Mathematical analysis of cost function and reliability condition for new proposed multilevel inverter topology

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ABSTRACT
In this paper cost function and reliability analysis of classic novel symmetric multilevel inverter topology has been presented. Cost function and reliability analysis are the economical factors of the efficiency of an inverter, this made the interest in this area. Cost function denotes the cost of the inverter based on the power flow, reliability explain the mean time failure propotional to the life span. Firstly the cost function of the novel topology has been proposed using mathematical calculation using various current rating and the results are validated compared with exiting topology. Secondly reliability approach is used to evaluate the reliability of the switch with respect to the failure rate and mean time period of the switch using fedis and markow reliability analysis equations and the results are evaluated for all the switches present in the topology. And the results are compared with the conventional multilevel inverter, cost function and reliability analysis of the proposed multilevel inverter.

Keywords: Cost function, Mathematical analysis, Mean time failure, Reliability analysis

1. INTRODUCTION
Now a day’s renewable energy resources like solar and wind plays a vital role in the field of energy production, particularly speaking the solar energy has numerous advantage compared to wind resources like less installation cost, enormous availability [1-4]. Cost function is defined as expressing the production cost of the product in terms of the amount produced for designing of circuit. It helps to decide the pricing of the particular product. Cost function is depends on the number of components are used in the inverter topology. If number of components is increased cost also increased. Cost function is related to cost of switch. It’s depends on the various factors in this implementing the factor of the blocking voltage across the switch. Performance is the one of the factor to cost fixing [5-8]. The capability of a product to perform a required function for the given time interval is called reliability. Demonstration and taking technical and physical factors have identified role in reliability. Reliability provides the electrical and mechanical components performance and life profile of the particular product. Main factor in reliability is failure rate of the each component. Failure mechanism means a set of cause’s effect relation for physical, chemical or other process that relates to the root cause of the failure rate for the component [9-12].

The proposed topology can produce 11-level and the level can be increase by cascading the topology both in symmetrical and as well as in unsymmetrical aspects. In this paper the cost function and reliability analysis has been analyzed and its cost function is compared with various same level existing topologies. The Figure 1 represents the new topology multilevel inverter which has 8 switches and 5 sources in symmetrical condition and can also be redrawn using three sources and two capacitor if it has been as unsymmetrical mode [13-18]. Load we are considering is practical RL load for medium voltage applications.
2. METHODOLOGY
First condition to design a novel multi level inverter topology is, it should have less number of power electronics components like less number of switches, sources and passive elements, so that the cost and size of the inverter is less [19-23]. Second condition is it should have better performance in its working condition like high voltage, current, less THD, cost function & reliability condition, here the new designed topology is analyzed based on its cost function and reliability, so that its results the economic condition of the designed inverter based on cost, life span & failure condition, here two analysis has been done using mathematical equations and fedis reliability conditions to verify the circuit efficiency based on cost and mean time failure. The cost function of the proposed circuit is given below in the Section 3:

3. COST FUNCTION
3.1. Cost function for the conventional multilevel inverter
For making the analysis at first we are considering the conventional multilevel inverter topology with 12 switches and 5 sources as shown in Figure 2.

To make the analysis understandable, consider the Switches S1 and S2: per unit value=1
From this assumption the voltage across each switch is given in, in open Condition each switch will block Voltages V 1 and V 2 i.e. 1+1=2V
Similarly, S3 and S4 each will block V2 and V3 i.e. 1+1=2V
Similarly, S5 and S6 each will block V3 and V4 i.e. 1+1=2V
Similarly, S7 and S8 each will block V4 and V5 i.e. 1+1=2V respectively.
Switches M1 and M4 each will block V1 and V5 i.e 1+1=2V
Similarly Switches M2 and M3 each will block V1 and V5 i.e 1+1=2V respectively

\[ S_4 = S_5 = 1 + 1 = 2V \]
\[ S_6 = S_7 = 1 + 1 = 2V \]
\[ M_1 = M_4 = 1V \]
\[ M_2 = M_3 = 1V \]

