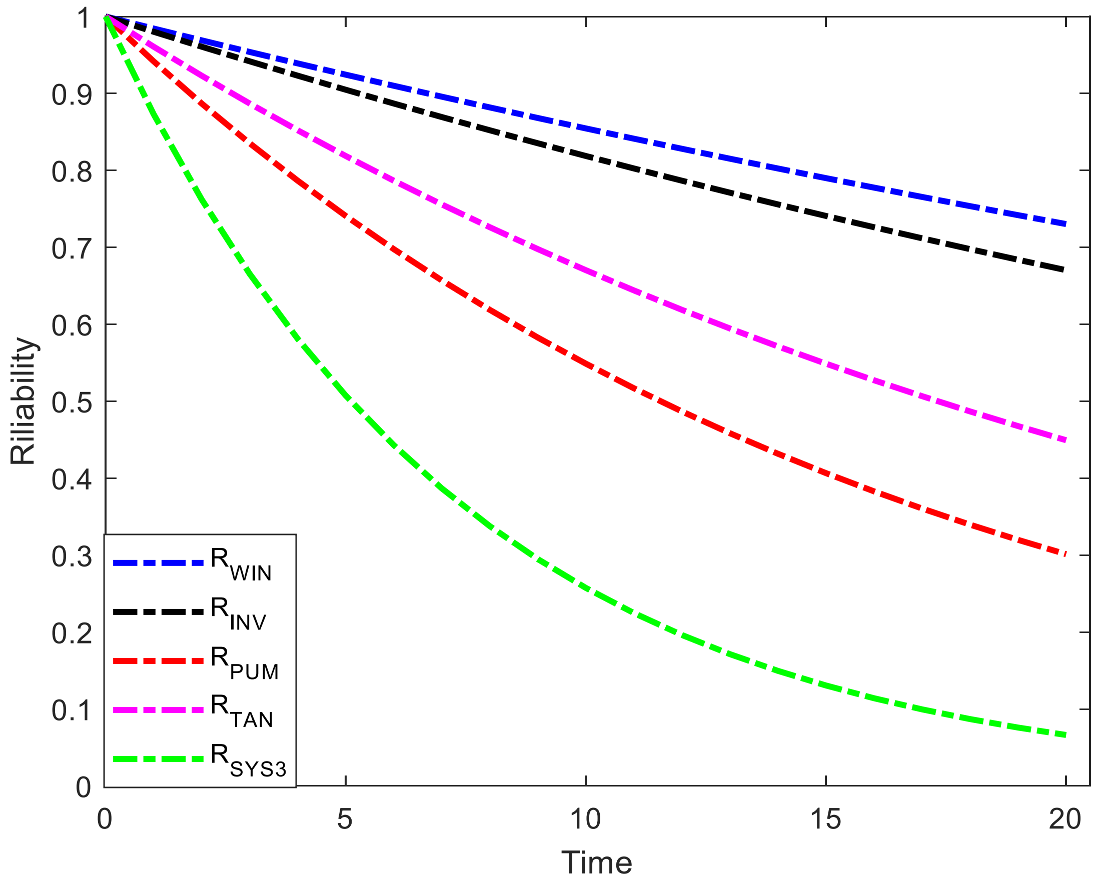

Fig. 12. Variation of subsystem reliability with time for case III.

