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Reliability analysis of single phase quazi Z source inverter for standalone photovoltaic system

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ABSTRACT

Quazi Z source inverter has an advantage that it can boost or buck voltage to be given to an inverter. Operation of a QZSI is similar to a Z source inverter (ZSI). A conventional photovoltaic application uses a two-stage topology of boost converter and an inverter. A QZSI can be replaced for a two-stage topology to serve the purpose. A 3 KW single phase QZSI is designed and simulated for a standalone photovoltaic system in this paper. The results for total harmonic distortion (THD) of output voltage and mean time between failure (MTBF) of the overall system is compared with a conventional ZSI and two-stage topology for the same rating. MTBF of the overall system is computed using reliability block diagram method. Reliability curve is also plotted for all the three considered topologies.

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1. INTRODUCTION

Photovoltaic (PV) application has gained importance in the recent years. The conventional topology for a PV application is a boost converter and an inverter. This system is termed as a two-stage topology. A single stage system proves economical than a two-stage system. In order to differentiate a two-stage and a single stage system reliability assessment becomes important from economy point of view. The advantage of using a Z source inverter (ZSI) in place of a conventional inverter is that it has the buck and the boost capability. Quazi ZSI (QZSI) offers advantage that the current at the DC supply side is continuous which makes it suitable for PV applications. Reliability comparison of QZSI with a two-stage conventional system is performed [1]. There are efficient control techniques for two-stage system whereas control techniques for QZSI system needs to be analyzed [2], [3]. QZSI is a derived topology of ZSI. The output voltage and efficiency of ZSI is analyzed and studied by simulation and practical implementation [4]-[10]. Several maximum power point tracking (MPPT) techniques are found in literature for the control of a PV system. Incremental conductance method is efficient than perturb & observe (P&O) MPPT method since it tracks quick change in solar radiation [11]. A 3 kW PV inverter is designed and simulated in MATLAB. Frequency spectrum for load current and load voltage is analyzed for RL load [12]. Two common types of sinusoidal pulse width modulation techniques for inverters are unipolar and bipolar switching. Unipolar switching for a conventional inverter is better than bipolar switching in terms of efficiency [13]. Comparison of single stage and two-stage topologies for PV application is performed in terms of power quality and efficiency [14]-[16]. Filters are required at the output of the inverter to obtain a sinusoidal waveform. Design equations for LC filter is referred in [17], [18]. Reliability computation of a system consisting of more converters in the system can be analyzed by reliability block diagram technique

[19]-[21]. Failure rate computation plays an important role in reliability assessment. The failure rate depends on stress factor of the individual components in a converter. Military handbooks (MIL-HDBK) 217 F a military handbook is a reference tool which describes the stress factor to be considered for individual components of the converter depending on application and other conditions [21]-[25].

Reliability comparison of a QZSI and a conventional ZSI is not considered previously in literature. This paper computes the total harmonic distortion (THD) and mean time between failure (MTBF) of the overall system for single stage topologies namely QZSI, ZSI and two-stage topology using unipolar, bipolar switching for the inverter. A single-phase system is considered for analysis. The computation for reliability of the overall system is performed using reliability block diagram (RBD) method. A comparison of topologies considered is analyzed in terms of performance and performance degradation.

2. METHOD

Reliability analysis gives an idea on the operating hours of a system. This information is vital when a system cannot be repaired. The reliability function is an exponential distribution for electronic components [20]. The system reliability is given by:

$$R = e^{-\lambda t} \tag{1}$$

Individual component failure rate λ is:

$$\lambda = \lambda b \left(\prod_{i=1}^{n} \pi_n\right) \text{ failures}/10^6 \text{ hours} \tag{2}$$

where, π_n are the various stresses in the components of the converter. Value for these stresses can be selected depending on the application and mounting environment. Which is outlined in MILHDBK-217F [21]. The overall converter failure rate is the summation of individual component failure rate,

$$\lambda_{overall} = \sum \lambda_{(individual\ component\ failure\ rate)} \text{ failures}/10^6 \text{ hours} \tag{3}$$

Converter MTBF can be obtained as:

$$MTBF = \frac{1}{\lambda_{overall}} hours \tag{4}$$

To compute the MTBF, failure rate equations and stress factors assumed for individual components are referred from MILHDBK [23] as in Table 1.

