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Reliability Evaluation of Power Electronic Inverter Using Cutset Approach

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Abstract

The development of PV systems for generation of renewable energy has been gaining lot of importance in the present day research. Moreover, probabilistic analysis of the various configuration of PV cell, Power Electronic converters etc. has been considered as the potential area of research with the appropriate assumptions. Evaluation of Basic Probability Indices (BPI) and Probabilistic Measures (PM) of an inverter configuration has been dealt with in the literature by considering failure of all components will lead to inverter failure, treating all such components in series from Probabilistic Logic Diagram (PLD). However, the evaluation of BPI has not been dealt with considering the operating strategies of the inverter.

In this paper, it is proposed to deal with the evaluation of the BPIs and PMs for single phase full bridge inverter with R and R-L Load conditions and the results of the proposed methods using cutsets will be compared with an existing method.

1. Introduction

Reliability evaluation of converter system used in solar PV systems has been gaining importance is the literature. Basic probability methods used in systems approach of network configurations has been dealt with in [4, 11]. The probabilistic methods of power system and HVDC reliability evaluations are given in [5]. A cutset approach for reliability evaluations of HVDC systems has been developed in which the concept of flow networks has been used and the probability of failure of transmission of required flow at the D.C terminal has been obtained [2]. Probabilistic failure data of the Semi-Conductor devices like diode, SCR, IGBT and components such as capacitor, inductor etc., are given in [1, 7]. Reliability evaluation and schematic diagrams of power system using PV arrays using inverters has been given in [9, 16-28].

A probabilistic method using minimal paths for multi-level converters has been described in [8]. More electric aircraft power system has been discussed in [13]. A dynamic Bayesians network approach for PV systems considering intermittent faults has been presented in [12]. Life time and array sizing of inverter with PV system has been presented in [14] using Monte Carlo Simulation technique. The reliability evaluations of PV array with different shaded configurations has been presented and a comparison is made [15].

Although different methods have been developed as stated above, cutset approach for reliability evaluations has not been discussed in detail. In [8], minimal path based approach is presented which is a combinational problem. The advantages of making reliability evaluation using cutset approach are well known in the literature [2, 4, 11].

In the literature, the authors have computed basic Probability indices [4, 11]. For single phase inverter configuration, all the elements are assumed to be in series from the Probability Logic Diagram point of view as the authors have considered that all the components are required for success state of the Inverter [9]. In this context, it is thought that cutsets from the Inverter configuration can be taken based on the performance of the inverter output results for different loading conditions.

In this paper, it is proposed to compute BPIs and PMs of single phase full bridge inverter configuration using cutset based approach. Computational results will be presented based on the failure rate of components such as SCRs, diodes, capacitor etc. Further, the comparison of Reliability Indices with the existing method [9] with the proposed method will be presented and analysed.

2. Proposed Methodology

In this section, computation of basic failure rates of components in the inverter and procedure for evaluation of Reliability Indices are presented.

2.1 Computation of Failure Rates for Components

In this paper, computation of failure rates of components of the single phase bridge inverter configuration as shown in Fig. 1 is considered.

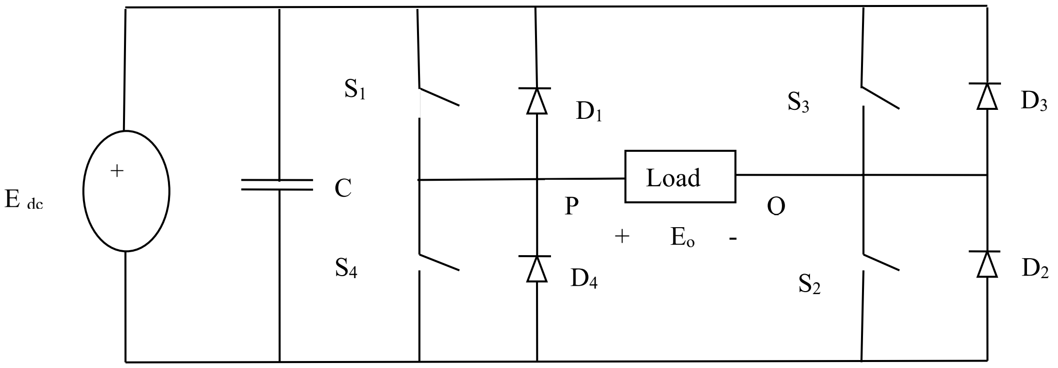

Fig. 1 *Single phase full bridge inverter*

The failure rates of components number of Failures per Million hours (F/Mhr) can be estimated as follows [9]:

i) For SCR; λ_{ij} is the element in inverter i, j = SCR, Diode.

$$\lambda_{SCR} = \lambda_{Sb} \Pi_{Ts} \Pi_{Qs} \Pi_{Es} \Pi_{Vs} \quad \text{F / Mhr} \tag{1}$$

ii) For Diodes

$$\lambda_{D} = \lambda_{db} \Pi_{Td} \Pi_{Sd} \Pi_{Cd} \Pi_{Qd} \Pi_{Ed} \quad \text{F / Mhr} \tag{2}$$

iii) For the Capacitor

$$\lambda_{C} = \lambda_{Cb} \Pi_{VC} \Pi_{CSR} \Pi_{QC} \Pi_{EC} \quad \text{F / Mhr} \tag{3}$$

where λ_{Sb}, λ_{db} and λ_{Cb} are the base failure rate of the devices SCR, and Diode respectively.

- Π_{Ts}, Π_{Td}, are the Temperature factors of the devices SCR, Diode, and Capacitor respectively.
- Π_{QS}, Π_{Qd}, Π_{QC} are the Quality factors of the devices SCR, Diode, and Capacitor respectively.
- Π_{ES}, Π_{Ed}, Π_{EC} are the Environmental factor of the devices SCR, Diode, and Capacitor respectively.
- Π_{VC} is the Capacitance factor for the capacitor.
- Π_{CSR} is the series resistance factor for the capacitor.

