Methodology of Reliability and Power Density Analysis of SST Topologies

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Abstract—This paper proposes a reliability analysis model and a power density analysis to evaluate the Solid-State Transformer (SST) topologies for different applications. The solid-state device rating and the redundancy number are considered as two major factors affecting the reliability. In each topology, the optimized selections of these two factors will be determined to reach sufficient reliability. The power density is influenced by the device volume, the transformer volume and the capacitor volume. In terms of these three aspects, the topology which has the highest power density is selected for the certain application. The effectiveness of the model is validated by the comparison between evaluation results and the actual industry products.

I. INTRODUCTION

Solid-State Transformer (SST) is widely discussed as the replacement of the Conventional Transformer (CT) in some applications. The purpose of using SST is to improve the controllability and increase the power density. However, the reliability and the cost are bottlenecks. The comparison between the SST and the CT in terms of costs, weights, volumes and losses was discussed in [1]. The comparison among different SST topologies considering the similar aspects was presented in [2] and [3].

The reliability of SST is relatively low due to the use of active solid-state devices in comparison of the conventional transformer with passive components. Thus, if an SST topology is designed for an application, a reliability requirement must be met. The comparison among different SSTs topologies in terms of the reliability is proposed in this paper.

The SST topologies can be classified according to the typical application: AC grid, DC grid, traction drive, substation, DC/AC charger. For these applications, there are topologies designed and fully tested by many companies and institutions [4]-[9]. In section 2, more possible topologies for these applications are proposed.

A detailed reliability analysis model is proposed in section 3 to have a more precise reliability evaluation. Reliability is influenced by two factors: device rating and redundancy. For a non-redundant system, the system reliability is the product of the reliability of each component. In this case, the use of semiconductor devices with higher rating results in fewer components. Then the reliability will be higher. For the redundant system, one more redundancy applied to a system will increase system reliability significantly. However, the reliability will not increase that much when the quantity of redundancy is beyond a certain number [10].

Based on the reliability analysis, an optimized combination of the device ratings and the redundancy is selected for each topology. The next step is to select the topology with highest power density for each application.

Power density is majorly associated with three factors: device rating, transformer size and capacitor size. As discussed before, higher device rating results in the fewer device count. Then the volume is smaller. The capacitor in half or full bridge inverter/rectifier is also relatively large because of the 2 current ripple. The high-frequency transformer takes a great portion because of its high voltage and current rating and high insulation level. However, the size of a transformer is relatively proportional to its power rating. As a result, for the same application, the sizes of transformers of those topologies are similar. Thus, the power density comparison among different topologies is presented in section 5 based on the comparison of the size of capacitors and devices.

Finally, the comparison between the evaluation results and the industrial selection shows the effectiveness of the methodology based on the reliability analysis and the power density analysis.

II. TOPOLOGY SCREENING OF SST

Four applications are discussed in this paper. ABBs HVAC-LVDC Power Electronic Traction Transformer (PET) (see Fig.
Fig. 1. Topologies for ABB Application (a) Half Bridge (b) Full Bridge (c) Half Bridge Multi-winding Transformer (d) MMC (e) Matrix

Fig. 2. Topologies for GE Application (a) Full Bridge (b) Half Bridge (c) Full Bridge Paralleled Output (d) Full Bridge Multi-winding Transformer (e) Half Bridge Multi-winding Transformer

Fig. 3. Topologies for UNIFLEX Application (a) Full Bridge (b) Three Level (c) Half Bridge

Fig. 4. Topologies for UNIFLEX Application (a) Three Level (b) Full Bridge (c) Half Bridge

III. RELIABILITY ANALYSIS

A. Reliability Model

The base of system reliability analysis is the failure rate which is also called Failure in Time (FIT) for each component. FIT of one device is equal to the number of failures within one billion ($10^9$) hours. The FIT data used for this analysis is shown in Table II, in which all the values are from the industrial database.