Table 1. Failure rate equations and stress factors considered for the components

Component	Equation	λb	πA	πQ	πE	πC	πcv	πS
MOSFET	$\lambda fet = \lambda b * \pi t * \pi A * \pi Q * \pi E$	0.012	10	5.5	6.0	-	-	-
Diode	$\lambda d = \lambda b * \pi t * \pi c * \pi Q * \pi s * \pi E$	0.069	-	5.5	6.0	1	-	0.054
Inductor	$\lambda p = \lambda b * \pi C * \pi E * \pi Q$	-	-	20	4	1	-	-
Capacitor	$\lambda p = \lambda b * \pi cv * \pi E * \pi Q$	-	-	10	2.0	-	$0.34*C^{0.18}$	-

To obtain the stress factor due to temperature, for the MOSFET,

$$\pi t = e^{\left(-1925\left(\frac{1}{(Tj+273)} - \frac{1}{298}\right)\right)} \tag{5}$$

For the diode,

$$\pi t = e^{\left(-3091\left(\frac{1}{(Tj+273)} - \frac{1}{298}\right)\right)} \tag{6}$$

Semiconductor device junction temperature can be computed as,

$$Tj = Tc + \theta jc * Ploss = Ta + \theta ja * Ploss + \theta jc * Ploss \tag{7}$$

where, Ta is ambient temperature: 30ºC; θja is ambient and junction thermal resistance of the device: 1ºC/w; θjc is junction and case thermal resistance: 0.95 (for switch): 1.6 (for diode), (from data sheets); $Ploss$ is power loss of semiconductor device. Data sheet specifications of IRFP150N MOSFET is considered for computation of power loss [23]-[25].

A practical system is represented as a combination of smaller networks/blocks. To assess the reliability of entire system, smaller networks which represent the entire system are identified as in Figure 1. These networks connected in series are said to be reliable if all the networks work for the success of the system. If there is a failure in any one network the system fails.

Figure 1. A series system representation

A series system reliability is

$$Rs(t) = R1(t).R2(t)..Rn(t) = \prod_{i=1}^{n} Ri(t) \tag{8}$$

A QZSI has operating modes similar to a conventional ZSI. The two modes of inverter operation are shoot through state, non shoot through state at the dc side. In traditional ZSI, voltage boost is provided for variation in dc bus creating an ac output at inverter side unlike the two-stage system which requires a boost converter. Figure 2 shows a single phase QZSI for a PV stand alone application considered as a single stage system.

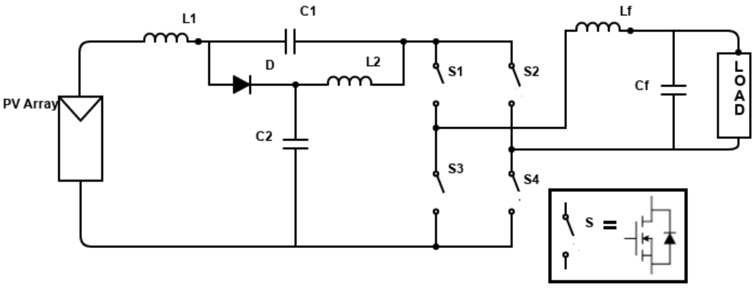


Figure 2. QZSI for PV stand alone application

A traditional ZSI is a Z network formed in X shaped by two capacitors and two inductors coupled to the inverter. Here too voltage is boosted by shoot through state. Figure 3 shows a traditional ZSI connected from a PV source to a load though a filter circuit.

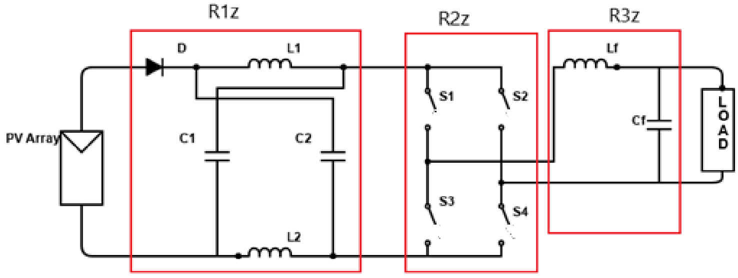


Figure 3. ZSI connected between PV source and load

To compute MTBF of overall system, the system can be divided into three networks or blocks (Figure 3). The blocks R1z, R2z, and R3z are considered for Z network, inverter circuit and the filter circuit. Reliability equation of each block from (1) is:

$$R1z(t) = e^{-\lambda c_1 t}.e^{-\lambda c_2 t}.e^{-\lambda l_1 t}.e^{-\lambda l_2 t}.e^{-\lambda D t} = e^{-2\lambda ct - 2\lambda lt - \lambda Dt} \tag{9}$$