2.2 Modelling of the Proposed Method

As stated in the Section 2.1, cutset approach of evaluation of basic probabilities indices has more significant advantages as cutsets directly represent the failure modes of any configuration. Consider the single phase full bridge inverter (voltages source inverter) Configuration with SCR, diodes, capacitor and voltages source as shown in Fig. 1.

The cutset of the configurations can be obtained with failures of

i) Only SCRs with R-Load
ii) Combinations of SCRs and Diode failures with R-L Load.
iii) Malfunctioning of the one of the OFF-state SCRs while two SCRs are in one of the operating modes.

Assumptions:

1) It is assumed the probability of the voltage source is unity i.e. No failure of the voltage source is considered.
2) Further, it is also assumed that in practical inverter, failures of the only diodes, which can be considered as cutset, have been neglected as they will not affect the inverter operations in general.
3) Moreover, failure of the capacitor has been considered in the analysis.
4) The repair time (in hrs.) for all the components, i.e. SCR, Diode, Capacitors is assumed to be same.

Based on the above discussion, the PLD using the cutset models have been developed. The formula for computations of basic probability indices such as Equivalent Failure Rate (EFR) λ_{eq}, Mean Outage Time (MOT) r_{eq}, Average Annual Outage Time (AAOT) U_{eq} and PMs such as Mean Time To Failure (MTTF), Mean Time To Repair (MTTR), Mean Time Between Failure (MTBF), Availability and Unavailability have been presented as follows [10, 11].

2.3 Evaluation of BPI and PM for Inverter with R-Load

Probability Logic Diagram for an Inverter using cutset with failures of SCRs with R-Load. Based on the inverter operation [6] the following three cutsets have been obtained (for Fig.1)

C_1: Capacitor **C_2:** S_1 S_2 **C_3:** S_3 S_4

The corresponding PLD and the corresponding simplifications are shown in Figs. 2 to 4 respectively.

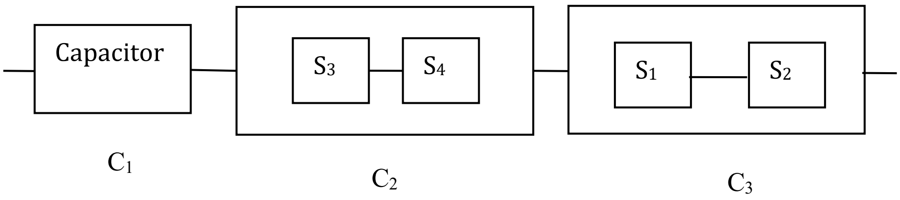

Fig. 2 *Probability logic diagram of a single phase inverter with R-Load*

The expressions for basic probability indices for Fig.2 can be written as [4, 11]

For Cutset 1:

$$\lambda_{C_1} = \lambda_{Capacitor} \tag{4}$$

For Cutset 2:

$$\lambda_{C_2} = \lambda_{S_3} + \lambda_{S_4} \tag{5}$$

For Cutset 3:

$$\lambda_{C_3} = \lambda_{S_1} + \lambda_{S_2} \tag{6}$$

Where $\lambda_{S_1}, \lambda_{S_2}, \lambda_{S_3}, \lambda_{S_4}$ are the failure rates of the SCRs which can be obtained from equations given in Section 2.1. Fig. 2 is reduced to Fig. 3 and Fig. 4 using network reduction technique.

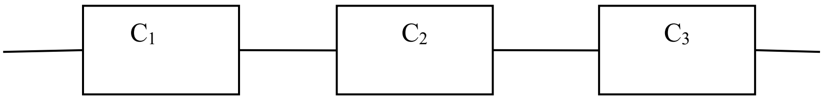

Fig. 3 *Reduced PLD of a single phase inverter for R-Load*

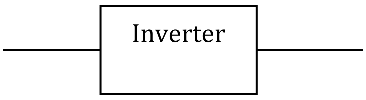

Fig. 4 *Final equivalent for R-Load*

EFR for Inverter:

$$\lambda_I = \lambda_{C_1} + \lambda_{C_2} + \lambda_{C_3} \tag{7}$$

Average Annual Outage Time of the inverter U_I from Fig.3 can be expressed as:

$$AAOT = U_I = \lambda_{C_1} r_{C_1} + \lambda_{C_2} r_{C_2} + \lambda_{C_3} r_{C_3} \tag{8}$$

$$\text{Where} \quad r_{C_2} = \frac{\lambda_{s_3} r_{s_3} + \lambda_{s_4} r_{s_4}}{\lambda_{s_3} + \lambda_{s_4}} ; \qquad r_{C_3} = \frac{\lambda_{s_1} r_{s_1} + \lambda_{s_2} r_{s_2}}{\lambda_{s_1} + \lambda_{s_2}} \tag{9}$$

$$MOTofInverter = r_I = \frac{U_I}{\lambda_I} \tag{10}$$

The PMs of Inverter with R-Load will be obtained from Eqns. (5.11) to (5.15) and is as follows:

$$MTTF_I = \frac{1}{\lambda_I} \tag{11}$$

$$MTTR_I = r_I \tag{12}$$

$$MTBF_I = MTTF_I + MTTR_I \tag{13}$$

$$A_I = \frac{MTTF_I}{MTBF_I} \tag{14}$$

$$U_I = (1 - A_I) \tag{15}$$

2.4 Evaluation of BPI and PM for Inverter with R-L Load

In this section modelling of the PLDs has been developed for configurations (ii) and (iii) as stated in section 2.2 and equations for computation of reliability indices are presented.

