Some of the typical constraints found in power electronics circuits are performance behavior, cost, efficiency, and Reliability.

Let's consider first that we are studying a particular device or component of a system.

Reliability is the probability that an item will operate without failure for a stated period of time under specified conditions.

Since reliability is a probability, it can only take values between 0 and 1.

We identify the reliability of an item with R.

The complement of the reliability is the unreliability F:

\[ F = 1 - R \]

Unreliability \( F \) is the probability that a component fails to work continuously over a stated time interval.

The use of the words “without failure” in the definition of reliability or the term “continuously” in the definition of
unreliability is not arbitrary. They imply that the concept of reliability can only be applied directly to systems or repairable items.

The terms that consider a system’s or a repairable item’s behaviour in normal operation and after a failure are availability and “unavailability”.

The term “availability” can be used in different senses depending on the type of system or item:

1) Availability (A) is the probability that a system/item works on demand → Definition appropriate for standby systems

2) Availability (A(t)) is the probability that a system/item is working at a specific time t → Definition appropriate for continuously operating systems

3) Availability (A) is the expected portion of the time that a system or item performs its required function → Definition appropriate for repairable systems

Unavailability → It is the probability that a system or item does not operate at a time t

\[ A = 1 - U_a \]
Simple model for system behavior

![Diagram showing state transition from working to failed via repair process]

- Reliability calculation:
  \[ P(t) = P(\text{a given item fails in } [0, t]) \]  \hspace{1em} (1)

  \[ \text{continuous operation is implicit} \]

  It is a probability distribution, with random variable +

  The probability density function is
  \[ f(t) = \frac{d}{dt} P(t) \]

  \[ f(t) dt = P(\text{a given item fails in } [t, t+dt]) \]  \hspace{1em} (2)

  Then \[ f(t) dt = P(t+dt) - P(t) \]

  or \[ P(t) = \int_0^t f(t) dt \]

A hazard function \( h(t) \) is created to characterize the transition to the failed state. \( h(t) \) is the expected rate at which failures occur.
Given that:

\[ h(t) \, dt = P(\text{an item fails between } t \text{ and } t + dt \mid \text{it has not failed until } t) \]

Since \( P(A \mid B) = \frac{P(A \cap B)}{P(B)} \)

But any item that fails between \( t \) and \( t + dt \) has not failed before \( t \) and \( t + dt \) has not failed before \( t \) \( \Rightarrow \) \( P(A \cap B) = \theta(t) \). Hence,

\[ h(t) \, dt = P(\text{component fails between } t \text{ and } t + dt) \]

\[ P(\text{no failure in } [0, t]) \]

And, from (1) and (2)

\[ h(t) \, dt = \frac{f(t) \, dt}{1 - F(t)} \rightarrow h(t) = \frac{f(t)}{1 - F(t)} \]

\[ \int_0^t h(t) \, dt = \int_0^t \frac{f(t)}{1 - F(t)} \, dt = \int_0^t \frac{f(t)}{1 - \int_0^t f(t) \, dz} \, dt \]

\[ P(t) = 1 - e^{-\int_0^t h(t) \, dz} \]
Typical form for $F(t)$:

1. Burn-in period
2. Useful life period
3. Wear out period

Typical failure causes:
- Poor welding
- Loose connections
- Wear
- Fatigue
- Corrosion
- Oxidation

With $h(t) = \lambda = \text{constant}$

Failure rate:

$F(t) = 1 - e^{-\lambda t}$

Reliability:

$R(t) = e^{-\lambda t}$

The mean is $MTTF = \mu_T = \int_0^\infty t f(t) dt = \frac{1}{\lambda}$

Mean time to failure

Now consider that an item or system can be repaired after it failed and be brought back into service.
There are several ways to study the reliability behavior of a system or repairable item. A good one is by using Markov analysis because it provides a graphical depiction of the process and a flexible way of addressing different situations.