Where $c_1=c_2=c$ and $l_1=l_2=l$

$$R2z(t) = e^{-\lambda S_1 t}.e^{-\lambda S_2 t}.e^{-\lambda S_3 t}.e^{-\lambda S_4 t} = e^{-4\lambda S_1 t} \tag{10}$$

Since, failure rate, $\lambda S_1 = \lambda S_2 = \lambda S_3 = \lambda S_4$

$$R3z(t) = e^{-\lambda L_f t}.e^{-\lambda C_f t} = e^{-\lambda L_f t - \lambda C_f t} \quad (11)$$

The overall reliability of the system becomes

$$Rz(t) = R1z(t).R2z(t).R3z(t) = e^{-(2\lambda c + 2\lambda l + \lambda D + 4\lambda S_1 + \lambda L_f t + \lambda C_f)t} \quad (12)$$

Therefore, from (4), MTBF can be written as:

$$MTBF = \frac{1}{2\lambda_c + 2\lambda_l + \lambda D + 4\lambda_{S1} + \lambda_{Lf} + \lambda_{Cf}} \text{ hours} \quad (13)$$

This MTBF equation holds good for Quazi Z source network connected between PV source and load too (Figure 2). The entire two-stage PV system is divided into three blocks R1t, R2t and R3t for boost converter, PWM inverter and LC filter circuit to filter harmonics in the output voltage as in Figure 4.

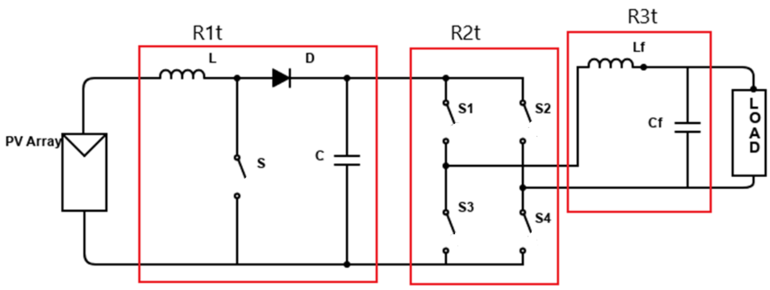


Figure 4. Two-stage PV system

Reliability equation of each block for the system can be written as:

$$R1t(t) = e^{-\lambda_S t}.e^{-\lambda_D t}.e^{-\lambda_L t}.e^{-\lambda_C t} = e^{-\lambda_L t - \lambda_S t - \lambda_D t - \lambda_C t} \quad (14)$$

$$R2t(t) = e^{-\lambda S_1 t}.e^{-\lambda S_2 t}.e^{-\lambda S_3 t}.e^{-\lambda S_4 t} = e^{-4\lambda S_1 t} \quad (15)$$

$$R3t(t) = e^{-\lambda L_f t}.e^{-\lambda C_f t} = e^{-\lambda L_f t - \lambda C_f t} \quad (16)$$

The overall reliability for two-stage system is:

$$Rt(t) = R1t(t).R2t(t).R3t(t) = e^{-(\lambda_L + \lambda_S + \lambda_D + \lambda_C + 4\lambda S_1 + \lambda L_f + \lambda C_f)t} \quad (17)$$

Therefore, MTBF of the two-stage becomes

$$MTBF = \frac{1}{\lambda_L + \lambda_S + \lambda_D + \lambda_C + 4\lambda_{S1} + \lambda_{Lf} + \lambda_{Cf}} \text{ hours} \quad (18)$$

3. CIRCUIT DESIGN

3.1. Z source inverter

The design equations for QZSI are similar to ZSI [8]. The control of ZSI or QZSI is through a simple boost control. Duty cycle (Do) for the shoot through pulse is obtained from,

$$B = \frac{Vo}{Vin} = \frac{1}{1-2Do} \quad (19)$$

Where, B is boost factor, Vo is output ac voltage of ZSI, V_{in} is input dc voltage.