2.4.1 Without Malfunctioning

Based on the inverter operation [6] the following five cutsets have been obtained (for Fig.1)

C_1: Capacitor
C_2: S_1 S_2
C_3: D_3 D_4
C_4: S_3 S_4
C_5: D_1 D_2

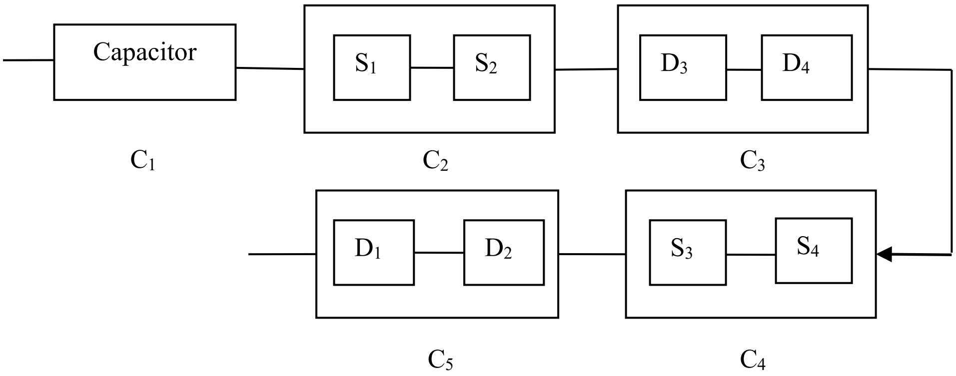

Fig. 5 *PLD of a single phase inverter with R-L-Load*

For Cutset 1:
$$\lambda_{C_1} = \lambda_{\text{Capacitor}} \tag{16}$$

For Cutset 2:
$$\lambda_{C_2} = \lambda_{S_1} + \lambda_{S_2} \tag{17}$$
$$U_{C_2} = \lambda_{S_1} r_{S_1} + \lambda_{S_2} r_{S_2} \tag{18}$$
$$r_{C_2} = \frac{U_{C_2}}{\lambda_{C_2}} \tag{19}$$

For Cutset 3:
$$\lambda_{C_3} = \lambda_{D_3} + \lambda_{D_4} \tag{20}$$
$$U_{C_3} = \lambda_{D_3} r_{D_3} + \lambda_{D_4} r_{D_4} \tag{21}$$
$$r_{C_3} = \frac{U_{C_3}}{\lambda_{C_3}} \tag{22}$$

For Cutset 4:
$$\lambda_{C_4} = \lambda_{S_3} + \lambda_{S_4} \tag{23}$$
$$U_{C_4} = \lambda_{S_3} r_{S_3} + \lambda_{S_4} r_{S_4} \tag{24}$$
$$r_{C_4} = \frac{U_{C_4}}{\lambda_{C_4}} \tag{25}$$

For Cutset 5:
$$\lambda_{C_5} = \lambda_{D_1} + \lambda_{D_2} \tag{26}$$
$$U_{C_5} = \lambda_{D_1} r_{D_1} + \lambda_{D_2} r_{D_2} \tag{27}$$
$$r_{C_5} = \frac{U_{C_5}}{\lambda_{C_5}} \tag{28}$$

Fig. 5 is reduced to Figs. 6 and 7 using network reduction technique. Accordingly, the simplification of PLD can be written as:

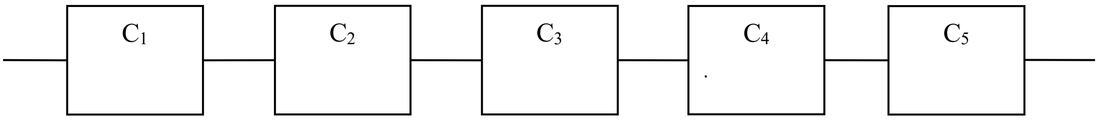

Fig. 6 *Final reduction of probability logic diagram with R-L load*

Fig. 7 *Final equivalent of PLD for R-L Load*

The evaluation of basic Probability indices for the single phase Full Bridge inverter with R-L Load with NMF will be as follows:

$$EFR = \lambda_{\text{I-NMF}} = \lambda_{C_1} + \lambda_{C_2} + \lambda_{C_3} + \lambda_{C_4} + \lambda_{C_5} \tag{29}$$

$$\text{AAOT} = \text{U}_{\text{I-NMF}} = \lambda_{C_1}\text{r}_{C_1} + \lambda_{C_2}\text{r}_{C_2} + \lambda_{C_3}\text{r}_{C_3} + \lambda_{C_4}\text{r}_{C_4} + \lambda_{C_5}\text{r}_{C_5} \tag{30}$$

$$MOT = r_{I-NMF} = \frac{U_{I-NMF}}{\lambda_{I-NMF}} \tag{31}$$

The PMs of Inverter with R-L Load and with NMF can be obtained similarly from Eqns. (11) to (15) respectively.

2.4.2 With Malfunctioning

When two of the SCRs are conducting in operating mode, any one of the remaining two SCRs which are expected to be in the OFF-State, if it were to be in ON-State then there will be a fatal failure of inverter. With this aspect, the modelling of PLDs with cutsets has been also dealt with (referred to as malfunctioning). Based on the inverter operation [6] with malfunctioning, the following four Cutsets have been obtained (for Fig.1)

C_1: S_1, S_2 ON and S_4 is malfunctioning it leading to failure of inverter, denoted as $S_{4\text{-MF}}$.
C_2: S_1, S_2 ON and S_3 is malfunctioning it leading to failure of inverter, denoted as $S_{3\text{-MF}}$.
C_3: S_3, S_4ON and S_1ismalfunctioning it leading to failure of inverter, denoted as $S_{1\text{-MF}}$.
C_4: S_3, S_4 ON and S_2 is malfunctioning it leading to failure of inverter, denoted as $S_{2\text{-MF}}$.

Although C_1 consists of three elements with two of the SCRs functioning and one SCR is malfunctioning, simultaneously all the three elements in ON-State will lead to the fatal failure of the inverter. Hence, all the elements of C_1 are considered to be in series as shown in Fig.8 (a). Similarly for other cutsets C_2, C_3 and C_4, which are shown in Fig. 8(b) to 8(d).