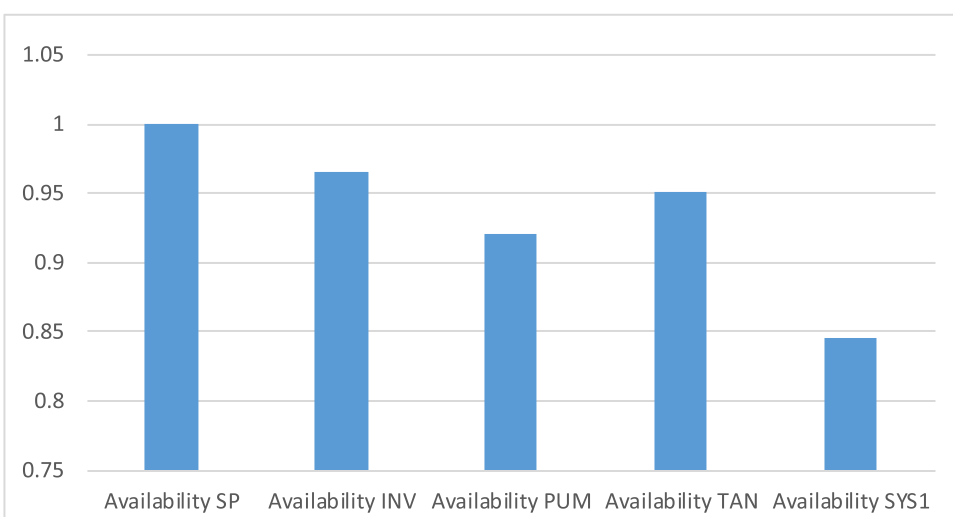

Fig. 13. Availability for case I system.

Table 7. Availability of case III system.

Availability for Case III				
AV_{WIN}	AV_{INV}	AV_{PUM}	AV_{TAN}	AV_{SYS3}
0.994868477	0.966101695	0.920000000	0.951219512	0.841118171

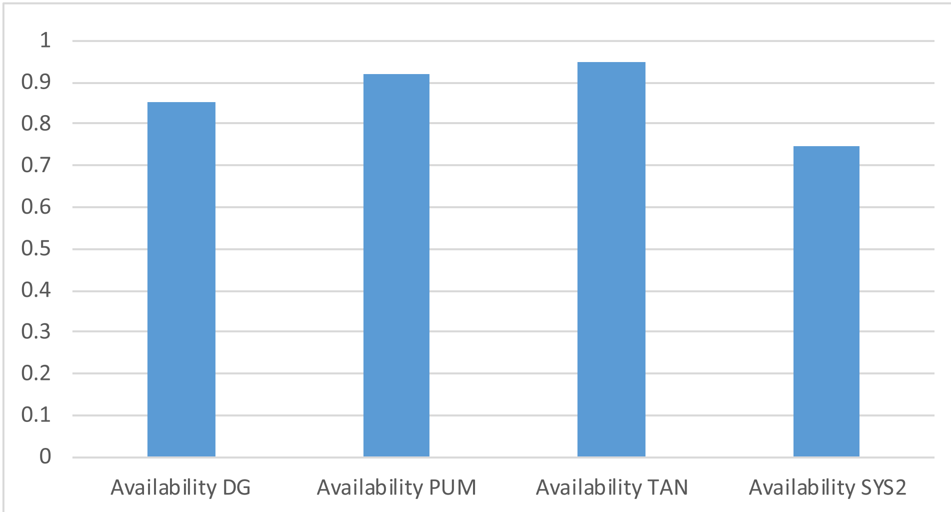

Fig. 14. Availability for case II system.

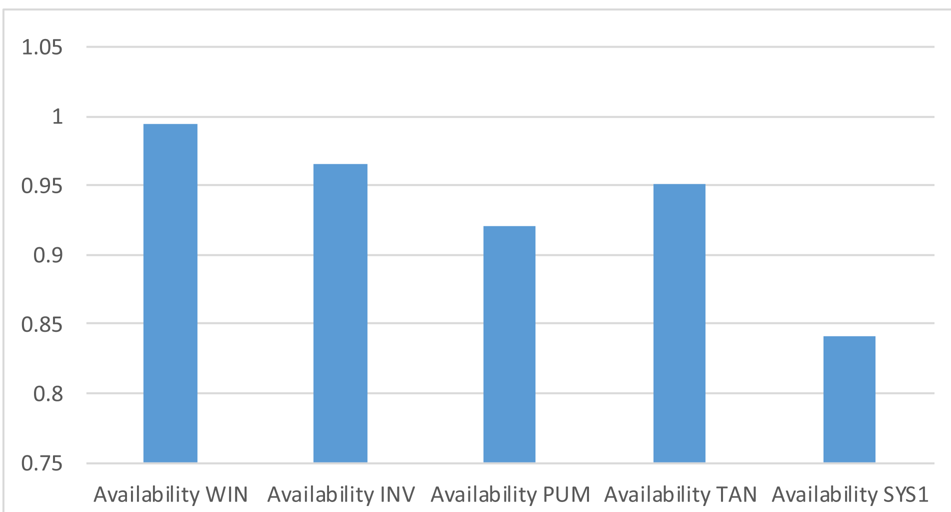

Fig. 15. Availability of case III system.

