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Reliability improvement in Z-source inverter with redundancy

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ABSTRACT

The proposed work deals with evaluation and improvement of a Z-source inverter using simulation. A Z-source inverter is a type of power inverter, a circuit that converts direct current to alternating current. It functions as a buck-boost inverter without making use of DC-DC converter-bridge due to its unique circuit topology. MIL-HDBK-217F (Military handbook) is used to evaluate the reliability of this Z-source inverter. We have proposed a system which has been theoretically proved to have lowest failure rate leading to reduced system repairing because of the use of redundant switches. The MTBF (mean time between failure) is high for redundant switches which will increase the life of the inverter. Simulation of the proposed system is done on MATLAB and comparison of reliability of Z-source inverter is done with the results found theoretically. In a conventional inverter if one switch of inverter fails the complete leg will fail. Whereas in our case that is in Z-source inverter, because of the intermediate shoot through stage redundant switch will replace the failed switch thus saving it from failure.

Keywords*: Z-source inverter, MIL-HDBK-217F, MATLAB, Redundant switch.*

1. INTRODUCTION

As a result of fast depleting fossil fuels and environmental concerns, the electricity generated from renewable energy sources (RES) has received so much attention as an option for the conventional power plants. With the increasing use of RES for electrical power generation, solar photovoltaic (PV) based power generation is gaining more and more popularity for its clean nature, zero greenhouse gas emissions, no fossil fuel consumption and availability in abundance.

Almost all the power electronic converters and inverters are based on semiconductor switches which are considered to be the most vulnerable to the faults which make these power electronic devices a major source of failure in the system. Hence the reliability of these inverters and converters play a significant role in evaluating and improving the reliability of the overall system. Many researchers are working in this area now a days for evaluating the reliability of the power electronic converters and inverters.

In order to increase the power handling capacity and to improve the overall reliability of the power electronic systems, interleaved boost converter (ILBC) can prove to be the better alternative to the conventional DC –DC boost converters. However, a distinguishing characteristic of a Z – source inverter (ZSI) makes it more reliable than ILBC. A ZSI has a capability of introducing shoot through switching states for boosting the output voltage. In the shoot through state both the switches in one leg of the inverter are turned on simultaneously and hence controlling of ZSI requires innovative modulation strategies.

For evaluating the reliability of power electronic devices under various operating conditions, a common platform is provided by military handbooks published by United States Department of Defense. The Part Stress and Part Count methods are by and large used to evaluate the reliability of these devices. Reliability of a component is an exponential function of the failure rate of that component. The base failure rates and other affecting factors for reliability evaluation are given in.

Most of the power electronic converters are manufactured without redundancy. Hence it is generally assumed in the analysis of failure rates that if one of the components fails, the entire system will fail. So reliability evaluation of each component is necessary. From reliability point of view, it can be assumed that all components are connected in series since failure of any one component may result in failure of the whole system. To avoid this, redundancy in the converters and inverters is a recognized option used to design electronic systems which will sustain the faults. The reliability analysis of such systems with redundancy proved increased lifetime of these systems.

This paper, hence, focuses on the reliability evaluation of various configurations of inverters with and without redundancy. Military Handbook MIL HDBK 217F is used as base for calculating the reliability and the results are presented which show that the ZSI with redundancy is the most reliable configuration of the inverter among all other configurations.

2. BASICS OF RELIABILITY EVALUATION

Basically, reliability of the complete system is the probability that each component of that system shall perform satisfactorily for a given period of time under specified conditions. Reliability *R(t)* of the overall generation system can be obtained as the product of all reliabilities.