Incremental conductance MPPT is used to obtain modulation index (M) of sine wave for creating PWM. M can be adjusted depending on the insolation and temperature of the PV panel, once shoot through duty cycle Do is obtained. $M = 1 - Do$. Shoot through duty cycle from which shoot through time period *(To)* can be obtained is,

$$Do = \frac{To}{T} \tag{20}$$

Where, *To* is time period for shoot through per switching cycle, *T* is switching time period which can be obtained for a known switching frequency *f*.
The inductor average current,

$$I_L = \frac{P}{V_{in}} \tag{21}$$

where, P is total power output,Vo is output voltage of ZSI, V_{in} is dc input voltage.
Capacitor voltage,

$$V_c = \frac{unboosted\ V + Boosted\ V}{2} = \left(\frac{1+B}{2}\right) vin \tag{22}$$

the inductor and capacitor values are obtained as:

$$L = L1 = L2 = \frac{V_c T_o}{I_L} \tag{23}$$

$$C = C1 = C2 = \frac{I_L T_o}{0.03\ V_c} \tag{24}$$

3.2. Two-stage system

The boost converter duty cycle is controlled by incremental conductance MPPT method. Here unipolar and bipolar modulation for the PWM inverter is considered for analysis. For a given total power output (P), input voltage (Vin), output voltage (Vo), duty cycle for the boost converter is:

$$D = (1 - \frac{Vin}{Vo}) \tag{25}$$

For a switching frequency f, load resistor (R)

$$R = \frac{(Vo)^2}{P} \tag{26}$$

For inductor current to be continuous, inductor (L)

$$L = 1.25 \frac{(D(1-D)^2 R)}{2f} \tag{27}$$

Capacitor (C)

$$C = \frac{D}{R\left(\frac{\Delta Vo}{Vo}\right) f} \tag{28}$$

Assuming ΔI_l as 20% of rated load current [18], filter inductance (Lf)

$$L_f = \frac{Vo}{4\ \Delta I_{lmax}\ f} \tag{29}$$

Where $\Delta I_{lmax} = \sqrt{2} * \Delta I_l$, filter capacitance (Cf)

$$C_f = \frac{1}{Lf}\left(\frac{10}{2\pi f}\right)^2 \tag{30}$$

4. RESULT AND DISCUSSION

A 3 Kw inverter is considered for analysis. Tata Power Solar systems TP250MBZ PV module is selected in MATLAB/Simulink. Six series modules connected in two parallel strings is implemented to obtain a power of 2.98 Kw for an input voltage, Vin=180 V and output voltage, Vo=310 V(peak). The switching frequency (*f*) is assumed as 10 KHz. The values obtained from computation are resistive load, R=34 Ω and resistive-inductive load, R=31 Ω and L=47 mH for 0.9 power factor. Single phase supply is considered for the inverter. The design specification is as shown in Table 2.

The irradiance pattern for the PV module considered is as shown in Figure 5. Incremental conductance MPPT is used for the control of the converter and single stage inverters. The components which are prone to failure in a power electronic converter are the switches and capacitors. A comparison of the different topologies shows that the total number of switches in two-stage topology is higher when compared to other topologies as in Table 3. Also, the number of capacitors in QZSI and ZSI is higher than two-stage topology.

Table 2. Design specifications

Topology	Quasi Z source	Z source	Two-stage
Duty cycle (D)	0.22	0.22	0.25 (Boost converter)
Modulation index (M)	0.78	0.78	0.7
Inductor **(L)**	50 µH	50 µH	0.169 mH
Capacitor **(C)**	590 µF	590 µF	1300 µF
Filter inductor **(Lf)**	3 mH	3 mH	2 mH
Filter capacitor **(Cf)**	9 µF	9 µF	15 µF

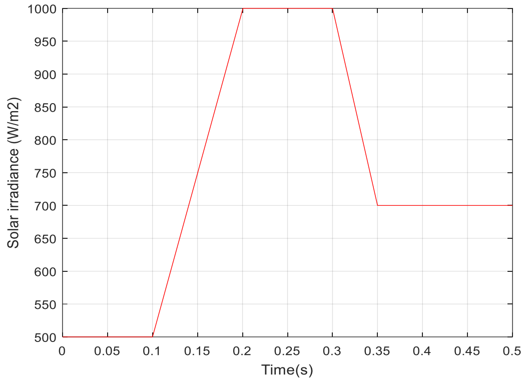


Figure 5. Irradiance pattern from PV array

Table 3. Total number of components used for each topology

Type	Inductors	Capacitors	Switches	Diodes	Total components
QZSI	3	3	4	1	11
ZSI	3	3	4	1	11
Two-stage	2	2	5	1	10