Table 8. Maintainability of subsystem for case I.

	M_{SYS1}				
Time (Month)	M_{SP}	M_{INV}	M_{PUM}	M_{TAN}	M_{SYS1}
2	0.617107114	0.680180978	0.748421447	0.789863929	0.248132437
4	0.853393038	0.897715793	0.936708232	0.955842832	0.685928401
6	0.943865237	0.967287565	0.984077148	0.990720986	0.890114971
8	0.978506399	0.989537941	0.995994152	0.998050144	0.962510046
10	0.991770253	0.996654035	0.998992215	0.999590265	0.987051081
12	0.996848888	0.998929897	0.999746463	0.999913900	0.995443974
14	0.998793462	0.999657761	0.999936215	0.999981907	0.998369886
16	0.999538025	0.999890545	0.999983953	0.999996198	0.999408784
18	0.999823113	0.999964994	0.999995963	0.999999201	0.999783279
20	0.999932271	0.999988805	0.999998984	0.999999832	0.999919893

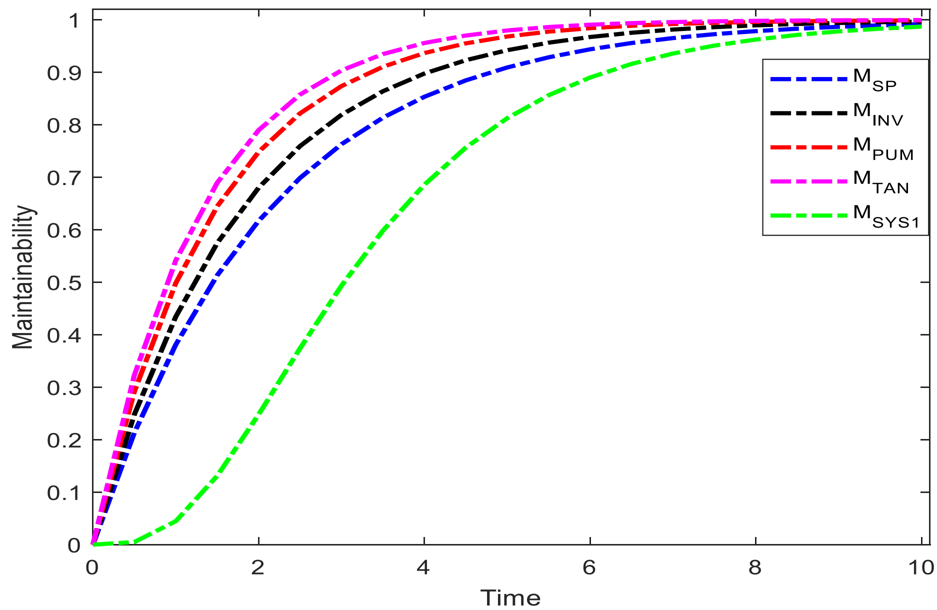

Fig. 16. Maintainability plot of subsystems with time for case I.