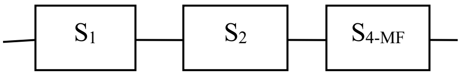

Fig. 8(a) *PLD using C_1*

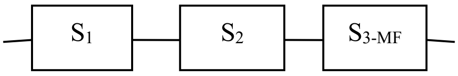

Fig. 8(b) *PLD using C_2*

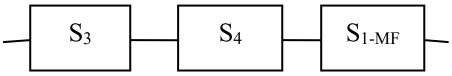

Fig. 8(c) *PLD using C_3*

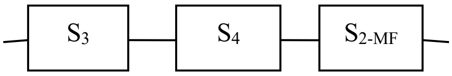

Fig. 8(d) *PLD using C_4*

The corresponding developed equations from Fig. 8(a) will be based on Union Rule of the unreliability for series configuration [4, 11].

$$Q_{C1} = Q_{S1} + Q_{S2} + Q_{S4\text{-}MF} - Q_{S1}\,Q_{S2} - Q_{S1}\,Q_{S4\text{-}MF} - Q_{S2}\,Q_{S4\text{-}MF} + Q_{S1}\,Q_{S2}\,Q_{S4\text{-}MF} \tag{32}$$

In the Eqn. (27), neglecting higher order terms, which can be referred to as summation rule [4, 11], expressed as:

$$Q_{C1} = Q_{S1} + Q_{S2} + Q_{S4\text{-}MF} \tag{33}$$

Similarly, from Figs. 8(b) to 8(d).

$$Q_{C_2} = Q_{S_1} + Q_{S_2} + Q_{S_{3-MF}} \tag{34}$$

$$Q_{C_3} = Q_{S_3} + Q_{S_4} + Q_{S_{1-MF}} \tag{35}$$

$$Q_{C_4} = Q_{S_3} + Q_{S_4} + Q_{S_{2-MF}} \tag{36}$$

And the corresponding reductions to single equivalent element for the inverter with malfunctioning R-L Load is as shown in Fig. 8(e) and Fig. 8(f) respectively.

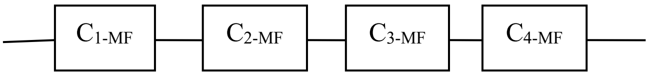

Fig. 8(e) *PLD of inverter for R-L load considering*

Fig. 8(f) *Final equivalent of PLD with MF*

The unreliability of the inverter from Fig. 8(e) can be obtained as:

$$Q_{I-MF} = Q_{C_1} + Q_{C_2} + Q_{C_3} + Q_{C_4} \tag{37}$$

The reliability of the inverter from Fig. 8(e).

$$R_{I-MF} = (\,1 - Q_{I-MF}\,) \tag{38}$$

$$R_{I-MF} = \left(\frac{\mu_{I-MF}}{\lambda_{I-MF} + \mu_{I-MF}} \right) \tag{39}$$

Where μ_{Im} be the transitional rate of the inverter during malfunctioning. From eqn. (39), Compute μ_{I-MF}. From Fig.8 (a) to Fig. 8(d).

$$\lambda_{C_{1-MF}} = \lambda_{S_1} + \lambda_{S_2} + \lambda_{S_{4-MF}} \tag{40}$$

$$\lambda_{C_{2-MF}} = \lambda_{S_1} + \lambda_{S_2} + \lambda_{S_{3-MF}} \tag{41}$$

$$\lambda_{C_{3-MF}} = \lambda_{S_3} + \lambda_{S_4} + \lambda_{S_{1-MF}} \tag{42}$$

$$\lambda_{C_{4-MF}} = \lambda_{S_3} + \lambda_{S_4} + \lambda_{S_{2-MF}} \tag{43}$$

The BPIs of inverter with malfunctioning is as follows:

$$\lambda_{I-MF} = \lambda_{C_1-MF} + \lambda_{C_2-MF} + \lambda_{C_3-MF} + \lambda_{C_4-MF} \tag{44}$$

$$r_{I-MF} = \frac{1}{\mu_{I-MF}} \tag{45}$$

$$U_{I-MF} = \lambda_{I-MF} \cdot r_{I-MF} \tag{46}$$

The PMs of Inverter with R-L Load with MF can be obtained similarly from Eqns. (11) to (15) respectively.

2.4.3 Overall Evaluation of BPIs and PMs for RL-Load

The overall equivalent failure rate of inverter will be

$$\mathrm{EFR} = \lambda_I = \lambda_{I-NMF} + \lambda_{I-MF} \tag{47}$$

The overall Average annual outage time of inverter will be

$$AAOT = \mathrm{U}_I = \mathrm{U}_{I-NMF} + \mathrm{U}_{I-MF} \tag{48}$$

and the overall Mean outage time of inverter will be

$$MOT = r_I = \frac{U_I}{\lambda_I} \tag{49}$$

The overall PMs of Inverter with R-L Load will be obtained similarly from Eqns. (11) to (15) respectively.

3. Results and Discussion

Data of components for Inverter are taken from [1].

- SCR → $\lambda = 4.7043 \times 10^{-5}$ failures / year.
- Diode → $\lambda = 25.63 \times 10^{-5}$ failures / year.
- Capacitor → $\lambda = 0.0212$ failures / year.
- It is assumed the probability of the voltage source is unity. i.e., No failure of the voltage source is considered.
- Repair rate is assumed to be equal for all the components.
  i.e., r = 1.062 hrs /year.

3.1 Based on Operation of Single Phase Full Bridge Inverter with R-Load

There are three cutsets have been obtained i.e., C_1, C_2 and C_3.

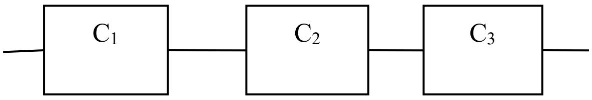

Fig. 9 *PLD of a single phase inverter with R-Load*

Cutset-1: $\lambda_{C_1} = 0.0212$ failure/year ; $r_{C_1} = 1.062$ hrs.

