General considerations for the crowbar design of the HL-LHC circuits

Hugues THIESEN (CERN)
On behalf of WP6B Warm Powering

8th HL-LHC Collaboration Meeting – Geneva - 15-18 October 2018
Contents

- Power converter crowbar
- Crowbar for superconducting circuits
- Crowbar for HL-LHC circuits
- Conclusion
Power converter crowbar
The main function of the crowbar is to protect the electrical circuit (PC, DC cables and magnet) by giving a path for current in case of PC trip.
Power converter crowbar

- Different types of crowbar
  - 1Q power converter => Diode
Power converter crowbar

- Different types of crowbar
  - 1Q power converter => Diode
  - 2Q (bipolar in V) power converter => Thyristor
Power converter crowbar

- Different types of crowbar
  - 1Q power converter => Diode
  - 2Q (bipolar in V) power converter => Thyristor
  - 4Q power converter => 2 thyristors back2back
Power converter crowbar

- The main parameters for the crowbar design:
  - $V_{\text{peak}}$, $I_{\text{peak}}$ and $P_{\text{peak}}$ are defined by the power converter
  - Energy and current decay ($\tau$) are defined by the magnet
  - Crowbar has to be natural air cooled (in case of water fault)
  - Auto-maintain (not need of external energy to maintain the crowbar ON)
The main parameters for the crowbar design:

- $V_{\text{peak}}$, $I_{\text{peak}}$ and $P_{\text{peak}}$ are defined by the power

$V_{\text{max}}$ defined by the rating of the PC

$I_{\text{max}}$ defined by the rating of the PC

$\tau = L/R$ defined by the load (magnet + DC cables)

$E < E_{\text{magnet}}$
Crowbar for superconducting circuits
Crowbar for superconducting circuits

- Superconducting circuits can have
  - High current (>1 kA) and high inductance (>1 H)
  - Low resistance (<10 mΩ, only DC cables)
- main part of the magnet energy is dissipated in the crowbar

**Series resistor can be added to reduce the constraints (E and τ) for the crowbar (diodes or thyristors)**
Crowbar for superconducting circuits

- Crowbar resistor
  - The *series resistor* absorbs a part of magnet energy and reduces the *time constant* of the discharge (positive point for the magnet)
Crowbar for superconducting circuits

- Crowbar resistor
  - Example: Crowbar resistor is used for the LHC 120A power converters.

Circuit | $R_{\text{cb}}$ [mR] | $V_{\text{cb}}$ [V] | $V_{\text{pc}}$ [V]
---|---|---|---
120A | 80 | 9.6 | 10

$V_{\text{cb}} < V_{\text{pc}}$
Crowbar for superconducting circuits

- Crowbar resistor
  - Example: Crowbar resistor is used for the LHC 120A power converters.

```
\begin{array}{|c|c|c|c|}
\hline
\text{Circuit} & \text{R\textsubscript{cb} [mR]} & \text{V\textsubscript{cb} [V]} & \text{V\textsubscript{pc} [V]} \\
\hline
120A & 80 & 9.6 & 10 \\
\hline
\end{array}
```

Can we go above nominal voltage of the power converter?
Crowbar for superconducting circuits

- Crowbar resistor
  - The [600A/10V] PCs power superconducting circuits with huge inductance and huge time constant (e.g. RU circuits with 4.8 H and 1000 s)
  - The crowbar resistor is 50 mΩ and the voltage across the PC during the discharge is 30V.
    - Constraints for the power converter (over voltage)
    - Constraints for the superconducting circuit (di/dt > nominal di/dt)
    - Constraints for the QDS (protection by global voltage)
Crowbar for superconducting circuits

- SC busbar can be protected by the Crowbar?
  - Risk to bypass the crowbar in case of PC short circuit
  - DC contactor added in series with the PC to increase the safety level of the discharge system
Crowbar for HL-LHC circuits
Crowbar for HL-LHC circuits

- HL-LHC circuits
Crowbar for HL-LHC circuits

- HL-LHC circuits

---

11T Dipole - Right and Left of Point 7

Legend:
- QP: Quench Protection
- QH: Quench Heaters
- EE: Energy Extraction System
- PC: Power Converter
- OC: Orbit Correctors
- n: Number of Circuits per IP Side
- ST HO: Superfluctric High Order
- n: Current Leads Connection
Crowbar for HL-LHC circuits

