Failure RatePrediction of Thyristor with Variable Duty Cycle and Change in Junction Temperature

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Abstract:
As electronic gadgets are becoming ever more popular in day by day activities, such as mobile devices, so do their operating conditions become harsher, means using electronic components at the threshold of their functional parameters and very close to or even exceeding their maximum operating temperature which leads to a dramatic decrease in component lifetimes. Under these extreme circumstances, classical failure prediction methodologies are perturbed, giving unreliable results. This generated the need to establish new methods of failure prediction.

In this study, we developed a system by which the reliability of thyristor can be predicted using statistical analysis method of predicting reliability most easily. The failure rate models that were applied are MIL-HDBK-217F N2 and RIAC 217Plus™, and these were compared in order to validate the effectiveness of the developed system.

This paper demonstrates the use of temperature and duty cycle as a health assessment tool for implementing prognostics and health management in thyristor and which can be further implemented to various other electronics components. It is intended that this work will provide the basis for future developments in data sheet provided by the manufacturer for not only thyristor, but also by various other component providers in the power electronics market.

For generating a refined pool of population, heuristic technique was implemented and for simulation, MATLAB was utilized.

Keywords: Failure Rate, Junction temperature, duty cycle, heuristic technique, MIL-HDBK-217F N2 and RIAC 217Plus™.

1. Introduction:
Sensor technology can very well inform the operator, about the current working of a device but in case of failure of an electronics circuit, it is not possible for sensor conditioning monitoring system to indicate or check which electronic component in the whole circuit has been stop working or failed or misfired. Before that failure prediction of component is must before installing them in the circuit. When failure of component occur due to any of the following reasons: shock, drop, vibrations, radiations, failure of over current/over voltage protection system etc, perfect health prognostics can’t be done as these are environmental or mishandling effects.

While the initial work has helped validate the that the physics of failure are correct and that the technique is applicable to develop a PHM for electronics system, a number of underlying issues must be addressed before fielding more advanced prototypes. The testing methods used to stress the electrical components to failure was a repeatable laboratory test. Real stress histories are not repeatable and incremental. Therefore the damage per drop cannot be used to determine the remaining useful life accurately [4].

Health of a component or circuit can be determined by either condition monitoring or by life consumption monitoring [2]. While condition monitoring can be done before installation or after installation of the component. Present methodology is designed to provide the pre-installation process to check the failure rate of a thyristor.

Among most sensitive electronic components, thyristor was identified as one of them, and as a result became the focus point of the lifetime prediction investigations. Several documented lifetime prediction methodologies have been discussed in the previous work [1].

As a result, it was concluded that the life prediction must be done prior to installation of device in the circuit, which not only help the manufacturer in estimating the device working capacity, but also to the consumer that when this part needs to be replaced. This work also fulfills the need of an algorithm which can be applied for different types of thyristors.

Failure of an electronic component can be broadly classified in to three categories: due to manufacturing defects, mechanical issues and electrical factors.

In the recent past much research has been outlined failure prediction models due to failure modes of thermal cycling, , manufacturing defects may include fatigue-creep, uneven doping.

Wearout happens due to mechanical issues are distortion, fracture, wear, corrosion, severe vibratory environments, mechanical loading etc. The applicability to determine mechanical failure of individual electrical components has been demonstrated in [5, 6] by using resistance based techniques. The paper is divided into following part: in part two, problem formulation has been discussed. In part three, failure rate prediction system are presented using MIL-HDBK-217F N2 and RIAC 217Plus™ failure rate models. For generating a refined pool of population, heuristic technique was implemented and for simulation, MATLAB was utilized. Part four consist of results and was followed by conclusion.

2. Problem formulation:
The rise in junction temperature \( T_R \) of a power thyristor in any particular situation intensely affects its performance and consistency. During its working life a thyristor can experience a wide range of temperatures.

Operating at below 50°C is not damaging but allowance must be made by the user for increased gate trigger current, latching
current and holding current as well as slow turn-on. Working in the range between room temperature and 125°C gives the best compromise between ease of operation and operational life. T_R = 125°C is chosen as the design maximum value since above this, blocking current starts to increase rapidly, thus degrading voltage rating. With variation in temperature, duty cycle, rms value of rated forward current, rated blocking voltage, environmental factor, and operating base failure rate etc varies at large extend. These variations and hence the failure rate prediction of thyristor have studied and compared. The failure rate models applied were MIL-HDBK-217F N2 and RIAC 217Plus™. For generating a refined pool of population, heuristic technique was implemented and for simulation, MATLAB was utilized.