Cutset-2: $\lambda_{C_2} = \lambda_{S_3} + \lambda_{S_4} = 9.408 \times 10^{-5}$ failure/year

$U_{C_2} = \lambda_{S_3} r_{S_3} + \lambda_{S_4} r_{S_4} = 9.9918 \times 10^{-5}$ hrs/year.

$r_{C_2} = 1.0619$ hrs ;

Cutset-3: $\lambda_{C_3} = \lambda_{S_1} + \lambda_{S_2} = 9.408 \times 10^{-5}$ failure/year.

$U_{C_3} = \lambda_{S_1} r_{S_1} + \lambda_{S_2} r_{S_2} = 9.9918 \times 10^{-5}$ hrs/year.

$r_{C_3} = 1.0619$ hrs ;

All three cut sets are in series configuration, the equivalent of PLD is shown in Fig. 10. The BPIs of Inverter with R-Load is as follows, presented in Table 1, and plotted as bar chart in Fig. 11.

Fig. 10 *Final equivalent of PLD for R-Load*

$$\mathrm{EFR} = \lambda_I = \lambda_{C_1} + \lambda_{C_2} + \lambda_{C_3} = 0.0214 \text{ Failure/year.}$$

$$\mathrm{AAOT} = U_I = \lambda_{C_1} r_{C_1} + \lambda_{C_2} r_{C_2} + \lambda_{C_3} r_{C_3} = 0.0227 \text{ hrs/year}$$

$$MOTofInverter = r_I = \frac{U_I}{\lambda_I} = 1.061 \text{ hrs.}$$

Table 1 *BPIs of inverter with R-Load*

BPI of Inverter as per the operation	EFR in failure/ year	MOT in hrs	AAOT in hrs /year
	0.0214	1.061	0.0227

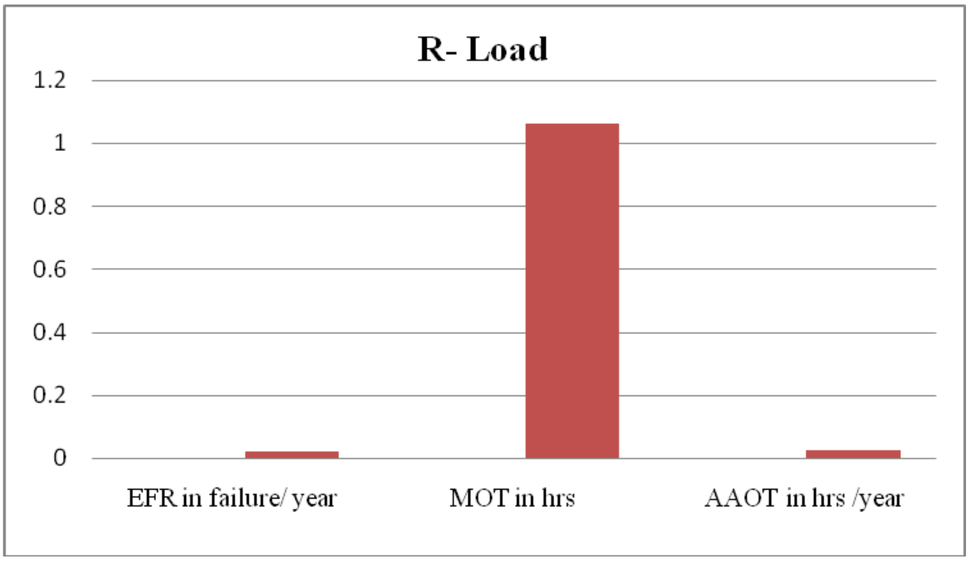

Fig. 11 *BPIs of inverter with R-Load*

The PMs for inverter with R-Load are computed using Eqns. (11) to (15) respectively as follows, presented in Table 2, and shown in Fig. 12.

Table 2 *PMs of inverter with R-Load*

S. No.	Probabilistic Measures	Inverter with R-Load
1	MTTF in years	46.7289
2	MTTR in hrs	1.061
3	MTBF in years	46.7290
4	Availability	0.99999764
5	Unavailability	0.00000236

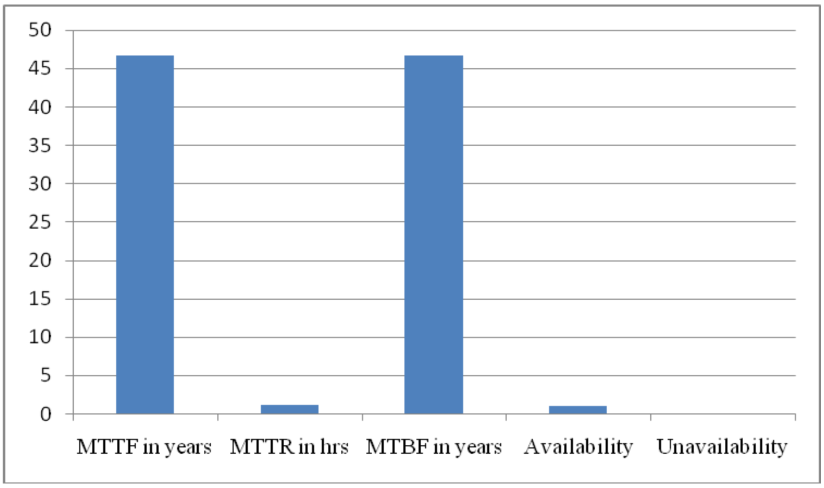

Fig. 12 *PMs of inverter with R-Load*

3.2 Based on Operation of Single Phase Full Bridge Inverter with R-L Load with NMF

There are five cutsets have been obtained i.e., C_1, C_2, C_3, C_4, C_5 respectively and shown in Fig. 13.