### HL-LHC circuits

<table>
<thead>
<tr>
<th>Circuit</th>
<th>I&lt;sub&gt;pc&lt;/sub&gt; [A]</th>
<th>V&lt;sub&gt;pc&lt;/sub&gt; [V]</th>
<th>Quadrant</th>
<th>Magnet</th>
<th>Crowbar</th>
<th>R&lt;sub&gt;cb&lt;/sub&gt; [mΩ]</th>
<th>V&lt;sub&gt;cb&lt;/sub&gt; [V]</th>
<th>Based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>120A</td>
<td>120</td>
<td>10</td>
<td>4Q</td>
<td>CP</td>
<td>Thy_B2B</td>
<td>80</td>
<td>9.6</td>
<td>LHC</td>
</tr>
<tr>
<td>200A</td>
<td>200</td>
<td>10</td>
<td>4Q</td>
<td>CP</td>
<td>Thy_B2B</td>
<td>50</td>
<td>10</td>
<td>LHC R2E</td>
</tr>
<tr>
<td>600A</td>
<td>600</td>
<td>10</td>
<td>4Q</td>
<td>OC(D2)</td>
<td>Thy_B2B</td>
<td>50</td>
<td>30</td>
<td>LHC R2E</td>
</tr>
<tr>
<td>2kA</td>
<td>2'000</td>
<td>10</td>
<td>4Q</td>
<td>OC(Q1toQ3)</td>
<td>Thy_B2B</td>
<td>7</td>
<td>14</td>
<td>New</td>
</tr>
<tr>
<td>13kA</td>
<td>13’000</td>
<td>8</td>
<td>1Q</td>
<td>D1/D2</td>
<td>Diode</td>
<td>-</td>
<td>0</td>
<td>LHC R2E</td>
</tr>
<tr>
<td>IT Main</td>
<td>18’000</td>
<td>10</td>
<td>2Q</td>
<td>Q1toQ3</td>
<td>Thy</td>
<td>0.5</td>
<td>9</td>
<td>New</td>
</tr>
<tr>
<td>IT Trim</td>
<td>2’000</td>
<td>10</td>
<td>4Q</td>
<td>Q1/Q3</td>
<td>Thy_B2B</td>
<td>7</td>
<td>14</td>
<td>New</td>
</tr>
<tr>
<td>IT kmod</td>
<td>35</td>
<td>8</td>
<td>4Q</td>
<td>Q1a</td>
<td>Thy_B2B</td>
<td>??</td>
<td>??</td>
<td>LHC</td>
</tr>
</tbody>
</table>
Crowbar for HL-LHC circuits

- 2kA power converter
  - Redundant power converter with 6 sub-PC in parallel
Crowbar for HL-LHC circuits

- 2kA power converter
  - 2 cases to take in account to design the 2 kA crowbar resistor
    - Power converters for OC(Q1toQ3)
    - Power converters for IT TRIM

<table>
<thead>
<tr>
<th>PC</th>
<th>Over Current [A]</th>
<th>R_cb [mΩ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC(Q1toQ3)</td>
<td>2’000</td>
<td>&lt; 25</td>
</tr>
<tr>
<td>TRIM(Q1&amp;Q3)</td>
<td>7’000</td>
<td>&lt; 7</td>
</tr>
</tbody>
</table>
Crowbar for HL-LHC circuits

- 2kA power converter
  - 2 cases to take in account to design the 2 kA crowbar resistor
    - Power converters for OC(Q1toQ3)
    - Power converters for IT TRIM

<table>
<thead>
<tr>
<th>PC</th>
<th>Over Current [A]</th>
<th>R_cb [mΩ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC(Q1toQ3)</td>
<td>2'000</td>
<td>&lt; 25</td>
</tr>
<tr>
<td>TRIM(Q1&amp;Q3)</td>
<td>7'000</td>
<td>&lt; 7</td>
</tr>
</tbody>
</table>
Crowbar for HL-LHC circuits

- 2kA power converter
  - If the crowbar is critical for the protection of the SC busbar then 400A fuses can be added in series with the DC contactor of each sub converter
Crowbar for HL-LHC circuits

- 18kA power converter
  - Huge energy stored in the circuit (Q1, Q2a, Q2b and Q3)
  - No DC cables
    - Time constant > 500 s
    - Full magnet energy dissipated in the crowbar
Crowbar for HL-LHC circuits

- 18kA power converter
  - N sub-converters with M sub-module in parallel
  - Diodes of the output stage in parallel with the crowbar

\[ V_{\text{cb}} < V_{\text{bat}} \text{ (24 V)} \]
\[ \tau > 250 \text{ s} \]
Crowbar for HL-LHC circuits

- **18kA power converter**
  - If $V_{cb} > 24$ V is requested then external 18 kA EE system is mandatory
Conclusion
Conclusion

- The function of the crowbar is to protect electrical circuit (PC, DC cables and magnet) by giving a path for current when the power converter is OFF (normal or fault off).

- Resistor in series with the crowbar can be added to reduce the time constant of the discharge but in this case the $V_{cb}$ shall be close to the $V_{pc}$

- For high discharge voltage, EE system must be used.
Thank you for your attention…