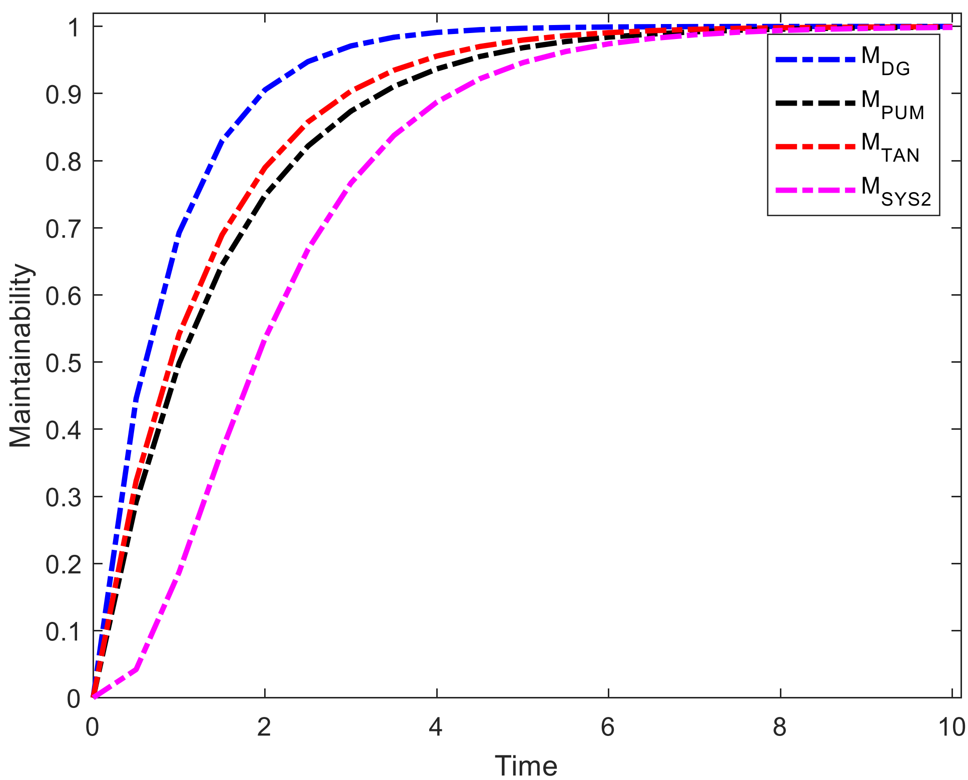

Fig. 17. Maintainability plot of subsystems with time for case II.

in Table 1. Although the maintainability of other subsystems appears excellent, greater attention to the subsystem is required by providing additional redundancy or immediate replacement of the affected subsystem. Furthermore, the results also depict that the maintainability of the overall system is lower than that of the individual subsystem.

Tables 11 to 13 and Figs. 19 to 21 below, reveals the dependability of various subsystems and systems respectively. The results shows that solar subsystem has

Table 9. Maintainability of subsystem for case II.

	M_{SYS2}			
Time (Month)	M_{DG}	M_{PUM}	M_{TAN}	M_{SYS2}
2	0.905579777	0.748421447	0.789863929	0.535334485
4	0.991084821	0.936708232	0.955842832	0.887363680
6	0.999158227	0.984077148	0.990720986	0.974125200
8	0.999920520	0.995994152	0.998050144	0.993973100
10	0.999992495	0.998992215	0.999590265	0.998575399
12	0.999999291	0.999746463	0.999913900	0.999659676
14	0.999999933	0.999936215	0.999981907	0.999918057
16	0.999999994	0.999983953	0.999996198	0.999980145
18	0.999999999	0.999995963	0.999999201	0.999995163
20	1.000000000	0.999998984	0.999999832	0.999998816

Table 10. Maintainability of subsystem for case III.

	M_{SYS3}				
Time (Month)	M_{WIN}	M_{INV}	M_{PUM}	M_{TAN}	M_{SYS3}
2	0.834701112	0.680180978	0.748421447	0.789863929	0.335624750
4	0.972676278	0.897715793	0.936708232	0.955842832	0.781804227
6	0.995483419	0.967287565	0.984077148	0.990720986	0.938793654
8	0.999253414	0.989537941	0.995994152	0.998050144	0.982917895
10	0.999876590	0.996654035	0.998992215	0.999590265	0.995118846
12	0.999979600	0.998929897	0.999746463	0.999913900	0.998570274
14	0.999996628	0.999657761	0.999936215	0.999981907	0.999572542
16	0.999999443	0.999890545	0.999983953	0.999996198	0.999870141
18	0.999999908	0.999964994	0.999995963	0.999999201	0.999960066
20	0.999999985	0.999988805	0.999998984	0.999999832	0.999987606