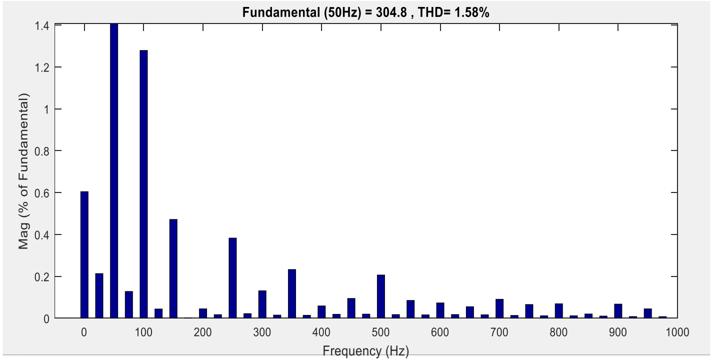
Figures 6(a) and (b) shows the plot of THD for output voltage of QZSI for resistive, resistive-inductive load. Similarly, Figures 7(a) and (b) shows the plot of THD for output voltage of ZSI for resistive, resistive-inductive load. Figures 8(a) and (b) shows the THD plot for bipolar switching of a two-stage topology for resistive, resistive-inductive load. Figures 9(a) and (b) shows the THD plot for unipolar switching of a two-stage topology for resistive, resistive-inductive load. THD plot of ZSI has higher magnitude of higher order harmonics. Also, bipolar switching topology has higher magnitude of higher order harmonics which may cause electromagnetic interference problems. Therefore, better filter circuit design is required for these topologies.

The comparison between the MTBF and THD for various topologies is shown in Table 4. As per IEEE-519, if a system as considered above has to be coupled to grid the THD voltage distortion needs to be less than 5%. Here ZSI has higher THD compared to other topologies.

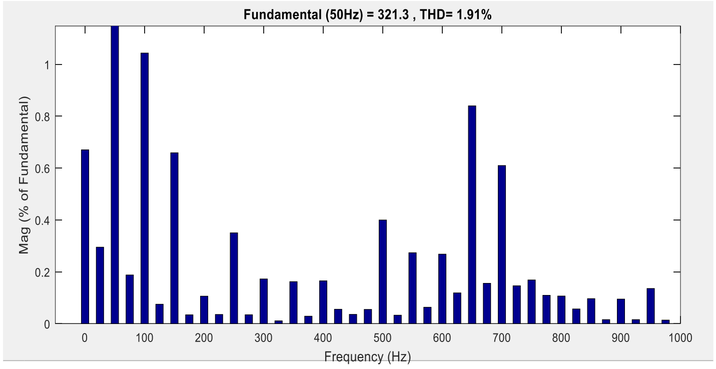
Table 4. Comparison of MTBF and THD for QZSI, ZSI and two-stage topology

	R load		RL load	
	MTBF (hours)	THD	MTBF (hours)	THD
QZSI	45490	1.58	45270	1.91
ZSI	46090	2.47	46030	3.12
Unipolar switching	42500	0.79	42430	1.40
Bipolar switching	42410	1.14	42380	1.92

From Figure 10, it can be seen that MTBF is highest for ZSI and lowest for two-stage topology with bipolar switching. Single stage topology has higher MTBF compared to the two-stage topology. That means single stage topology is more reliable than two-stage topology. This holds good for resistive and resistive-inductive load.