The reliability of a device is as presented in (1).

$$R_i(t) = e^{-\lambda_i t}$$  \hspace{1cm} (1)

The reliability of the non-redundancy system is the product of reliability of each component because all the components are regarded as series connected as shown in Fig. 5. If one component breaks down, the whole system will fall in failure. Thus, the reliability of the system is presented in (2).

$$R_s = R_1 \times R_2 \times R_3 \cdots \times R_k$$  \hspace{1cm} (2)

The redundancy part of the system can be considered as a parallel-connected component. The system with redundancy is shown in Fig. 6. If the block with redundancy contains $N$ necessary components and $x$ redundant components, the
Fig. 5. Reliability Model without Redundancy

Fig. 6. Reliability Model with Redundancy

### TABLE II
FIT OF THE COMPONENTS

<table>
<thead>
<tr>
<th>Component</th>
<th>High Voltage IGBT</th>
<th>Power diode</th>
<th>Gate Driver</th>
<th>Single-winding Transformer</th>
<th>Electrolytic Capacitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage and current sensor</td>
<td>250</td>
<td>800</td>
<td>20</td>
<td>200</td>
<td>40</td>
</tr>
<tr>
<td>Inductor</td>
<td>300</td>
<td>80</td>
<td>300</td>
<td>2400</td>
<td>110</td>
</tr>
</tbody>
</table>

The reliability of this block \( R_r \) is determined by (3) in which \( R \) is the reliability of each component.

\[
R_r = \frac{1}{N+x} \sum_{i=0}^{N} \frac{(N+x)!}{(N+x-i)!i!} R^{N+x-i} (1-R)^i
\]  
(3)

Because the different redundant blocks are series connected, so the reliability of the whole system is calculated by (2).

To have a further description of the series system and parallel system in one circuit, ABB’s Power Electronic Traction Transformer in Fig. 1(a) is taken as an example. One module is defined as one full bridge rectifier together with one DC-DC converter. 8 modules are necessary, and the remaining 1 is the redundant module. (1) and (2) are used to calculate the reliability of one module because the components in one module are series connected. The operating time \( t \) is set to be 5 years (43800 hours) in (1), (3) is used to calculate the reliability for the system, because the necessary modules and the redundant modules are parallel connected. In (3), \( N = 8 \), \( x = 1 \), and \( R \) is the reliability of each module calculated in (2).

In the calculations shown above, the normal operating possibility of the system after operating 5 years is evaluated. And it is assumed that the value of reliability above 0.6 is acceptable for the system under evaluation.

### B. The Possible Selections of Device Rating and the Redundancy Number

Table III shows the number of components for reliability calculation in ABB’s half-bridge topology. The number of components is counted based on Fig. 1. All the other topologies are analyzed according to the same method.

![Reliability of ABB Topologies with N+1 Redundancy](image1)

![Reliability of UNIFLEX Topologies with N+1/N+0 Redundancy](image2)

### C. The Impact of Device Rating to Reliability

For ABB topologies, different device ratings are compared in terms of reliability for each topology at N+1 redundancy as in Fig. 7. As shown in this figure, for most of the topologies of ABB application, the higher device rating results in higher reliability. The analysis on GE and EPRI topologies gives the same result.

However, for MMC topology, the reliability is not enhanced significantly while the device rating is increased. Another exception is the UNIFLEX topology. The dual output stages can respectively have N+0, N+1 or N+2 redundancy. The topologies based on 1.7kV devices and 3.3kV devices give the similar reliability results for each redundancy design and topology, as shown in Fig. 8. There are two possible reasons for the exception: 1) The device count is decreased insignificantly
with the increase in device rating; 2) The redundancy is the dominant effect.

The result shows that the selection of higher device rating is preferred for most of the topologies. However, if the topologies with lower device rating can have adequate reliability, a lower device rating can be selected for lower cost and loss.