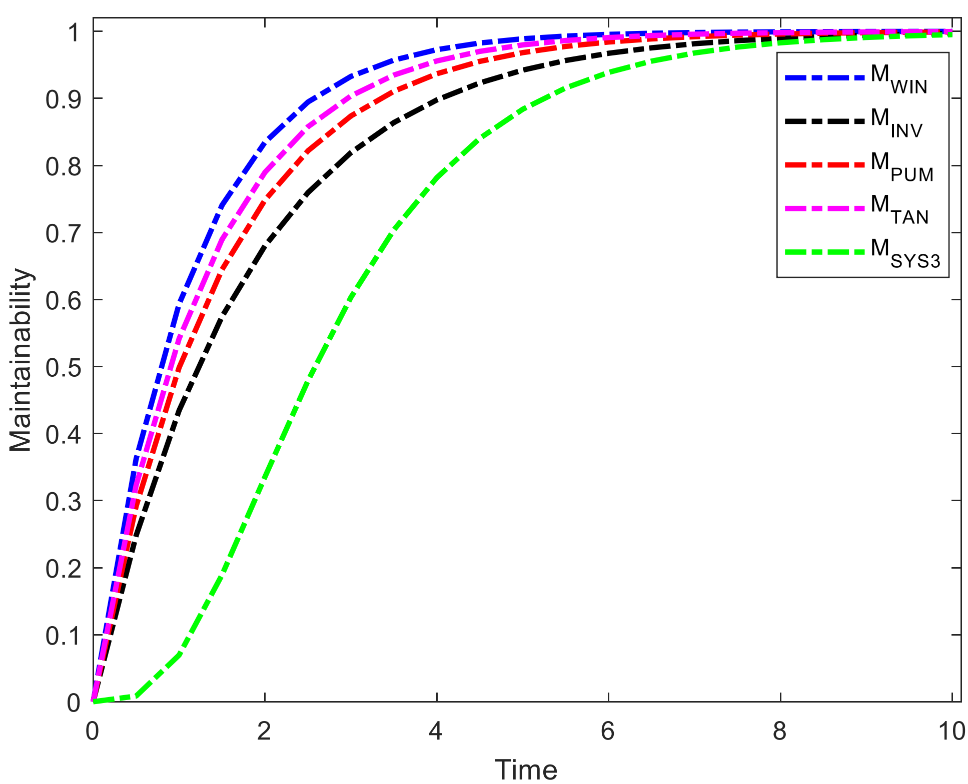

Fig. 18. Maintainability plot of subsystems with time for case III.

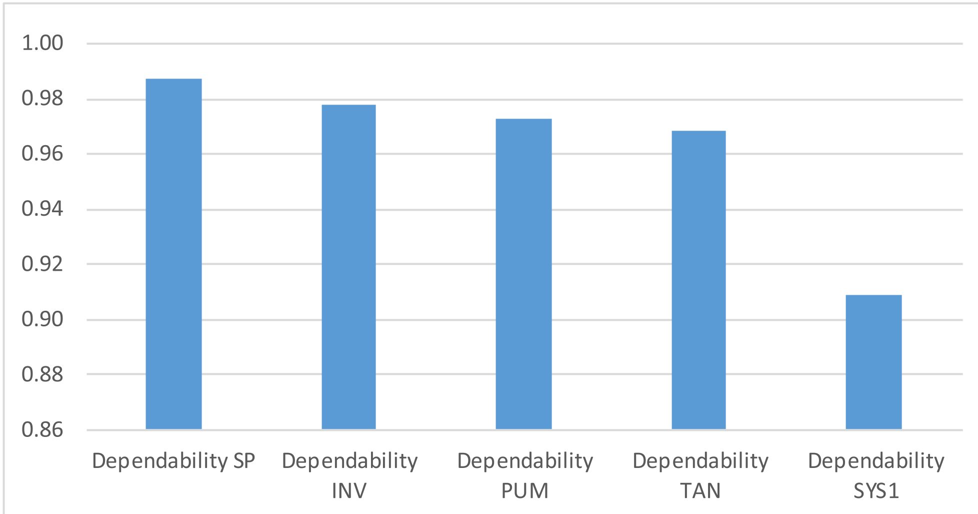

Fig. 19. Dependability for case I system.