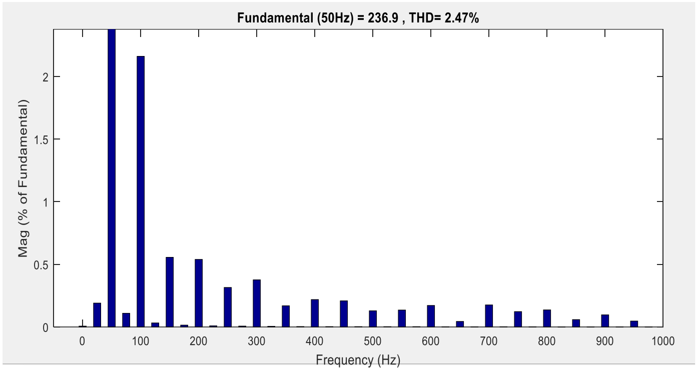


(a)

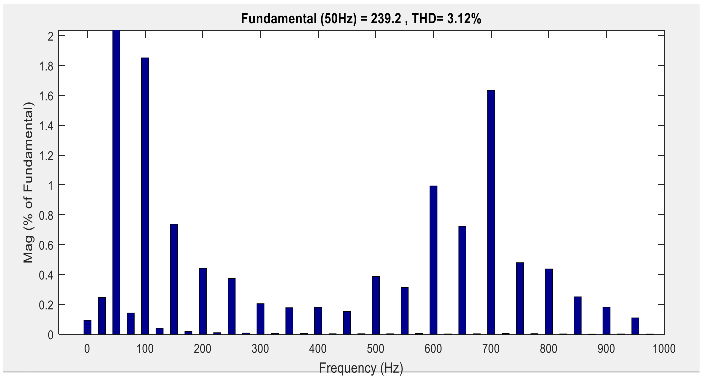


(b)

Figure 6. THD plot for QZSI (a) resistive load and (b) resistive-inductive load

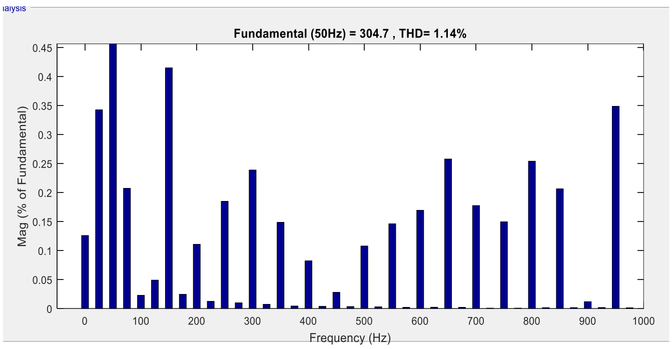


(a)

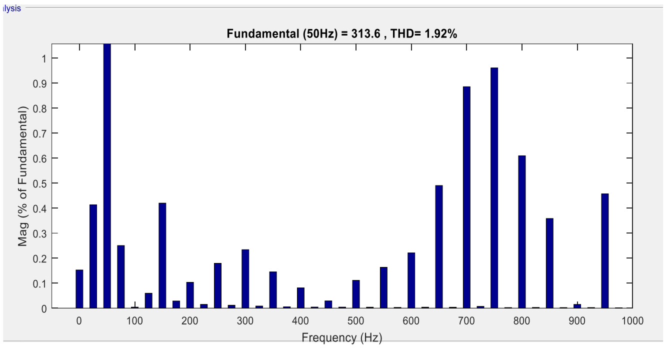


(b)

Figure 7. THD plot for ZSI (a) resistive load and (b) resistive-inductive load

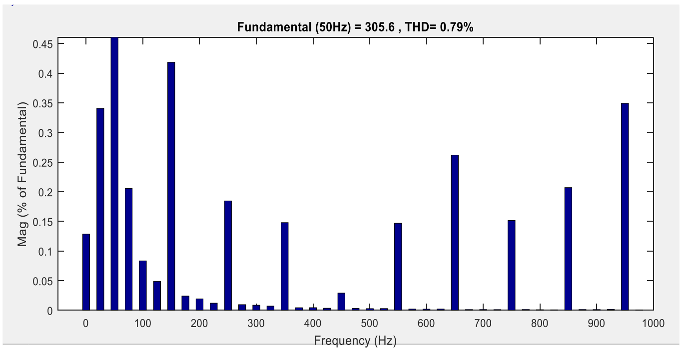


(a)