D. The Impact of Redundancy Number to Reliability

As shown in Fig. 9, the higher redundancy number is, the higher reliability is. However, it is not necessary to have more than 3 redundancy. The reasons are shown below: 1) When the redundancy number is beyond a certain point, the reliability increases at very low rate. 2) A reliability above 0.6 is adequate as discussed in Subsection A. In this condition, the increase in the redundancy number causes significant rise of the cost while the reliability is not improved appreciably.

For the higher device rating, the fewer redundancy number could be selected to reach adequate reliability. The ABB topologies are taken as an example as shown in Fig. 9. If the device rating is 3.3kV, N+3 redundancy is needed for FB, HBMW and Matrix topologies, N+2 redundancy is needed for half-bridge topology, and for MMC topology, N+1 redundancy is needed. If the device rating is changed to be 6.5kV, the redundancy for each topology (except MMC topology) is decreased by 1 level.

E. The Guideline for the Selection of Device Rating and Redundancy

In the reliability model, it is preferred to have fewer modules series connected and more modules parallel connected. In this condition, higher reliability can be reached. For the topologies in these section, it is preferred to have the higher device rating and the higher redundancy number. However, cost and volume must be taken into consideration. Thus, a combination between these two factors must be optiminal designed.

For most of the topologies, the highest device rating would be selected. This option results in the fewest device count, which provides the higher reliability as well as the lowest volume. The selections of the redundancy number of these topologies are selected based on this highest device rating. The redundancy number can be minimized for lower volume and cost to reach sufficient reliability.

The exceptions occur when the device rating is not dominant effect as discussed in Subsection C. For example, the ABB MMC topology can have a high reliability with 4.5kV device. In this condition, the 6.5kV device is not necessary.

All the selections are shown in Table. IV.

IV. POWER DENSITY ANALYSIS

After optimizing all the topologies, the final selections of the topology applied to each application are determined based on power density analysis.

Power density of a SST is influenced by three factors: the device volume, the transformer volume and the capacitor volume. However, Because the size of a transformer is relatively proportional to its power rating, the sizes of transformers of the topologies for same application are similar. The semiconductor device volume is determined by the device rating and device count. For each of the topology, the devices and the capacitors are approximately selected according to the electrical stress. The volumes of the whole system can be approximately calculated as shown in Fig. 10. The same method can be applied to other applications.
The total volumes of ABB topologies are compared in Fig. 10. For ABB application, all the topologies have similar device volumes. It is shown that topologies with more devices (Full-bridge and Matrix topology) are smaller in size. However, when considering the cost of the devices and the size of the cooling systems, the topologies with more devices should be rejected. It is apparent that the MMC topology and the half-bridge topology are both small in size. In [4], it is announced that the PET designed by ABB has been updated for several times and the latest version of the PET is designed as the half-bridge topology. The result matches the industrial selection well. The author of [4] also suggested that the MMC topology should be rejected due to its low power density. However, based on the analysis in this paper, the power density of MMC is competitive. The MMC topology is highly recommended to be used in the PET application in the future.

For GE application, the full-bridge topology has smaller device volume. And the half-bridge topology has larger size due to the significant increase in capacitor quantity. For UNIFLEX applications, full-bridge and half-bridge topologies are comparable due to their small size. For EPRI, full-bridge and three-level topologies should be selected for further comparison.

The differences between conventional and multi-winding transformer are due to the winding current. Because of the skin effect, the integrated windings on the secondary side would have larger winding cross-section area than discrete windings when the total amount of current are the same. Therefore, the discrete single winding should have smaller size than the multi-winding. Thus, all the topologies with multi-windings are not suggested.

Based on the discussion above, the half-bridge topology should be selected for the ABB, the full-bridge topology should be selected for the GE, the full-bridge topology or the half-bridge topology should be used for the UNIFLEX and the three-level topology or the full-bridge topology should be used for the EPRI. As shown in Table IV, for higher reliability, 3-level for EPRI is a better selection. These topology selection results are matched with the industry product shown in Fig. 1 Fig. 4.