The equivalent of the hazard rate in repairable processes is the failure rate $\lambda(t)$

$$\lambda(t) \, dt = \frac{P[\text{component fails in } (t, t+dt)]}{P[\text{component was working at } t-t]}$$

For the repair process, the equivalent to $\lambda(t)$ is the repair rate $\mu(t)$. A simple Markov's representation of a single repairable component process is:

![Markov diagram](image.png)

The probability that the above item is in the failed state (unavailability) after $dt$ is given by:

$$P(x(t+dt) = 1) = P(\text{item was working at } t = t \text{ and undergoes failure during } dt \text{ or the component was failed at } t = t \text{ and it wasn't repaired during } dt)$$
\[ P(x(t) = 1) = P(x(t) = 0) \lambda(t) dt + P(x(t) = 1) \mu(t) dt \]

\[ P_r(t + dt) = P_r(t) \lambda(t) dt + P_r(t)[1 - P_f(t)] dt \]

\[ \frac{d}{dt}[P_r(t)] = \frac{dP_r(t)}{dt} = \frac{dP_r(t)}{dt} = \lambda \cdot P_r(t) - \nu \cdot P_r(t) \]

\[ \frac{dP_r(t)}{dt} = \lambda \cdot P_r(t) - \nu \cdot P_r(t) \]

I assume the failure initially working

Initial cond.: \[ P_r(0) = 0 \]

And since \[ P_w(t) = 1 - P_r(t) \]

We could have reached the diff. equations is from the following property of the diagram:

Assuming constant failure and repair rates
\[ \frac{dP_{\text{state}}}{dt} = (\text{Rate of entering the state}) - (\text{Rate of leaving the state}) \]

In terms of rates, Markov's diagram becomes:

\[ P_{F} = \lambda P_{W} - \mu P_{E} \]

\[ P_{W} = \frac{dP_{F}(t)}{dt} = \lambda P_{W}(t) \]

If we plot \( P_{F}(t) \) vs \( P_{W}(t) \) we obtain:

Steady state probabilities of being failed or working, i.e. how likely it is that after being “there” for a long time the item is working or not.

This fits the definitions of availability and unavailability.

Hence, \( A = \frac{\lambda}{\lambda + \mu} \), \( U = \frac{\mu}{\lambda + \mu} \).
In the same way that for the case when \( h(x) = x = \text{constant} \) we found out that \( \text{MTTF} = \mu_r = \frac{1}{\lambda} \), now:

For \( x(t) = x = \text{constant} \) \( \Rightarrow \text{Mean up time} = \text{MUT} = \frac{1}{\lambda} \)

For \( 0 + t = 0 = \text{constant} \) \( \Rightarrow \text{Mean down time} = \text{MDT} = \frac{1}{\lambda} \)

So the process goes like this:

\[
\begin{array}{c}
\text{MUT} \quad \text{MDT} \quad \text{MUT} \\
\text{MDT} \quad \text{Failure} \quad \text{Restart} \quad \text{Failure}
\end{array}
\]

Mean time between failures (MTBF)

MDT includes:
- detection
- fault repair
- put the system back into service

The concepts of MUT, MDT and MTBF apply to repairable systems only.

Notes:
1) \( \text{MTBF} = \text{MUT} + \text{MDT} \)
2) \( \text{MUT} \neq \text{MTTF} \). When a system is restarted after it has been repaired, not all the failed components may not necessarily have been repaired. The MUT characterizes the mean operating time until the next failure. The MTTF characterizes the mean operating time of a system which is entirely repaired (new) before being restarted.
\[ A = \frac{1}{D+2} = \frac{1}{\text{MTTR}} \times \frac{1}{\text{MUT}} = \frac{\text{MUT}}{\text{MTBF}} \]

\[ U_2 = \frac{\text{MUT}}{\text{MTBF}} \]

Reliability network is another technique to calculate availability of systems with multiple components.

A reliability network is a representation of the reliability dependencies between components of a system.

The network has always the following features:

1. A starting node
2. An ending node
3. A set of nodes
4. A set of edges
5. An incidence function that associates each edge with an ordered pair of nodes

- The edges represent the components
- The nodes represent system architecture
- The expected operating condition of the system is represented by paths through the network.

If there is at least one path from the starting node to the ending node then the system is working.