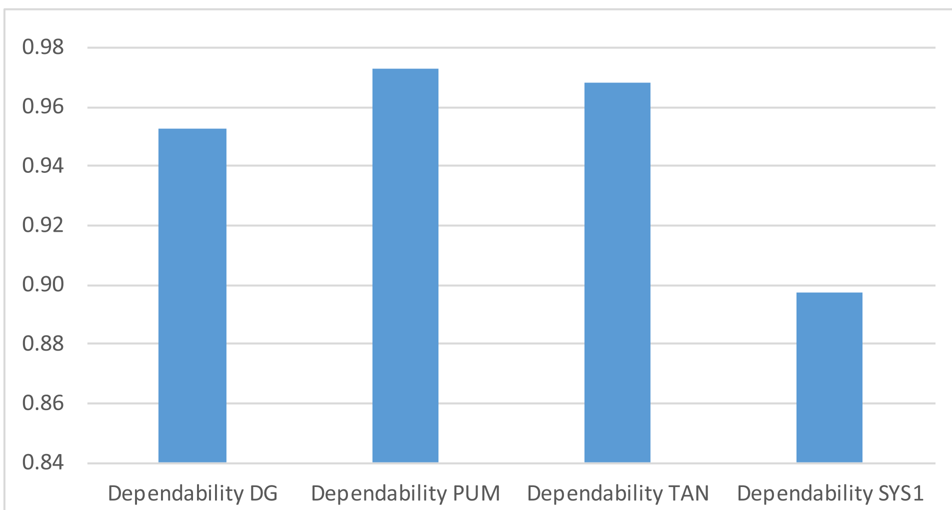

Fig. 20. Dependability for case II system.

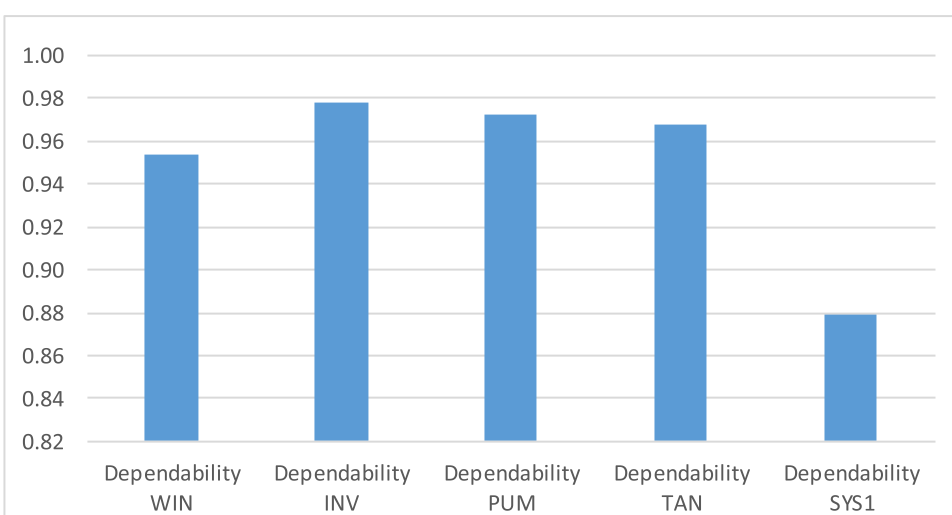

Fig. 21. Dependability for case III system.

Table 11. Dependability of case I system.

