Performance of 3-Phase 4-Wire Solid State Transformer under Imbalanced Loads

Tao Yang, Ronan Meere, Orla Feely and Terence O'Donnell

School of Electrical, Electronic and Communications Engineering
University College Dublin
Dublin, Ireland

March 2014
Overview

- Introduce Solid State Transformers (SST)
  - Advantages and Disadvantages
  - Each Stage of SST Design and Operation
- How can a SST deal with imbalance?
  - Compare different topologies
- Conclusions and Future Work
Solid State Transformer (SST): Basic Concept

- Take 50/60 Hz input voltage
- Use power electronics switches to chop 50/60 Hz into much higher frequency AC (e.g. 10’s kHz)
- Pass this high frequency through a transformer
- Use power electronics to “re-make” and regulate the 50 Hz voltage.
Advantages/Disadvantages

• Advantages?
  – Reduced size and weight
  – SST is active, controllable device
    • Output and input waveforms can be decoupled
    • Eliminate harmonic distortion
    • Improve voltage regulation
    • Control active and reactive power
  – Could have a DC input/output for connection of DG, energy storage

• Disadvantages?
  – Efficiency,
  – Reliability
  – Cost
Motivation
Motivation of our study

1. Improve the disadvantages of SST?
2. In an SST-fed distribution system, Can SST ensure that certain tolerances on phase loads imbalance at its output terminals. (few publications have addressed the issue)
Imbalance Loads

Three-phase Imbalance Loads

- Unevenly distributed single-phase load.
- Balanced three-phase load running at a fault condition.

Imbalance Factors of Loads\(^1\)
\[
\frac{Z_{\text{Max}(\text{phase})} - Z_{\text{Min}(\text{phase})}}{Z_{\text{Rated}(\text{phase})}}
\]

Imbalance Degree of Output\(^2\)
\[
\frac{V_{a,b,c \text{ Max}(\text{RMS})} - V_{a,b,c \text{ Min}(\text{RMS})}}{V_{\text{Rated}(\text{Phase RMS})}}
\]

- Imbalanced phase loading causes negative sequence and zero sequence to flow in the power system.

Each Stage of SST Design and Operation
Single Phase Rectifier Stage
Dual Active Bridge (DAB) Stage

\[ P_o = \frac{V_{in}^2}{2L_0 f_H N} d \frac{\phi}{\pi} \left(1 - \frac{\phi}{\pi}\right) d = N \frac{V_o}{V_{in}} \]

Phase-shift Control for Single DAB

Vo(V_LVDC)  K-factor (P-I)  Phase Angle Saturation  Phase Shift Modulation  To Gate Drivers

Low DC output voltage of DAB

Step Load  Start-up

Voltage/V  t/s  wt(Degree)
Single phase DC-AC Inverter Stage

The diagram illustrates the circuit design for a single phase DC-AC inverter stage. It shows the components and the flow of current and voltage. The circuit includes a DC link, a filter inductor (L), a DC voltage source (V_LDC), and a load (V_load). The inverter stage uses transistors (Sc1, Sc2, Sc3, Sc4) and a proportional integral (PI) controller with a gain (Kpwm) to regulate the output voltage (Vo) and current (Io).

The output voltage and current are depicted in the graph below the diagram. The voltage and current waveforms show the response of the system to step load changes labeled 'Step Load 1' and 'Step Load 2'.
Two Topologies of 3-stage 3-Phase SST

3-phase 3-wire SST (SST1)

3-phase 4-wire SST (SST2)
Systems Performances simulations under Imbalanced Loads: 3-phase 3-wire SST VS 3-phase 4-wire SST

<table>
<thead>
<tr>
<th>Input Voltage $V_{in}$</th>
<th>$3.39 \times 3$ kV (amplitude) AC Phase voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>High Voltage DC reference</td>
<td>3.8*3 kV</td>
</tr>
<tr>
<td>DAB Frequency</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Low Voltage DC reference</td>
<td>400 V</td>
</tr>
<tr>
<td>Output Voltage reference</td>
<td>311 V (amplitude) AC Phase voltage</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load Conditions</th>
<th>Imbalance factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>5%</td>
</tr>
<tr>
<td>Case2</td>
<td>10%</td>
</tr>
<tr>
<td>Case3</td>
<td>15%</td>
</tr>
</tbody>
</table>
Performance comparison with case 2 loads condition

3-phase 3-wire SST output voltage

3-phase 4-wire SST output voltage

Performance comparison with case 3 loads condition

3-phase 3-wire SST output Voltage

3-phase 4-wire SST output voltage
Why 3-Phase 4-Wire SST can handle the imbalance loads conditions better:

- Provide neutral wire to handle the neutral current caused by an imbalanced loads;
- Attain 3 phases fully decoupled and independently controlled.
Conclusions and Future Work

• Yes, SST can be an excellent system for ensuring distribution level feeder voltage balance in the face of significant loads imbalance.

But...

- Compare both topologies designs to see is there a difference in power efficiency?
- Is there a design method which can both handle imbalance loads and improve the power efficiency?
Thank you for listening…

Questions ?