If not the system has failed.
Simple architectures:

\[ A = \begin{pmatrix}
-\lambda_1 - \lambda_2 & \lambda_1 & \lambda_2 & 0 \\
\lambda_1 & -\lambda_1 - (\lambda_2 + \lambda_3) & 0 & 0 \\
\lambda_2 & 0 & -\lambda_2 - (\lambda_2 + \lambda_3) & \lambda_1 \\
0 & 0 & \lambda_1 & -\lambda_1 - (\lambda_2 + \lambda_3)
\end{pmatrix} \]

\[ P_{S_1}(t \to \infty) = \frac{\lambda_1 \lambda_2}{(\lambda_1 + \lambda_2) (\lambda_2 + \lambda_3)} \]

\[ P_{S_2}(t \to \infty) = \frac{\lambda_2 \lambda_1}{(\lambda_1 + \lambda_2) (\lambda_2 + \lambda_3)} \]

\[ P_{S_3}(t \to \infty) = \frac{\lambda_2 \lambda_1}{(\lambda_1 + \lambda_2) (\lambda_2 + \lambda_3)} \]

\[ P_{S_4}(t \to \infty) = \frac{\lambda_1 \lambda_2}{(\lambda_1 + \lambda_2) (\lambda_2 + \lambda_3)} \]

- Green → System healthy
- Red → System failed

\[ P_{S_4}(t) = A P_{S_4} \]

Mean time in each state:

\[ T_1 = \frac{1}{\lambda_1 + \lambda_2} \]

\[ T_2 = \frac{1}{\lambda_1 + \lambda_2} \]

\[ T_3 = \frac{1}{\lambda_2 + \lambda_3} \]

\[ T_4 = \frac{1}{\lambda_1 + \lambda_2} \]
a) Series system

\[ P_{\text{sys}}(s) = \frac{e^{-\lambda_{\text{sys}} s}}{\prod_{i=1}^{n} R_i(s)} \]

where \( \lambda_{\text{sys}} = \sum_{i=1}^{n} \lambda_i \) and \( MTF_{\text{sys}} = \frac{1}{\lambda_{\text{sys}}} \)

For 2 repairable components

\[ A = P_{\text{sys}}(s) \Big|_{s \to \infty} = \frac{D_1 D_2}{(D_1 + \lambda_1)(\lambda_2 + D_2)} \]

\[ A = \frac{D_1 D_2}{(D_1 + \lambda_1)(\lambda_2 + D_2)} = \frac{D_1}{D_1 + \lambda_1} \cdot \frac{D_2}{\lambda_2 + D_2} \]

\[ A = a_1 \cdot a_2 \]

For \( n \) components

\[ A_{\text{sys}} = \prod_{i=1}^{n} a_i \]

Parallel repairable systems

\[ \frac{e^{-\lambda_{\text{sys}} s}}{\prod_{i=1}^{n} R_i(s)} \]

From above \( U_{\text{sys}} = P_{\text{sys}}(s) \Big|_{s \to \infty} = \frac{a_1 a_2}{(\lambda_1 + D_1)(\lambda_2 + D_2)} \)

Hence \( U_{\text{sys}} = \frac{a_1}{\lambda_1 + D_1} \cdot \frac{a_2}{\lambda_2 + D_2} = \frac{(1-a_1)}{(1-a_1)} \frac{(1-a_2)}{(1-a_2)} \)
For \( n \) components in \( \frac{1}{U} \) we have:

\[
U_{\text{sys}} = \prod_{i=1}^{n} (1-\alpha_i)
\]

**n+1 redundancy**

Suppose now that we have a modular system with a total power \( P_o \) and each module has an output of \( P_m \). Then, without redundancy we need

\[
n = \lceil \frac{P_o}{P_m} \rceil
\]

The upper integer value of \( \frac{P_o}{P_m} \)

\[\text{E.g. } P_o = 7 \text{ kW} \quad \frac{P_o}{P_m} = 3.5 \quad n = 4\]

The problem with lack of redundancy is that if one module fails then there is not enough capacity to power the load.

With \( n+1 \) redundancy we provide 1 extra module for those needed. Then

\[
n = \left\lceil \frac{P_o}{P_m} \right\rceil + 1
\]

So with \( n+1 \) redundancy it is required that \( n \) of the \( n+1 \) modules work for full system operation.
\[ A_{sys} = P(\text{system working}) = \]
\[ = P(\text{n modules working}) + P(\text{\(n+1\) modules working}) \]
\[ = \binom{n}{r} a^r Ma + \binom{n}{r+1} a^{r+1} \]

All possible arrangements of \(n+1\) elements taken in groups of \(n\) where the order doesn't matter to distinguish among arrangements. 