Dependability for Case I				
D_{SP}	D_{INV}	D_{PUM}	D_{TAN}	D_{SYS1}
0.986912000	0.978052000	0.972873000	0.968082000	0.909093748

Table 12. Dependability of case II system.

Dependability for Case II			
D_{DG}	D_{PUM}	D_{TAN}	D_{SYS2}
0.952907000	0.972873000	0.968082000	0.897467671

Table 13. Dependability of case III system.

Dependability for Case III				
D_{WIN}	D_{INV}	D_{PUM}	D_{TAN}	D_{SYS3}
0.954008000	0.978052000	0.972873000	0.968082000	0.878784236

Table 14. RAMD indices for the subsystems.

	RAMD of Subsystems					
RAMD Indices	Solar	Wind	DG	Inverter	Pump	Tank
Reliability	$e^{-0.0004711t}$	$e^{-0.015718t}$	$e^{-0.02581t}$	$e^{-0.02t}$	$e^{-0.06t}$	$e^{-0.06t}$
Maintainability	$1-e^{-0.48t}$	$1-e^{-0.9t}$	$1-e^{-1.18t}$	$1-e^{-0.57t}$	$1-e^{-0.69t}$	$1-e^{-0.78t}$
Availability	0.999575	0.994868	0.8536537	0.966102	0.920000	0.9512195
Dependability	0.986912	0.954008	0.952907	0.978052	0.972873	0.968082

Table 15. RAMD indices for the systems.

	RAMD of System		
RAMD Indices	Case I	Case II	Case III
Reliability	$e^{-0.120471t}$	$e^{-0.12581t}$	$e^{-0.135718t}$
Maintainability	$1-e^{-0.01t}$	$1-e^{-0.0858t}$	$1-e^{-0.01701t}$
Availability	0.845097737	0.747051082	0.841118171
Dependability	0.909093748	0.897467671	0.878784236

Table 16. Variation of system reliability due to changes in failure rate of subsystem for case I.

	Solar Subsystem			System Reliability for Case I		
Time (years)	$\beta = 0.01$	$\beta = 0.02$	$\beta = 0.03$	$\beta = 0.01$	$\beta = 0.02$	$\beta = 0.03$
2	0.9801987	0.960789439	0.94176453	0.771051586	0.755783741	0.740818221
4	0.9607894	0.923116346	0.88692044	0.594520548	0.571209064	0.548811636
6	0.9417645	0.886920437	0.83527021	0.458406011	0.431710523	0.40656966
8	0.9231163	0.852143789	0.78662786	0.353454682	0.326279795	0.301194212
10	0.9048374	0.818730753	0.74081822	0.272531793	0.246596964	0.22313016
12	0.8869204	0.786627861	0.69767633	0.210136071	0.186373976	0.165298888
14	0.8693582	0.755783741	0.65704682	0.162025751	0.140858421	0.122456428
16	0.8521438	0.726149037	0.61878339	0.124930212	0.106458504	0.090717953
18	0.8352702	0.697676326	0.58274825	0.096327638	0.080459607	0.067205513
20	0.8187308	0.670320046	0.54881164	0.074273578	0.060810063	0.049787068

the highest dependability value for case I and pump subsystem for cases I and II respectively, this is because of their dependability ratio and also the system dependability is less than the individual subsystems.

The RAMD indices, for the systems and subsystems are summarized in Tables 14 and 15 respectively. According to the numerical values of these tables, the solar subsystem has the highest value for reliability, availability, and dependability. It is, therefore, selected among the energy sources for the system. Consequently, case I is recommended for selection among the three cases. Since the maintainability of

Table 17. Variation of system reliability due to changes in failure rate of subsystem for case II.