### Table III

<table>
<thead>
<tr>
<th>Device Selection</th>
<th>6.5kV Device 8 + x Redundancy</th>
<th>4.5kV Device 11 + x Redundancy</th>
<th>3.3kV Device 14 + x Redundancy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Per Module</td>
<td>Per Topology</td>
<td>Per Module</td>
</tr>
<tr>
<td>IGBT</td>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Diode</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Gate Driver</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Power Supply</td>
<td>6</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Capacitor</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Multi-Winding</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Transformer</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Isolation</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Control Platform</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Sensor</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table IV

<table>
<thead>
<tr>
<th>Topology</th>
<th>Reliability</th>
<th>Redundancy</th>
<th>Device Rating</th>
<th>Topology</th>
<th>Reliability</th>
<th>Redundancy</th>
<th>Device Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABB Half Bridge</td>
<td>0.61</td>
<td>N+1</td>
<td>6.5kV</td>
<td>GE Full Bridge</td>
<td>0.7</td>
<td>N+1</td>
<td>10kV</td>
</tr>
<tr>
<td>ABB Full Bridge</td>
<td>0.68</td>
<td>N+2</td>
<td>6.5kV</td>
<td>GE Half Bridge</td>
<td>0.73</td>
<td>N+1</td>
<td>10kV</td>
</tr>
<tr>
<td>ABB Half Bridge</td>
<td>0.73</td>
<td>N+2</td>
<td>6.5kV</td>
<td>GE Full Bridge Paralleled Output</td>
<td>0.67</td>
<td>N+1</td>
<td>10kV</td>
</tr>
<tr>
<td>Multi-winding Transformer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABB MMC</td>
<td>0.64</td>
<td>N+1</td>
<td>4.5kV</td>
<td>GE Full Bridge Multi-winding Transformer</td>
<td>0.68</td>
<td>N+1</td>
<td>10kV</td>
</tr>
<tr>
<td>ABB Matrix</td>
<td>0.61</td>
<td>N+2</td>
<td>4.5kV</td>
<td>GE Half Bridge Multi-winding Transformer</td>
<td>0.7</td>
<td>N+1</td>
<td>10kV</td>
</tr>
<tr>
<td>UNIFLEX Full Bridge</td>
<td>0.60</td>
<td>N+1/N+0</td>
<td>1.7kV</td>
<td>EPRI 3-level</td>
<td>0.74</td>
<td>N+0</td>
<td>4.5kV</td>
</tr>
<tr>
<td>UNIFLEX 3-level</td>
<td>0.67</td>
<td>N+1/N+0</td>
<td>1.7kV</td>
<td>EPRI Full Bridge</td>
<td>0.61</td>
<td>N+0</td>
<td>4.5kV</td>
</tr>
<tr>
<td>UNIFLEX Half Bridge</td>
<td>0.63</td>
<td>N+1/N+0</td>
<td>1.7kV</td>
<td>EPRI Half Bridge</td>
<td>0.63</td>
<td>N+0</td>
<td>4.5kV</td>
</tr>
</tbody>
</table>
V. CONCLUSION

In this paper, a reliability analysis model is proposed to evaluate the topologies for different applications. Device rating and redundancy number are considered as two major factors to affect the reliability. An approximate power density analysis is proposed to have a further selection of the topologies. The procedure to have a selection of the topology for an application is shown here. 1) Screening all the possible topologies for this application. 2) Considering the semiconductor device rating. It is recommended to have a higher device rating to reach fewer modules and lower device count. 3) Considering the redundancy. Selecting a proper redundancy number to reach sufficient reliability. It is recommended to have redundancy number as few as possible to avoid unnecessary cost. 4) The power density gives the final selection among the topologies. The analysis based on loss, cost and weight is also necessary[2][3].

This methodology is proved to be applicable because the results are similar to the topologies selected by industry. Further work can be focused on the research on FIT of difference devices at different operating conditions. Detailed researches on capacitors, transformers, cooling system and insulation will give more accurate power density approximation.

REFERENCES