Blocking Voltage across the Switch is given by \( \frac{V_{\text{max}}}{V_{\text{block}}} \) (1)

Consider \( V_{\text{max}} = 5V \)

\[ S_1=S_2=\frac{5}{2} = 2.5V \]
\[ S_3=S_4=\frac{5}{2} = 2.5V \]
\[ S_5=S_6=\frac{5}{2} = 2.5V \]
\[ S_7=S_8=\frac{5}{2} = 2.5V \]
\[ M_1=M_4=\frac{5}{1} = 5V \]
\[ M_2=M_3=\frac{5}{1} = 5V \]

The Blocking Voltages across the Switches are

\[ S_1+S_2+S_3+S_4+S_5+S_6+S_7+S_8+M_1+M_2+M_3+M_4 = (2.5 * 8) + (5 * 4) = 40V \]

\[ V_{PV} = \frac{\text{Total voltage}}{\text{Number of Switches}} \] (2)

Cost function=\( N_{\text{IGBT}} + \alpha V_{\text{PV}} \) (3)

where \( \alpha \) is current rating

a) If \( \alpha=0.5 \)
\[ C.F = 8 + 0.5(8) = 12 \]

b) If \( \alpha=1.5 \)
\[ C.F = 8 + 1.5(8) = 20 \]

c) If \( \alpha=2.5 \)
\[ C.F = 8 + 2.5(8) = 28 \]

d) If \( \alpha=3.5 \)
\[ C.F = 8 + 3.5(8) = 36 \]

e) If \( \alpha=4.5 \)
\[ C.F = 8 + 4.5(8) = 44 \]

3.2. Cost function of the proposed multilevel inverter

In connection with earlier analysis in section 3.1, we are moving to the comparative analysis for proposed novel topology 11-level inverter with reduced power components as shown in Figure 3.

![Proposed novel topology 11-level inverter](image-url)
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Consider the switches $S_4$ and $S_5$
In open Condition each switch will block Voltages $V_1$ and $V_2 = 1 + 1 = 2V$
Similarly, $S_6$ and $S_7$ each will block voltage $V_3 = 1V$
Similarly, $S_1$ block voltage $V_1, V_2, V_3, V_4 = 4V$
Similarly, $S_8$ block voltage $V_1, V_2, V_3, V_4, V_5 = 5V$

Blocking voltage across the switch $\frac{V_{max}}{V_{block}}$ $V_{max}=5V$

$$S1 = \frac{5}{4} = 1.25V, \quad S8 = \frac{5}{2} = 2.5V$$

$$S2, S3 = \frac{5}{5} = 1V, \quad S4, S5 = \frac{5}{2} = 2.5V$$

$$S6, S7 = \frac{5}{1} = 5V$$

Total blocking voltage circuit given by

$$V_{PV} = \frac{\text{Total voltage}}{\text{Switch}} = \frac{20.75}{5} = 4.15V$$

Cost function $= N_{IGBT} + \alpha \cdot V_{PV}^\text{switch}$
where $\alpha$ is current rating

a) If $\alpha = 0.5$
   $$C.F = 8 + 0.5(4.15) = 10.075$$

b) If $\alpha = 1.5$
   $$C.F = 8 + 1.5(4.15) = 14.225$$

c) If $\alpha = 2.5$
   $$C.F = 8 + 2.5(4.15) = 18.375$$

d) If $\alpha = 3.5$
   $$C.F = 8 + 3.5(4.15) = 22.525$$

e) If $\alpha = 4.5$
   $$C.F = 8 + 4.5(5) = 26.675$$

3.3. Comparison of cost function between conventional and new topology multilevel inverter

Table 1 represents the comparison of the cost function between conventional multilevel inverter and new topology multilevel inverter, from the results it is evident that the cost function of new topology has better performance in all the variants of “$\alpha$” compared to the conventional topology.