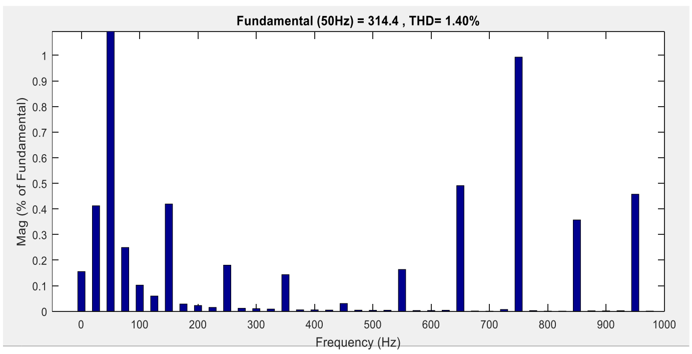


(b)

Figure 8. THD plot for bipolar switching (a) resistive load and (b) resistive-inductive load



(a)



(b)

Figure 9. THD plot for unipolar switching (a) resistive load and (b) resistive-inductive load

There is no much difference in the reliability plot for resistive and resistive-inductive load as in Figure 11 and Figure 12. The QZSI and ZSI reliability plot are coinciding for both types of loads considered. Also, the bipolar and unipolar switching reliability plot are coinciding for both the loads. Using (1) and (4), for 1 year or 8,760 hours, the probability of success for QZSI is 0.824, ZSI is 0.826, unipolar switching is 0.814 and for bipolar switching is 0.813. Although the probability of success of QZSI is slightly lower than ZSI, it has the advantage of better THD than ZSI.

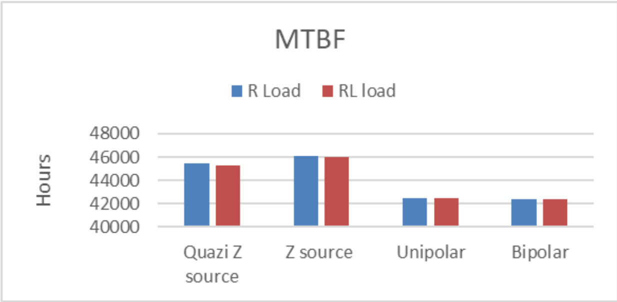


Figure 10. Chart of MTBF for QZSI, ZSI, and two-stage topology

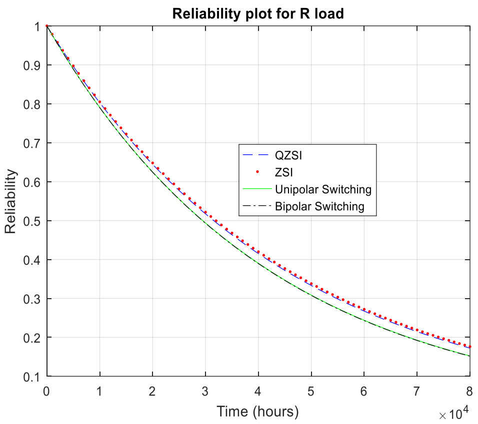


Figure 11. Reliability plot for resistive load

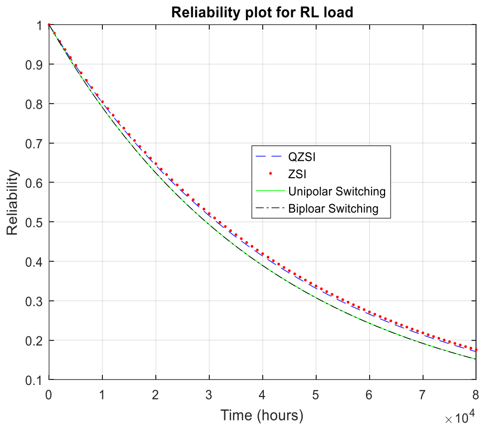


Figure 12. Reliability plot for resistive-inductive load

5. CONCLUSION

In this paper comparison of THD of output voltage and MTBF of the overall system for the three topologies namely QZSI, ZSI, and two-stage topology is performed. The results are simulated in MATLAB for a single-phase stand-alone PV system considering resistive, resistive inductive load. Results show that the QZSI has lower THD than ZSI. MTBF of ZSI is higher than QZSI, which shows that ZSI is reliable than QZSI. Although the THD for the two-stage topology is lesser than the ZSIs, the MTBF of the topology is also lesser. From the reliability plot, the order of reliable topologies is ZSI, QZSI, two-stage topology. The drawback of ZSI is it requires an accurate design for simulation and practical implementation. Therefore, QZSI can be recommended when compared to a two-stage topology for stand alone PV applications. The future scope is QZSI need to be developed practically and the results are to be verified.

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