$$R(t) = \prod_{i=1}^{n} R_i(t) \tag{1}$$

where *Ri(t)* is the reliability of i^{th} component and *n* is the number of components. In general, the Mean Time Between Failures (MTBF) applies to equipment that is going to be repaired and returned to service. Mean Time to Failure (MTTF) applies to parts that will be thrown away on failing. MTBF/MTTF is given by (2);

$$\text{MTBF/MTTF} = 1/\lambda \tag{2}$$

Where, λ is the failure rate

Let $\lambda_i(t)$ be the failure rate function for the i^{th} failure mode

Then,

$$R_i(t) = \exp\left[-\int_0^t \lambda_i(\tau)d\tau\right] \tag{3}$$

And

$$R(t) = \prod_{i=1}^{n} \exp\left[-\int_0^t \lambda_i(\tau)d\tau\right] \tag{4}$$

$$R(t) = \exp\left[-\int_0^t \sum_{i=1}^{n} \lambda_i(\tau)d\tau\right] \tag{5}$$

$$R(t) = \exp\left[-\int_0^t \lambda(\tau)d\tau\right] \tag{6}$$

Where,

$$\lambda(t) = \sum_{i=1}^{n} \lambda_i(t)$$

Hence the reliability is exponential function of failure rate which is the sum of all the individual failure rates.

3. PROPOSED ZSI WITH REDUNDANCY

3.1 Proposed Z–Source Inverter

Figure 2 below shows ZSI with two redundant switches. In case of ZSI, if one switch of the inverter fails, because of intermediate shoot through stage, the same can be replaced by a redundant switch so that unlike conventional inverter, the complete leg does not fail and hence the failure rate of the overall inverter thus reduces to one fourth of that of the conventional inverter. Hence the reliability of this configuration of ZSI increases by four times of the original value. In case of Z – Source Topology with redundant switches, the failure in IGBT at one leg shall withstand this failure due to impedance source network and will provide sufficient time for the logic circuit to replace the faulty switch.

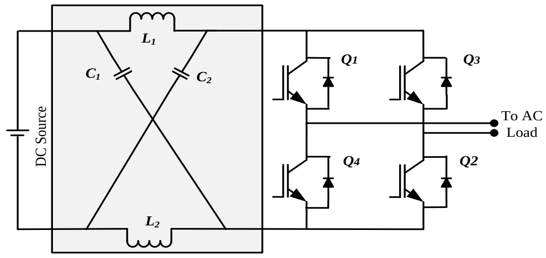

Fig no.1: Impedance Source Inverter (Z – Source Inverter)

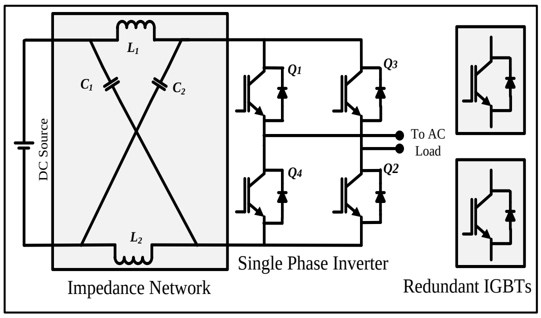

Fig no.2: ZSI with redundancy

3.2 Procedure to evaluate reliability of Z-Source Inverter

Table 1: Failure rates and values of corresponding components

COMPONENTS	FAILURE RATE MODEL	VALUE(failure/ hour X10^{-6})
Capacitor	λC=λc,bπTπCπSπSR πQπE	0.0045
Inductor	λL = λL,bπTπQπE	8.3700e-005
Diode	λD = λD,bπTπCCπSπQπE	0.0418
IGBT Module	λS= λS,bπTπAπQπE	4.1690

The overall failure rate of the system can be calculated by adding the individual failure rates of all the components of that system. For example:

Consider a ZSI system with two inductors & capacitors and an IGBT (without redundancy). Then, overall failure rate can be calculated as follows,

$$\lambda_{ZSI} = \{[2 \text{ x } (\lambda_L + \lambda_C)] + (\lambda_{IGBT})\} \text{x } 10^{-6}$$

Hence, Overall failure rate of Z – Source Inverter (λ_{ZSI}) is -

$$\lambda_{ZSI} = \{[2 \text{ x } (\lambda_L + \lambda_C)] + (\lambda_{IGBT})\} \text{x } 10^{-6}$$

$$= [2 \text{ x } ((8.3700\text{x}10^{-5}) + 0.0045) + (4.1690)] \text{ x } 10^{-6}$$

$$\boldsymbol{\lambda_{ZSI} = 4.1782 \text{ x } 10^{-6} \text{ Failures / Hour}}$$