3. Failure Rate Prediction System

3.1 MIL-HDBK-217F N2 System

The military handbook data has been analyzed sample has been generated using genetic algorithm and simulated by using MATLAB

3.1.1 Population Generation:

Heuristic approach has been utilized in the purposed work merely to generate refined population from a big pool of data. Rise in junction temperature has been considered in the range of 50 °C to 125 °C, with each small increment of 0.1 °C, which will give us 751 samples. Similarly, in case of rms value of rated forward current, which has been considered in the range of 1A to 175A, with each small increment of 5 A, will give us 36 samples. The rated blocking voltage has been taken from 0.3V to 1V with 0.1V increment which gives us seven options. The fourth gene, environmental factor, has been considered from 0.5 to 43 with each small increment of 0.5 unit, where all the three (except space) bases viz. ground, naval and airborne were considered as the environmental condition. Fourth gene provides 87 options. These four variable quantities were considered as four genes and together form a chromosome population, whose sample chromosome has been shown in figure 1.

<table>
<thead>
<tr>
<th>Chromosome-1</th>
<th>Temperature (°C)</th>
<th>Rated Forward Current (Ampere)</th>
<th>Rated Blocking Voltage (Volts)</th>
<th>Environmental Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.7</td>
<td>10</td>
<td>0.7</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1: Sample Data of MIL-HDBK

New solutions are generated by a random process as in a conventional genetic algorithm and put into a pool if those solutions are feasible and no identical solutions already exist. These variable combinations generates 1,64,64,924 chromosomes [9]. A crossover operator is applied to the parents (two randomly selected solutions from the pool) to produce two new solutions, the offspring. Only the genes that differ between parents are eligible for crossover, and, of these, a limited set of genes will be randomly chosen from a predefined maximum number. There is strict limitation on the numbers of genes allowed to crossover in the process, the structure of the offspring would be very similar to the parent. This is decisive in ensuring good information assortment.

The mutation rate is kept low, usually below 1.5%. If it occurs, a stochastic process is again applied to select one gene from each offspring and alter the information inside the gene. Finally after ten consecutive runs, we got a reduced population of 19152 chromosomes. This polished population will then fed to MATLAB for simulating results.

3.1.2 Simulation:

The failure rate equation of the microcircuits in the MIL specification [7] is as follows.

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

Temperature factor, \( \pi_T \), is given by

\[ \pi_T = e^{-3002 \left( \frac{1}{R + 273 - \frac{1}{298}} \right)} \]  

Current ratting factor, \( \pi_R \), depends mainly on rms value of rated forward current, is given by

\[ \pi_R = \left( I_{f rms} \right)^{0.4} \]  

Voltage stress factor, \( \pi_S \), depends mainly on value of rated blocking voltage, is given by

\[ \pi_S = \left( V_s \right)^{1.9} \]

Nomenclature:

\( \lambda_p \) Predicted failure rate
\( \lambda_b \) Base failure rate
\( \pi_T \) Temperature factor
\( \pi_R \) Current ratting factor
\( \pi_S \) Voltage stress factor
\( \pi_E \) Environmental factor
\( \pi_Q \) Quality factor depends upon class of device

The simulation results obtained from MATLAB were shown in figures 2-4.
3.2 RIAC 217Plus™ System

The data has been collected using RIAC 217Plus system and using Genetic algorithm, sample has been generated and simulated using MATLAB

3.2.1 Population Generation:

For RIAC 217Plus™ System, rise in junction temperature has been considered in the range of 50 °C to 125 °C, with each small increment of 0.1 °C, which will give us 751 samples. Similarly, in case of duty cycle, which has been considered in the range of 10% to 80%, with each small increment of 1%, will give us 71 samples. The operating base failure rate has been taken from $3.22 \times 10^{-4}$ to $3.27 \times 10^{-4}$ with $0.01 \times 10^{-4}$ increment which gives us seven options. These three variable quantities were considered as three genes and together form a chromosome population, whose sample chromosome has been shown in figure 5.

<table>
<thead>
<tr>
<th>Chromosome-1</th>
<th>Operating Base Failure Rate</th>
<th>Duty Cycle (%)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000324</td>
<td>15</td>
<td>50.5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5: Sample data of RIAC-217 Plus

These variable combinations generate 3,19,926 chromosomes. A crossover operator is applied to the parents to produce two new solutions, the offspring. The mutation rate is kept low, usually below 1.5% as in previous case. After ten consecutive runs, we got a reduced population of 2265 chromosomes [9]. This polished population will then be fed to MATLAB for simulating results.

3.2.2 Simulation:

The failure rate equation for thyristor [3], [7] is:

$$
\lambda_P = \pi_G \left[ \lambda_{DB} \pi_{DCO} \pi_{TO} + \lambda_{EB} \pi_{DCN} \pi_{TE} + \lambda_{TCB} \pi_{CR} \pi_{DT} \right] + \lambda_{SJ} \pi_{SJD} + \lambda_{IND}
$$

(5)

Where various terms used in the above expression are expressed as below.