<table>
<thead>
<tr>
<th>Cost Function</th>
<th>$\alpha=0.5$</th>
<th>$\alpha=1.5$</th>
<th>$\alpha=2.5$</th>
<th>$\alpha=3.5$</th>
<th>$\alpha=4.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Multilevel Inverter</td>
<td>12</td>
<td>20</td>
<td>28</td>
<td>36</td>
<td>44</td>
</tr>
</tbody>
</table>

4. RELIABILITY OF PROPOSED MULTILEVEL INVERTER

4.1. Reliability analysis
Calculate failure rate of each switch according to data sheet to the used thyristor [24-27].

a) Calculate the failure rate for used thyristor.

$$\lambda = \lambda_{\text{physical}} \cdot \pi_{\text{PM}} \cdot \pi_{\text{Process}}$$ (4)

$\lambda$ is failure rate
$\pi_{\text{PM}}$ is part manufacturing represents quality and technical control over manufacturing of item.
$\pi_{\text{Process}}$ is quality and technical control over manufacturing and usage.

$$\lambda_{\text{physical}} = \lambda_b$$

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\[ \pi_{PM} = \pi_T \pi_Q \pi_E \]
\[ \pi_{Process} = \pi_R \pi_S \]
\[ \lambda_p = \lambda_b \pi_T \pi_Q \pi_E \pi_R \pi_S \]

where
- \( \lambda_b \) is base failure rate.
- \( \pi_T \) is temperature factor
- \( \pi_Q \) is quality factor
- \( \pi_E \) is environmental factor
- \( \pi_R \) is current rating factor
- \( \pi_S \) is voltage stress factor

Used switch ratings:
- Junction temperature = 150°C \( I_{\text{rms}} = 30\) A
- Case temperature = 75°C \( V_s = 500\) V
- Marine application

Substitute in (5)

\[ \lambda_p = \lambda_b \pi_T \pi_Q \pi_E \pi_R \pi_S \]

According to datasheet all values are having numerical values
- \( \lambda_b = 0.002 \) (for all type devices same value)
- \( \pi_T = 150°C \)

\[ = e^{\left(-3082\left(\frac{1}{273+150} + \frac{1}{273+75}\right)\right)} = e^{\left(-3082\left(\frac{1}{423} + \frac{1}{348}\right)\right)} = 21 \]

where \( T_j \) = junction temperature.

0°C temperature converted into Kelvin = 273

At room temperature 25°C converted into Kelvin = 273 + 25 = 298
- \( \pi_Q \) is quality factor = 1.0
- \( \pi_E \) is environmental factor = \( N_s = \) marine application = 9.0
- \( \pi_R \) is current rating factor = \( I_{\text{rms}} \) = 30A
  \[ = (30)^{0.40} = 3.9 \]
- \( \pi_S \) is voltage stress factor = \( V_s \) = 500V = 0.5
  \[ = (0.5)^{1.9} = 0.27 \]

b) \[ \lambda_p = \lambda_b \pi_T \pi_Q \pi_E \pi_R \pi_S = 0.002 \times 21 \times 1.0 \times 9.0 \times 3.9 \times 0.27 = 0.437 \text{ failure/}10^6\text{ hours} \]

Failure rate for selected model switch (hardware) = 0.437 failure/10^6 hours

Now,

Failure rate per year:

The failure rate for each phase \( \lambda_{\text{physical}} = \sum_{i}^{\text{phase}} \frac{\text{annual time phase}}{8760} \times \lambda_{\text{phase}} \) (5)

For 1-\( \varphi \) consider operation for 265 days = 265*24 = 6360 hours
365 days = 365*24 = 8760 hours

Failure rate of the selected switch \( \lambda_{\text{phase}} \) = 0.437 per 10^6 hours

\[ \lambda_{\text{physical}} = \frac{6360}{8760} \times 0.437 = 0.3712 \text{ per } 10^6 \text{ hours} \]

On-mission failure rate:

\[ \lambda_{\text{mission}} = \lambda_{\text{calander}} \times \frac{\text{calander duration}}{\text{duration on-mission}} \] (6)

\[ = 2 \times 365 \times 24 \times 10^9 \times \frac{8760}{6360} \text{ for } 2 \text{ years} \]

\[ = 2.412 \times 10^5 \text{ hours} \]
Now this all values applied to the multilevel inverter switching operation its depends on the switch on condition in each level.