\(a\) \(\rightarrow\) availability of each module

\(Ma\) \(\rightarrow\) unavailability of each module

I can think of the process as having \(n\) trials and requiring \(k\) or more successes for the system to work.

Recall that \(\binom{n}{r} = \frac{(n+1)!}{(n+1-r)!r!} = \frac{(n+1)!}{n!} = n+1\)

So \(A_{sys} = (n+1)Ma + a^2 \) \(a^n = (n+1)(1-a) + a \) \(a^n\)

Is \((n+1)\) redundancy always better than other options?

Consider a fuel cell with \(a = 0.9\) and variable number
So as the number of modules increase the system availability decreases.

The best reliability option is "1+1"

parallel

This extra capacity has it cost ($/kWh)

so the extra redundant capacity represented by the "+1" is less

But modules are larger and the extra capacity is very large (equals the load)

One option to improve economics is to use the extra capacity to power something else other than the load. For example, the extra power can be injected back into the grid and in this way economics are improved.
Markov for a general system

\[ E_0 \rightarrow \text{Set of operating states (e.g., 2 import parallel): } E_0 = \{ s_1, s_2, s_3 \} \]

\[ E_{n0} \rightarrow \text{Set of minimal operating states (states that have at least one transition to the failed state): e.g., 2 import parallel: } E_{n0} = \{ s_2, s_3 \} \]

\[ E_0 \rightarrow \text{Set of failed states (e.g., 2 import parallel): } E_0 = \{ s_1, s_2, s_3 \} \]

\[ E_n \rightarrow \text{Set of minimal failed states (the ones with at least one transition} \]

\[ P_{so} = \frac{\prod_{j=1}^{n} d_j}{\prod_{j=1}^{n} (\lambda_j + d_j) - \sum_{j=1}^{n} d_j} \]

\[ P_{sW} = \frac{\prod_{j=1}^{n} \lambda_j}{\prod_{j=1}^{n} (\lambda_j + d_j) - \sum_{j=1}^{n} d_j} \]

\[ P_{o,j} = \frac{\prod_{i=1}^{j} d_i}{\prod_{j=1}^{n} (\lambda_j + d_j) - \sum_{j=1}^{n} d_j} \rightarrow \text{1 failure in component } i \]
\[ P_{S_{ik}} = \frac{\lambda \sum_{j=1}^{n} D_{j}}{\prod_{j=1}^{n} (\lambda_{j} + D_{j}) - \prod_{j=1}^{n} D_{j}} - 2 \text{ failures (components outside)} \]

\[ P_{S_{k}} = \frac{\lambda^{n-m+1}}{(\lambda + D)^{n-m}} \]

Probability of all states with \( m \) failed components:

\[ \prod_{i \in \mathcal{E}_{F}} \prod_{i \in \mathcal{E}_{S}} \frac{\lambda_{i}}{P_{S_{i}}(t)} \rightarrow \text{ with } \sum_{i=1}^{n} \lambda_{i} = \sum_{j=1}^{n} \lambda_{j} \]

\[ \mathcal{E}_{F} = \{ S_{1} \ldots S_{n} \} \]

\[ \mathcal{E}_{S} = \{ S_{0} \ldots S_{n} \} \]

\[ U_{S_{x}}(t) = \frac{\sum_{i=x}^{e} \lambda_{i} P_{S_{i}}(t)}{\sum_{i=x}^{e} P_{S_{i}}(t)} \rightarrow \text{ with } \sum_{i=1}^{n} \lambda_{i} = \sum_{j=1}^{n} \lambda_{j} \]

\[ \lim_{t \to \infty} \frac{U_{S_{x}}(t)}{U_{S_{x}}(t) + \sum_{i=x}^{e} P_{S_{i}}(t)} \]

\[ D(t) = \frac{U_{S_{x}}(t)}{U_{S_{x}}(t) + \sum_{i=x}^{e} P_{S_{i}}(t)} \]

In general \[ \mathbf{P}^{t} = \mathbf{P}^{t+1} \]
\[ \mathbf{a}_{ij} = \text{ arrows going from } i \text{ to } j \]

\[ \mathbf{a}_{ij} = \sum_{j=1}^{n} a_{ij} \]
One useful summary table:

<table>
<thead>
<tr>
<th>Non-Refarable component</th>
<th>Refarable component</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(t) = e^{-xt}$</td>
<td>$A(t) = \frac{A}{2+\lambda} (1 - e^{-(\lambda+\mu)t})$</td>
</tr>
<tr>
<td>$E(t)$</td>
<td>$\Upsilon_{a}(t) = \frac{A}{2+\lambda} (1 - e^{-(\lambda+\mu)t})$</td>
</tr>
<tr>
<td>$M = \text{MTTF}$</td>
<td>$\mu = \text{MTTF}$ only if all components repaired</td>
</tr>
<tr>
<td>$\xi = \text{MTTR}$</td>
<td>$M_{D} = $</td>
</tr>
<tr>
<td>$\lambda = \frac{1}{\text{MTTF}}$</td>
<td>$\lambda = \frac{1}{\text{MTBF}}$</td>
</tr>
<tr>
<td>$\nu = 0$</td>
<td>$\nu = \frac{1}{\text{MTR}}$</td>
</tr>
<tr>
<td>$\rho(t = \infty) = 0$</td>
<td>$\Delta(t = \infty) = \frac{\nu}{\lambda + \nu}$</td>
</tr>
<tr>
<td>$\rho(t = \infty) = 1$</td>
<td>$\Upsilon_{a}(t = \infty) = \frac{\lambda}{\lambda + \nu}$</td>
</tr>
</tbody>
</table>

Nothing

Failure rate

Repair rate

Microgrids can serve as a good model to help us understand system availability calculations with reliability diagrams.
Based on these techniques we can calculate microgrid availability. For example, let's consider the following microgrid:

![Diagram of microgrid]

The availability can be calculated with the following diagram:

![Diagram of availability calculation]

\[
A_{sys} = A_{ng} A_{pt} A_c
\]

What if we have a more complicated structure? We can use Markov analysis or we can use the concept of paths in a reliability network:

- **Path set**: A list of edges such that if they all work, then the system is also in the working state, i.e., any path between the start node and the end node.

- **Minimal path set**: A path set such that if any one item is removed, the system will no longer work, i.e., any given path between the start node and the end node assuming that all other paths are interrupted due to at least one failed component.

- **Cut set**: A list of components such that if all fail then the system is also in the failed state.

- **Minimal cut set (K)**: A cut set such that if any one item is removed from the list, the system will no longer fail. The probability that a minimal cut set will occur is given by
\[ P(K) = \prod_{i=1}^{N_k} u_i \]

where \( u_i \) is the unavailability of the \( i \)-th edge of the \( N_k \) components in the minimal cut set \( K \).

For a system with repairable components, the unavailability can be calculated from [277]

\[ U = P \left( \bigcup_{j=1}^{M_c} K_j \right) \]

where \( M_c \) is the number of minimal cut sets in the system. Calculation of (B.6) is usually extremely tedious. However, the calculation can be simplified by recognizing that \( U \) is bounded by

\[ \sum_{i=1}^{M_c} P(K_i) - \sum_{i=1}^{M_c} \sum_{j=1}^{i-1} P(K_i \cup K_j) \leq U \leq 1 - \prod_{i=1}^{M_c} [1 - P(K_i)] \leq \sum_{i=1}^{M_c} P(K_i) \]

Thus, if the components are highly available, i.e., \( q_i \ll 1 \), then \( U \) can be approximated to

\[ U \approx \sum_{j=1}^{M_c} P(K_j) \]

So let's consider the following microgrid:

\[ \text{So the reliability network is:} \]
we have 2 inputs

Minimal cut sets: $k_1: \{ \text{ng}, D \}, k_2: \{ \text{mt}, D \}, k_3: \{ \text{C}_1, D \}$

$k_4: \{ \text{ng}, C \}, k_5: \{ \text{mt}, C \}, k_6: \{ \text{C}_1, C \}$

$k_2: \{ \text{ng}, C_2 \}, k_3: \{ \text{mt}, C_2 \}, k_4: \{ \text{C}_1, C_2 \}$

So $\mu = \sum_{i=1}^{9} P(k_i)$

where $P(k_i) = \mu_{\text{ng}} \mu_{\text{mt}}$

So, how do we know the values of the different unavailabilities?