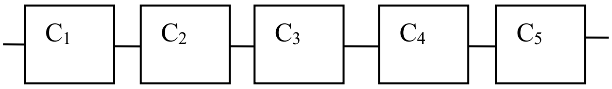

Fig. 13 *Probability logic diagram for R-L load without malfunction*

Cutset-1: λ_{C_1} = 0.0212failure/year; $r_{C_1} = 1.062$ hrs.

Cutset-2: $\lambda_{C_2} = \lambda_{S_1} + \lambda_{S_2}$ = 9.408 x10^{-5} failure/year.

$U_{C_2} = \lambda_{S_1} r_{S_1} + \lambda_{S_2} r_{S_2}$ =9.9918 x10^{-5} hrs/year.

$r_{C_2} = 1.0619$ hrs.

Cutset-3: $\lambda_{C_3} = \lambda_{D_3} + \lambda_{D_4}$ = 51.26 x10^{-5} failure/year.

$U_{C_3} = \lambda_{D_3} r_{D_3} + \lambda_{D_4} r_{D_4}$ = 54.438 x10^{-5} hrs/year.

$r_{C_3} = 1.0619$ hrs.

Cutset-4: $\lambda_{C_4} = \lambda_{S_3} + \lambda_{S_4}$ = 9.408 x10^{-5} failure/year.

$U_{C_4} = \lambda_{S_3} r_{S_3} + \lambda_{S_4} r_{S_4}$ = 9.9918 x10^{-5} hrs/year.

$r_{C_4} = 1.0619$ hrs.

Cutset-5: $\lambda_{C_5} = \lambda_{D_1} + \lambda_{D_2}$ = 51.26 x10^{-5} failure/year.

$U_{C_5} = \lambda_{D_1} r_{D_1} + \lambda_{D_2} r_{D_2}$ =54.438 x10^{-5} hrs/year.

$r_{C_5} = 1.0619$ hrs.

All Five cut sets are in series configuration, the equivalent of PLD of inverter without malfunction is shown in Fig. 14. The BPI of Inverter with R-L Load is as follows and shown in Table 3.

Fig. 14 *Final equivalent of PLD for RL-Load*

$$\text{EFR} = \lambda_{\text{I-NMF}} = \lambda_{C_1} + \lambda_{C_2} + \lambda_{C_3} + \lambda_{C_4} + \lambda_{C_5} = 0.0244\ failure/year\ ;$$

$$\text{AAOT} = \text{U}_{\text{I-NMF}} = \lambda_{C_1} r_{C_1} + \lambda_{C_2} r_{C_2} + \lambda_{C_3} r_{C_3} + \lambda_{C_4} r_{C_4} + \lambda_{C_5} r_{C_5} = 0.0237\ \ hrs/year$$

$$MOT of\ Inverter = r_{I-NMF} = \frac{U_{I-NMF}}{\lambda_{I-NMF}} = 1.058\ hrs;$$

The PMs for single phase inverter with R-L Load for NMF are computed using Eqns. (11) to (15) respectively as follows and shown in Table 4.

3.3 Based on Operation of Single Phase Full Bridge Inverter with R-L Load with MF

There are Four cutsets have been obtained i.e., $C_{1\text{-MF}}$, $C_{2\text{-MF}}$, $C_{3\text{-MF}}$ and $C_{4\text{-MF}}$, and shown in Fig. 15.

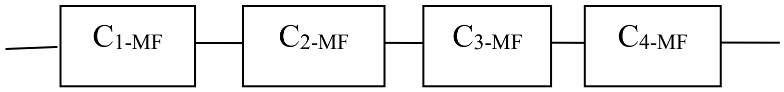

Fig. 15 *PLD of inverter considering malfunctioning*

All four Cutsets are in series, Unreliability of the inverter considering malfunctioning of SCRs obtained from Eqn. (37) is as follows:

$$Q_{I-MF} = Q_{C_1} + Q_{C_2} + Q_{C_3} + Q_{C_4} = 0.000048\ \times 4\ \ = 0.000576$$
$$R_{I-MF} = (\,1\text{-}\ Q_{I-MF}) = (1 - 0.000576) = 0.99942$$

The transitional rate of the inverter during malfunctioning is obtained from Eqn. (39) is as follows: $\mu_{\text{I-MF}}$ = 0.97271 hrs. The BPIs of Inverter with Malfunction are computed as follows and shown in Table. 3.

$$\lambda_{I-MF} = \lambda_{C_{1-MF}} + \lambda_{C_{2-MF}} + \lambda_{C_{3-MF}} + \lambda_{C_{4-MF}} = 5.645\ \times 10^{-4} failures/year;$$

$$r_{I-MF} = \frac{1}{\mu_{I-MF}} = 1.028 hrs;$$
$$U_{I-MF} = \lambda_{I-MF} \cdot r_{I-MF} = 5.8033\ \times 10^{-4}\ hrs/year;$$

The PMs for Inverter with R-L Load for MF can be computed similarly using Eqns. (11) to (15) respectively as follows and shown in Table.4.