Reliability growth failure rate multiplier ($\pi_G$) is expressed as

$$
\pi_G = e^{-\beta(V-1993)}
$$

(6)

$\pi_{DCO}$, operating failure rate multiplier for duty cycle is given by

$$
\pi_{DCO} = \frac{DC}{DC_{1op}}
$$

(7)

$\pi_{TO}$, operating failure rate multiplier for temperature will be

$$
\pi_{TO} = e^{\left(\frac{-E_{dop}}{0.00000617(T_{AO}+T_{RA}+273)}\right)}
$$

(8)

$\pi_{DCN}$, duty cycle (non-operating) failure rate multiplier will be

$$
\pi_{DCN} = \frac{1-DC}{DC_{1nonop}}
$$

(9)

$\pi_{CR}$, cycling rate failure rate multiplier is

$$
\pi_{CR} = \frac{CR}{CR_1}
$$

(10)

$\pi_{DT}$, delta temperature failure rate multiplier,

$$
\pi_{DT} = \left(\frac{T_{AO}+T_{R}-T_{AE}}{DT_1}\right)^2
$$

(11)

$\pi_{SJD}$, solder joint delta temperature failure rate multiplier,
\[ \pi_{SJDT} = \left( \frac{T_{AO} + T_R - T_{AE}}{44} \right)^{2.26} \] (12)

The simulation results obtained from MATLAB were shown in figures 6-9.

**Nomenclature:**

- \( \lambda_P \): Predicted failure rate
- \( \pi_G \): Reliability growth failure rate multiplier
- \( \beta \): Growth constant
- \( \lambda_{OB} \): Operating base failure rate
- \( \pi_{DCO} \): Duty cycle operating failure rate multiplier
- \( \pi_{TO} \): Temperature operating failure rate multiplier
- \( E_{\text{op}} \): Operating activation energy
- \( T_{AO} \): Ambient operating temperature
- \( T_R \): Rise in junction temperature above the ambient operating temperature
- \( T_J \): Junction temperature
- \( \lambda_{EB} \): Environmental base failure rate
- \( \pi_{DCN} \): Duty cycle (non-operating) failure rate multiplier
- \( \pi_{TE} \): Temperature (environment) failure rate multiplier
- \( E_{\text{nonop}} \): Non-operating activation energy
- \( \lambda_{TCB} \): Temperature cycling base failure rate
- \( \pi_{CR} \): Cycling rate failure rate multiplier
- \( \pi_{DT} \): Delta temperature failure rate multiplier
- \( \lambda_{SJB} \): Solder joint base failure rate
- \( DC \): Duty cycle
- \( T_{AO} \): Operating ambient temperature, \( (^\circ C) \)
- \( T_{AE} \): Non-operating ambient temperature, \( (^\circ C) \)
- \( CR \): Cycling rate

**4. Results:**

Figure 6: Temperature versus Failure rate

Figure 7: Duty Cycle versus Failure Rate

Figure 8: Temperature versus Failure Rate with variable duty cycle
condition monitoring procedure in preventive maintenance or can be implemented for the same purpose as part of the control.

Appendix:
The data for various constants used in the failure rate prediction by RIAC 217Plus™ System and MIL System are mentioned in Table 1

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Constant</th>
<th>Value</th>
<th>S. No.</th>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$\lambda_{EB}$</td>
<td>0.001011</td>
<td>9.</td>
<td>TR$_{\text{default}}$</td>
<td>60</td>
</tr>
<tr>
<td>2.</td>
<td>$\lambda_{TCB}$</td>
<td>0.002030</td>
<td>10.</td>
<td>VS$_{\text{default}}$</td>
<td>0.37</td>
</tr>
<tr>
<td>3.</td>
<td>$\lambda_{SIB}$</td>
<td>0.000870</td>
<td>11.</td>
<td>E$_{\text{aop}}$</td>
<td>0.4</td>
</tr>
<tr>
<td>4.</td>
<td>$\lambda_{IND}$</td>
<td>0.020010</td>
<td>12.</td>
<td>E$_{\text{nonop}}$</td>
<td>0.4</td>
</tr>
<tr>
<td>5.</td>
<td>$\beta$</td>
<td>0.2</td>
<td>13.</td>
<td>DT$_1$</td>
<td>73</td>
</tr>
<tr>
<td>6.</td>
<td>CR$_1$</td>
<td>508.77</td>
<td>14.</td>
<td>$\lambda_0$</td>
<td>0.0022</td>
</tr>
<tr>
<td>7.</td>
<td>$\text{DC}_{\text{top}}$</td>
<td>0.26</td>
<td>15.</td>
<td>$\lambda_Q$</td>
<td>0.5 (for S-class)</td>
</tr>
<tr>
<td>8.</td>
<td>$\text{DC}_{\text{nonop}}$</td>
<td>0.74</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Standard values of various Constants

References