From different sources

<table>
<thead>
<tr>
<th>Item and origin of the value</th>
<th>MTTF/MUT* (Hours)</th>
<th>MDT** (hours)</th>
<th>Availability $a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reciprocating Engine</td>
<td>823</td>
<td>5</td>
<td>0.9939</td>
</tr>
<tr>
<td>PV arrays ****</td>
<td>3636</td>
<td>14</td>
<td>0.996</td>
</tr>
<tr>
<td>Fuel Cell (performance degradation)</td>
<td>5000</td>
<td>166.6</td>
<td>0.967742</td>
</tr>
<tr>
<td>Microturbine</td>
<td>8000</td>
<td>50</td>
<td>0.993789</td>
</tr>
<tr>
<td>Wind turbine ****</td>
<td>1900</td>
<td>80</td>
<td>0.9595</td>
</tr>
<tr>
<td>ac mains</td>
<td>2440</td>
<td>2.08</td>
<td>0.999150</td>
</tr>
<tr>
<td>Diesel / Gas</td>
<td>2 M</td>
<td>50</td>
<td>0.999975</td>
</tr>
</tbody>
</table>

*MUT: Mean up-time (used for repairable system components)

**MDT: Mean down-time (only applicable to repairable components)

***NR: Not repairable

****Operational MUT and MDT depend on the actual energy availability
For the converters we can calculate the availability by estimating the MTF and by calculating the MTTF from

$$MTTF = \frac{1}{\lambda_{\text{conv}}}$$

where $\lambda_{\text{conv}}$ can be calculated by considering that from a reliability perspective all components are in series, i.e.,

$$\lambda_{\text{conv}} = \sum_{i=1}^{n} \lambda_i$$

each component $i$.

The values of $\lambda_i$ can be obtained from the nominal values.

<table>
<thead>
<tr>
<th>Part Description</th>
<th>$\lambda_i$ (FIT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistor</td>
<td>0.5</td>
</tr>
<tr>
<td>Capacitor Ceramic</td>
<td>1.0</td>
</tr>
<tr>
<td>Capacitor Tantalum</td>
<td>5.0</td>
</tr>
<tr>
<td>Diode</td>
<td>6.0</td>
</tr>
<tr>
<td>Transistor</td>
<td>6.0</td>
</tr>
<tr>
<td>Coil</td>
<td>19.0</td>
</tr>
<tr>
<td>MOSFET</td>
<td>20.0</td>
</tr>
<tr>
<td>IC (20 Transistors)</td>
<td>19.0</td>
</tr>
</tbody>
</table>

Information from:


The availability is affected by temperature and electrical stress (e.g., volts).

$$\lambda_{\text{comp}} = \lambda_{\text{n}} \cdot T_T \cdot T_E$$

Production quality $\approx$ Usually $= 1$

Nominal value

$T_T$ = Temperature factor

$T_E$ = Electrical stress
$T_{T}$ → Temperature factor → Arrhenius rate model

$$\frac{T_{T}}{T_{R}} = \exp \left( \frac{E_{a}}{k_{B}} \right)$$

- $T_{T}$ → Reference temperature
- $T_{R}$ → Boltzmann constant
- $k_{B}$ → Boltzmann constant
- $E_{a}$ → Failure activation energy → defects on
- $k_{B}$ → Failure mechanism

**Calculation of $T_{T}$:**

<table>
<thead>
<tr>
<th>Part Description</th>
<th>Stress Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25%</td>
</tr>
<tr>
<td>Resistor</td>
<td>0.72</td>
</tr>
<tr>
<td>Capacitor Ceramic</td>
<td>0.36</td>
</tr>
<tr>
<td>Capacitor Tantalum</td>
<td>0.23</td>
</tr>
<tr>
<td>Diode</td>
<td>0.48</td>
</tr>
<tr>
<td>Transistor</td>
<td>0.30</td>
</tr>
<tr>
<td>Coil</td>
<td>1.00</td>
</tr>
<tr>
<td>MOSFET</td>
<td>0.55</td>
</tr>
<tr>
<td>IC (25 Transistors)</td>
<td>1.00</td>
</tr>
<tr>
<td>IC (70 Transistors)</td>
<td>1.00</td>
</tr>
<tr>
<td>IC (150 Transistors)</td>
<td>1.00</td>
</tr>
<tr>
<td>Optocoupler</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**Final note: Fault tolerant strategies (to avoid single point of failures):**

- **Redundancy:** Having more of the minimum number of the same system components
- **Diversity:**Having multiple paths
- **Distributed systems:** Spread a critical function