3.4 The Overall Evaluation of BPIs and PMs for Inverter with R-L Load

The overall BPI for inverter with R-L Load are computed using the Eqns. (47) to (49) as follows, presented in Table 3, and shown in Fig. 16.

$$\text{EFR} = \lambda_{\text{I}} = \lambda_{\text{I-NMF}} + \lambda_{\text{I-MF}} = 0.02296\ \text{failure/year.}$$
$$AAOT = \text{U}_{\text{I}} = \text{U}_{\text{I-NMF}} + \text{U}_{\text{I-MF}} = 0.02428\ \text{hrs/year.}$$
$$\text{MOT} = r_{\text{I}} = \frac{\text{U}_{\text{I}}}{\lambda_{\text{I}}} = 1.0575\ \text{hrs.}$$

Table 3 *BPIs of inverter with R-L load for NMF, MF and overall*

S. No.	**BPI of Inverter as per the operation**	**EFR** (in failure/ year)	**MOT** (in hrs)	**AAOT** (in hrs/year)
1	With NMF	0.0244	1.0580	0.0237
2	With MF	$5.645\text{x}10^{-4}$	1.0280	$5.8033\text{x}10^{-4}$
3	Overall BPI for Inverter	0.02296	1.0575	0.02428

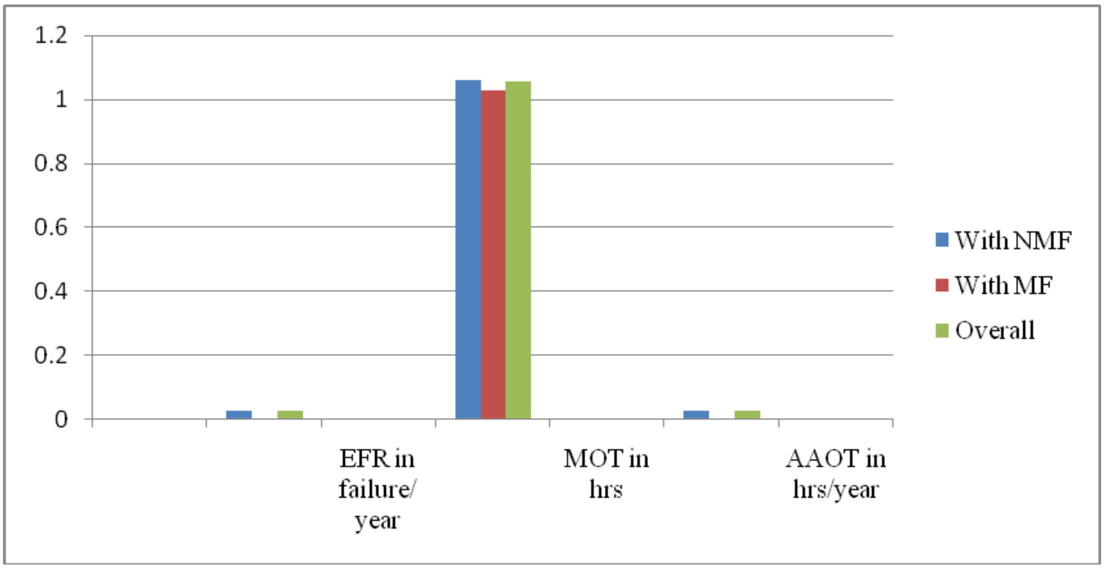

Fig. 16 *BPIs of inverter with R-L load for NMF, MF and overall*

The overall PMs for Inverter with R-L Load are computed using similarly Eqns. (11) to (15) respectively as follows, presented in Table 4, and shown in Fig. 17.

Table 4 *PMs of inverter with R-L load for NMF, MF and overall*

S. No.	PMs	NMF	MF	Overall
1	MTTF in years	44.6428	1771.4791	43.5540
2	MTTR in hrs	1.058	1.028	1.0575
3	MTBF in years	44.6429	1771.4792	43.5541
4	Availability	0.99999779	0.999999943	0.9999977
5	Unavailability	0.00000223	0.000000057	0.0000023

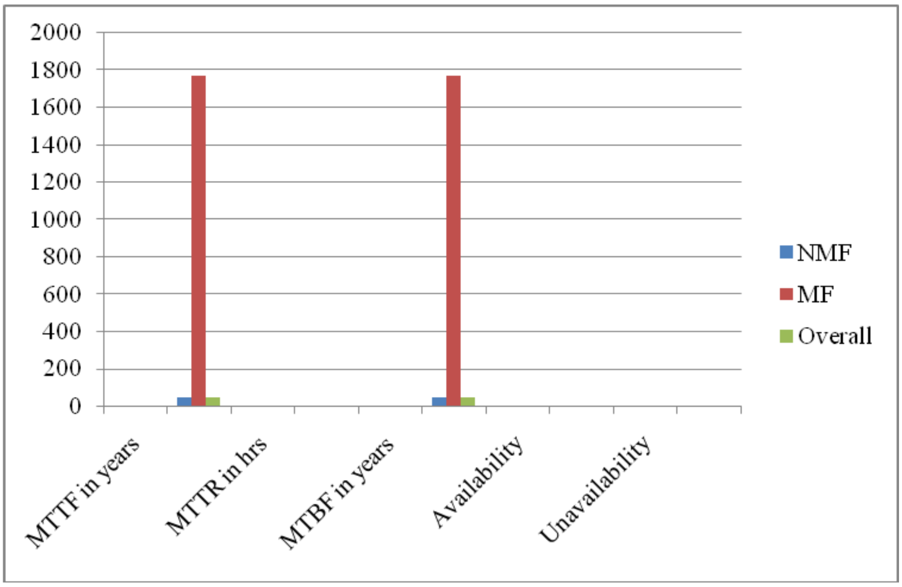

Fig. 17 *PMs of inverter with R-L load for NMF, MF and overall*

The results obtained are presented in Tables. 5 and 6 for BPIs and PMs for Inverter configuration with R-L Load. The results are also compared with the existing method [9] and the proposed method, and presented in Figs. 18 and 19 respectively.