Switch 1:- it conducts in 4 levels.

\[
T_{\text{conduction}} = T_{\text{total}} - (T_{\text{on}} - T_{\text{off}})
\]

\[
T_{\text{on}} = 0.985 \times 10^{-6}
\]

\[
T_{\text{off}} = 0.005 \times 10^{-6}
\]

Total conduction period \(T_{\text{conduction}} = 2 \times (0.0985 \times 10^{-6} - 0.005 \times 10^{-6}) = 1.9\) sec

Total failure rate of the switch \(S_1 = T_{\text{conduction}} \times \text{no. of levels on-condition} \times \lambda_p = 1.9 \times 4 \times 0.437 = 0.0033212\) w-sec

Total failure rate of the switch \(S_2 = T_{\text{conduction}} \times \text{no. of levels on-condition} \times \lambda_p = 1.9 \times 5 \times 0.437 = 0.0041515\) w-sec

Total failure rate of the switch \(S_3 = T_{\text{conduction}} \times \text{no. of levels on-condition} \times \lambda_p = 1.9 \times 5 \times 0.437 = 0.0041515\) w-sec

Total failure rate of the switch \(S_4 = T_{\text{conduction}} \times \text{no. of levels on-condition} \times \lambda_p = 1.9 \times 5 \times 0.437 = 0.0041515\) w-sec

Total failure rate of the switch \(S_5 = T_{\text{conduction}} \times \text{no. of levels on-condition} \times \lambda_p = 1.9 \times 5 \times 0.437 = 0.0041515\) w-sec

Total failure rate of the switch \(S_6 = T_{\text{conduction}} \times \text{no. of levels on-condition} \times \lambda_p = 1.9 \times 5 \times 0.437 = 0.0041515\) w-sec

Total failure rate of the switch \(S_7 = T_{\text{conduction}} \times \text{no. of levels on-condition} \times \lambda_p = 1.9 \times 5 \times 0.437 = 0.0041515\) w-sec

Total failure rate of the switch \(S_8 = T_{\text{conduction}} \times \text{no. of levels on-condition} \times \lambda_p = 1.9 \times 4 \times 0.437 = 0.0033212\) w-sec

On-machine failure rate per year:- for 265 days 265*24 = 6360 hours

Switch 1, 8:-

\[
\lambda_{\text{physical}} = \frac{6360}{8760} \times 0.0033212 = 2.4112 \times 10^{-3}\text{hours}
\]

Switch 2, 3, 4, 5, 6, 7:-

\[
\lambda_{\text{physical}} = \frac{6360}{8760} \times 0.0041515 = 3.0141 \times 10^{-3}\text{hours}
\]

According to the manufactured material:-

All switches are made of germanium material is a chemical element with symbol Ge and atomic number 32.

\[
S_i, S_8 = \text{total loss*material atomic number}
= 2.4112 \times 10^{-3} \times 32
= 0.0771\text{per} 10^6\text{hours}
\]

\[
S_2, S_3, S_4, S_5, S_6, S_7 = \text{total loss*material atomic number}
= 3.0141 \times 10^{-3} \times 32
= 0.0964\text{per} 10^6\text{hours}
\]

5. **CONCLUSION**

The cost of the proposed multilevel inverter quite lesser compared with the conventional multilevel inverter topology and the number of dc sources and switches also less for same level of output voltage generation. Reliability analysis has been performed towards the proposed multilevel inverter based on the mean time failure with various equations given in the FEDI reliability mathematical modeling design the results of the proposed multilevel inverter is having lesser failure rate and it is good for fewer chances of failure for medium voltage high power applications.
REFERENCES


BIOGRAPHIES OF AUTHORS

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