	DG Subsystem			System Reliability for Case II		
Time (years)	$\beta = 0.015$	$\beta = 0.025$	$\beta = 0.035$	$\beta = 0.015$	$\beta = 0.025$	$\beta = 0.035$
2	0.970445534	0.95122942	0.93239382	0.794533603	0.778800783	0.763379494
4	0.941764534	0.90483742	0.869358235	0.631283646	0.606530660	0.582748252
6	0.913931185	0.86070798	0.810584246	0.501576069	0.472366553	0.444858066
8	0.886920437	0.81873075	0.755783741	0.398519041	0.367879441	0.339595526
10	0.860707976	0.77880078	0.704688090	0.316636769	0.286504797	0.259240261
12	0.835270211	0.74081822	0.657046820	0.251578553	0.223130160	0.197898699
14	0.810584246	0.70468809	0.612626394	0.199887614	0.173773943	0.151071809
16	0.786627861	0.67032005	0.571209064	0.158817426	0.135335283	0.115325121
18	0.763379494	0.63762815	0.532591801	0.126185782	0.105399225	0.088036833
20	0.740818221	0.60653066	0.496585304	0.100258844	0.082084999	0.067205513

Table 18. Variation of system reliability due to changes in failure rate of subsystem for case III.

	Wind Subsystem			System Reliability for Case III		
Time (years)	$\beta = 0.025$	$\beta = 0.045$	$\beta = 0.065$	$\beta = 0.025$	$\beta = 0.045$	$\beta = 0.065$
2	0.951229425	0.913931185	0.878095431	0.748263568	0.718923733	0.690734331
4	0.904837418	0.835270211	0.771051586	0.559898367	0.516851334	0.477113916
6	0.860707976	0.763379494	0.677056874	0.418951549	0.371576691	0.329558961
8	0.818730753	0.697676326	0.594520548	0.313486181	0.267135302	0.227637688
10	0.778800783	0.637628152	0.522045777	0.234570288	0.192049909	0.157237166
12	0.740818221	0.582748252	0.458406011	0.175520401	0.138069237	0.108609109
14	0.70468809	0.532591801	0.402524224	0.131335521	0.099261252	0.07502004
16	0.670320046	0.486752256	0.353454682	0.098273586	0.07136127	0.051818917
18	0.637628152	0.444858066	0.310366941	0.073534544	0.05130331	0.035793105
20	0.60653066	0.40656966	0.272531793	0.055023220	0.036883167	0.024723526

the solar subsystems appears lower than the other two energy sources, greater attention to the subsystem is required by providing additional redundancy or immediate replacement of the solar subsystem.

Tables 16 to 18 show the behavior of system reliability with different energy subsystem sources (solar, DG and wind) with respect to time and variation of failure rates. From these tables, it can be seen that as the failure rate increases, the reliability of these energy source subsystem decreases with the reliability of the system. The wind subsystem is the most critical and highly sensitive energy source subsystem, which requires special intervention to improve the reliability of the system. Furthermore, if maintenance personnel properly monitor the failure rates of subsystems, it will be an effective way to enhance the reliability of the system.

The outcome of this research is similar to the work of [24] and [25]. Whereas [24] considered only one energy source, while [25] did not consider any energy source. This study assessed the RAMD of various energy sources for both conventional and non-conventional energy source.

4. Conclusion

In this paper, an empirical analysis was performed for various subsystems connected in series in order to obtain their associated RAMD metrics as presented in Tables 13 and 14. Tables 2 to 4 and Figs. 1 to 3 present the reliability of the systems with variation of time for different cases. These tables and figures show that reliability decreases with the passage of time for the various subsystems and systems in all cases considered. The numerical values for a period of 10 months, the reliability of the systems are 0.299778623 for case I, 0.284193481 for case II and 0.257385582 for case III respectively. In addition, the reliability of the system is less than the reliability of each subsystems for all cases; this is because of the serial configuration of each components subsystems. It is observed from the results in the tables that subsystem pump has the least reliability value compared to other subsystems in all cases considered. Furthermore, the DG subsystem has the least reliability value compared to other subsystem energy sources. Based on this study, it can be inferred that case I is the best among other cases and subsystem pump is the most critical within each subsystem. Hence, system designers must develop a maintenance strategy for the pump subsystem to improve the system reliability. Future research can consider the RAMD analysis via other renewable energy sources like biomass, geothermal or hybrid renewable system to provide more understanding of the gains and challenges for system designer's.

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