Table 5 *BPIs for inverter with existing and proposed method*

S. No.	BPI Indices	Existing Method [9]	Proposed Cutset Method			
			R-Load	R-L Load With Non-Malfunction	R-L Load with Malfunction	Overall BPI for R-L Load
1	**EFR** (in failures/ year)	0.0224	0.0214	0.0224	$5.645\text{x}10^{-4}$	0.02296
2	**AAOT** (in hrs/year)	0.0237	0.0227	0.0237	$5.8033\text{x}10^{-4}$	0.02428
3	**MOT** (in hrs)	1.061	1.061	1.0580	1.0280	1.0575

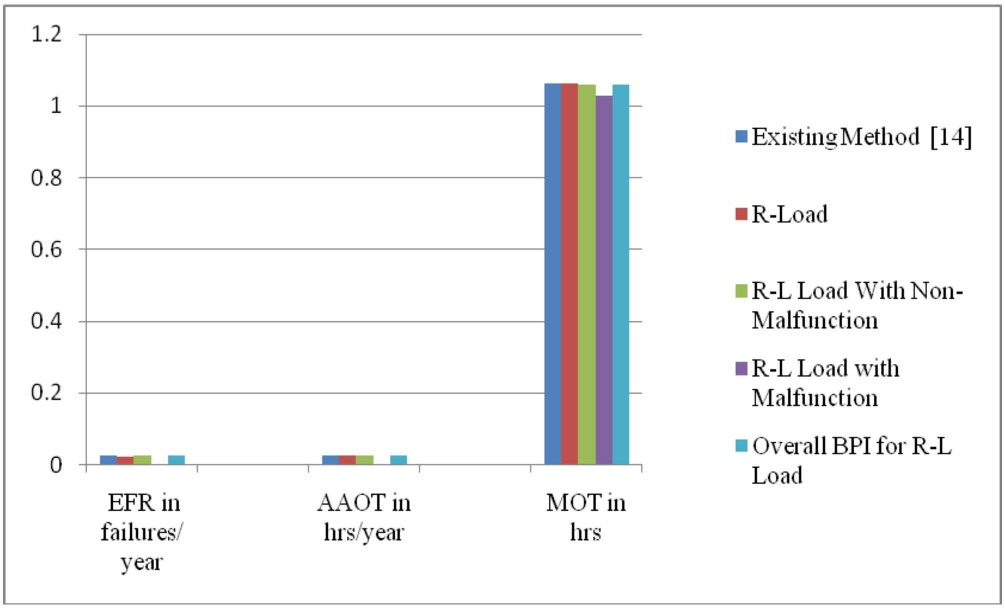

Fig. 18 *BPIs for inverter with existing and proposed method*

It has been observed from Table 5 that, for R-L load, when there is no malfunctioning effect, BPIs are same as that of the series configuration although cutset models have been developed based on the operation of the inverter. Further, including malfunctioning of the SCRs, it is observed that EFR and AAOT of the BPIs will increase i.e. the reliability will decrease which is more realistic. Further, it is also observed that MOT is more or less same.

The modelling of PLDs using cutset has been developed and it is observed that the Equivalent Failure Rate and Average Annual Outage Time are decreased while there is no change in Mean Outage Time. This is due to the fact that the failure of diodes will not affect the operation of the inverter.

Table 6 *PMs for inverter with existing and proposed method*

S. No.	Probabilistic Measures	Existing Method [9]	Proposed Cutset Method			
			R-Load	R-L Load With NMF	R-L Load with MF	Overall BPI for R-L Load
1	MTTF (in years)	44.6428	46.7289	44.6428	1771.4791	43.5540
2	MTTR (in hrs)	1.061	1.061	1.058	1.028	1.0575
3	MTBF (in years)	44.6429	46.7290	44.6429	1771.4792	43.5541
4	Availability	0.99999776	0.99999764	0.99999776	0.999999943	0.9999977
5	Unavailability	0.00000224	0.00000236	0.00000224	0.000000057	0.0000023

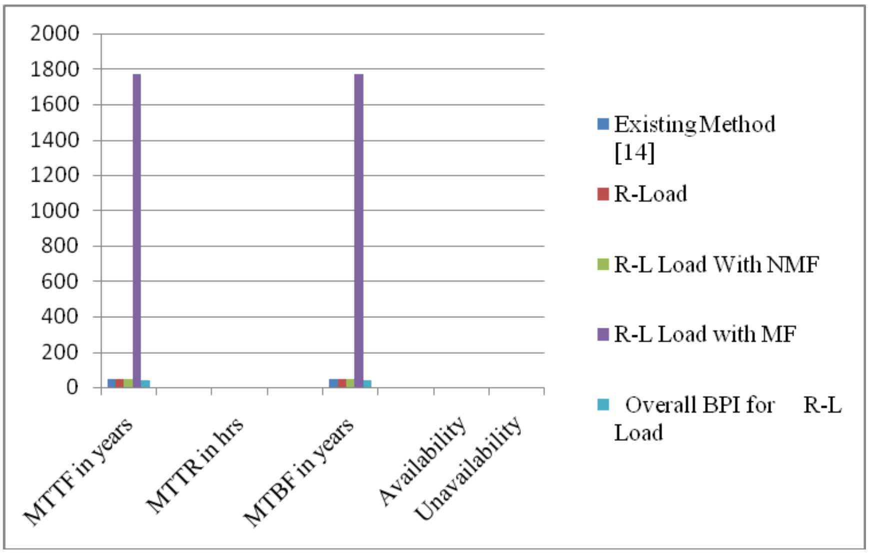

Fig. 19 *PMs for inverter with existing and proposed method*

From Table 6, it can be concluded that the PMs MTTF and MTBF will be increasing for R-Load, which means that operating time of the inverter will be more. This is due to the fact that there will be no effect of the diode in the R-Load in inverter configuration. Further, MTTF, MTBF decreases from the existing method for R-L Load as compared to the proposed method considering the overall indices including the effect of malfunctioning of the SCRs.

4. Conclusions

In this paper, the modelling of single phase full bridge inverter using cutsets has been developed for computation of BPIs and PMs for R and R-L Loads. Considering the operation strategies of the inverter, four modes of operation has been considered and PLDs have been developed, where as in the existing method series network configuration of PLD only and considered irrespective of the load conditions [9].

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Conflict of Interest

The authors declare that there is no conflict of interest.

Authors Contribution

All authors contributed equally to the conceptualization, formal analysis, investigation, methodology, and writing and editing of the original draft. All authors have read and agreed to the published version of the manuscript.

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