So, the MTBF of Z – Source Inverter can be evaluated as;

$$MTBF = \frac{1}{\lambda}$$

$$MTBF = \frac{1}{4.1782e-6}$$

MTBF = 239337 Hours

MTBF = 27. 32 Years

Hence, the reliability of the Z – Source inverter is obtained as follows;

$$R(t) = exp(-\lambda t)$$
$$= exp\ (-\ 4.1782\ X\ 10^{-6}\ X\ 24\ X\ 365)$$
$$R(t) = 0.9640$$
$$\mathbf{R(t) = 96.40\%}$$

Now, considering ZSI (with redundancy):
Since there is a redundant leg present in the configuration, it logically gets into operation when any one leg of the inverter is short circuited. Hence the failure rate of the inverter reduces to half of the original inverter principally. Hence the reliability of this configuration of ZSI increases exponentially according to the corresponding failure rate

Hence, Overall failure rate of proposed ZSI (λ_{ZSIR}) is –

$$\boxed{\lambda_{ZSIR} = \frac{\lambda_{ZSI}}{2}}$$

$$\lambda_{ILBC} = \frac{4.1782 \times 10^{-6}}{2}$$

$$\mathbf{\lambda_{ILBC} = 2.0891 \times 10^{-6}\ Failures\ /\ Hour}$$

So, the MTBF of ZSI with redundancy can be evaluated as;

$$MTBF = \frac{1}{\lambda}$$

$$MTBF = \frac{1}{2.0891 \times 10^{-6}}$$

MTBF = 478675 Hours

MTBF = 54.64 Years

Hence, the reliability of the ZSI with redundancy is obtained as follows;

$$R(t) = exp(-\lambda t)$$
$$= exp\ (-\ 2.0891\ X\ 10^{-6}\ X\ 24\ X\ 365)$$
$$R(t) = 0.9819$$
$$\mathbf{R(t) = 98.19\%}$$

4. BLOCK DIAGRAM

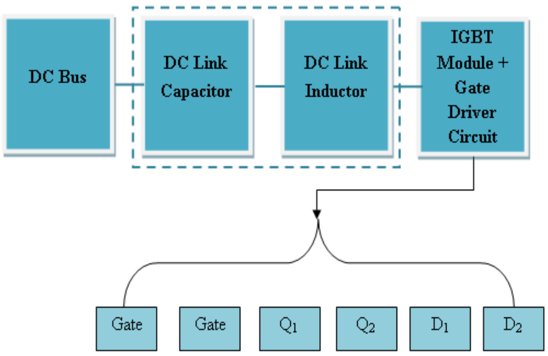

Fig no.3: Reliability Block Diagram of a Z – Source inverter

The reliability block diagram for the circuits shown in figure. It contains a unique impedance network of inductors and capacitors, the Z shoot through states by gating on both the upper and lower switches in the same legs. The network contains L1 and L2 which are series arm inductances, C1 and C2 which are diagonal arm capacitance. Each leg consists of two switches and their antiparallel diodes. Each leg is switched in such a way that when one of them is in off state, the other is in on state. Assuming that all the components are connected in series from reliability point of view as the failure of any single component may reduce the reliability to zero making the overall system to shut down.

5. SIMULATION RESULT

The simulation is carried out in MATLAB and the results of the Z – source inverter is presented. The simulation details are as follows:

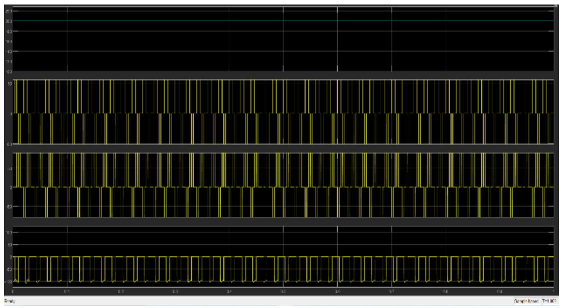

Fig no.4: Waveform of inverter Output Voltage under open circuit condition

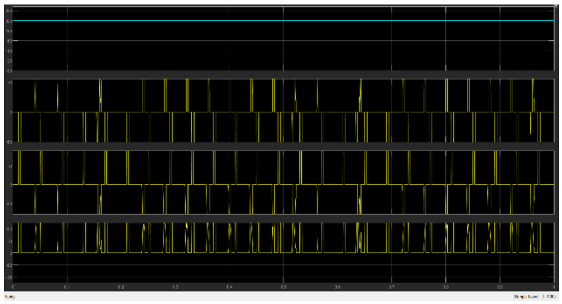

Fig no.5: Waveform of inverter output voltage under short circuit condition

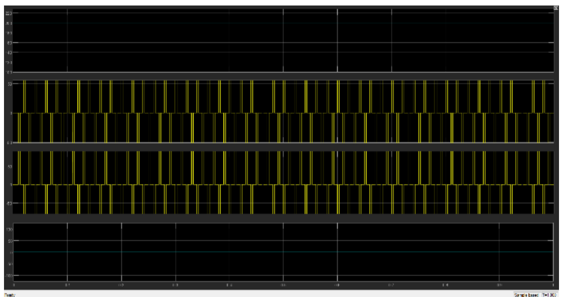

Fig no.6: Waveform of inverter output voltage under one leg failure condition

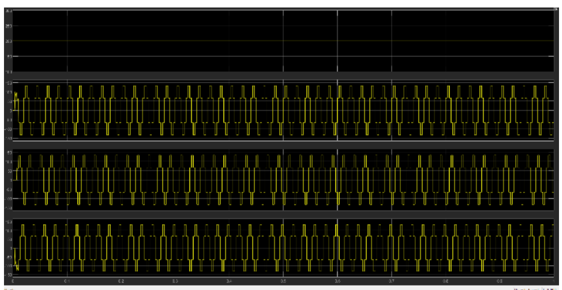

Fig no.7: Waveform of inverter Output Voltage with redundant switches

CASE 1: OPEN CIRCUIT FAULT

Power switch open-circuit can be caused by a fault in the control electronics resulting in unavailable gate drive signal. An open

IGBT fault can lead to over stresses on healthy power switches as well as pulsating current. This can in turn lead to failures in other components. The output voltage of three phase ZSI when fault is occurred is in shown in Fig no.4. The output of inverter when the fault is occurred will contain the pulsating dc voltage that is positive only which is seen in last block which represents phase voltage (Vca).

CASE 2: SHORT CIRCUIT FAULT

Power semiconductors short-circuit faults are the most critical failure modes because of its potentially destructive consequences. There are two main reasons to happen a short: (i) a fault in the control or drive electronics resulting in a continuous drive signal, or (ii) an overcurrent leading to temperature rising above critical temperatures (250ºC-300ºC). The fig no.5 displays the output waveform three phase ZSI under short circuit fault condition. From the output we can conclude that the whole system has been disturbed due to this short circuit fault.

CASE 3: ONE LEG FAILURE CONDITION

Due to one leg failure, it imposes over stress on other power devices. In output waveform, after failure of one leg, one of phase voltage becomes zero and other two waveforms get distorted as seen in fig no.6.

CASE 4: ZSI WITH REDUNDANT SWITCHES

Since the redundant leg is connected in the configuration, it will logically get into operation when any of the fault takes place. Hence the reliability of the system with redundant switches increases. Fig no.7 represents the output waveform with redundant switches. After replacing the faulty switches with redundant switches, the continuity of the system will be maintained and it will prevent the failure of complete system.

6. CONCLUSION

- In case of Z-Source Inverter if one switch of the inverter fails, because of intermediate shoot through stage a redundant switch can replace the same so that unlike conventional inverter, the complete leg does not fail.
- Theoretically it is proven that the failure rate of ZSI with redundant switches is found to be less than the ZSI without redundant switches using Military Data Book MIL 217F.
- The failure rate of proposed system is lowest and repairing of the system reduces significantly because of redundant switches.
- Also the MTBF (Mean time between failure) is high with redundant switches which upgrades the life of Z-source inverter.
- Thus, with MATLAB simulation we have compared the reliability of Z-source inverter with the theoretical results.

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