A Hybrid Voltage Regulation Transformer Based on Interline Power Converters

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Introduction

• Conventional Step Voltage Regulator (SVR)
  – Auto-transformer based configuration
  – Preventive transformer and equalizer windings to balance the branch current
  – Increase and decrease the tap position to regulate load voltage at the distribution stage

• Issues and Challenges
  – Arcing when the metal contacts move from the energized taps
  – Contact wearing and oil degradation due to the frequent arc
  – Renewable energy penetration causes more frequent tap changes
  – Constraints on SVR lifetime and maintenance frequency
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Proposed Hybrid Voltage Regulation Transformer

- **Circuit Topology**
  - Additional winding placed in series with the secondary winding
  - Two series transformers are connected in series with top and bottom branches
  - An interline back-to-back power converter connects two series transformers

- **Operation Principle**
  - Rectifier regulates the DC bus voltage while the inverter controls the bottom winding voltage to regulate load voltage
  - The current distribution in the branches changes accordingly as the top and bottom winding voltage changes.
  - Rectifier affects the voltage distribution in the loop and also participates in the voltage regulation
Proposed Hybrid Voltage Regulation Transformer

• Converter Control
  – Rectifier regulates the DC bus voltage with unity power factor
  – Inverter regulates the load voltage
Proposed Hybrid Voltage Regulation Transformer

- **Operation Principle**
  - At the nominal source voltage, no regulation is required. Top and bottom branches share the load current equally and the voltages on top and bottom windings are the same.
  - The maximum power rating of the converter in the interline voltage regulation transformer is half of the series voltage regulation solutions.

\[
\begin{align*}
V_{\text{load}} &= V_{\text{sec}} + V_{\text{bot}} \\
V_{\text{load(nominal)}} &= V_{\text{sec}} + 0.5V_{\text{range}} \\
I_{\text{top}} + I_{\text{bot}} &= I_{\text{load}} \\
V_{\text{range}} &= V_{\text{top}} + V_{\text{bot}} \\
P_{\text{rec}} &= V_{\text{top}}I_{\text{top}} = P_{\text{inv}} = V_{\text{bot}}I_{\text{bot}} \\
P_{\text{series(max)}} &= \Delta V \cdot I_{\text{load}} \\
V_{\text{range}} &= 2 \cdot \Delta V \\
P_{\text{interline(max)}} &= 0.5V_{\text{range}} \cdot 0.5I_{\text{load}} = 0.5P_{\text{series(max)}}
\end{align*}
\]
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Simulation Results

- Simulation for Function Validation
  - The simulation specifications are listed in Table I, II and III for comparison.
  - The proposed interline solution requires half of the maximum converter power than the series solution.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary winding voltage $V_{pri}$</td>
<td>4 kV</td>
</tr>
<tr>
<td>Secondary winding voltage $V_{sec}$</td>
<td>3.6 kV</td>
</tr>
<tr>
<td>Additional winding voltage $V_{range}$</td>
<td>800 V</td>
</tr>
<tr>
<td>Nominal branch current $I_{top}/I_{bot}$</td>
<td>10 A</td>
</tr>
<tr>
<td>Nominal branch voltage $V_{top}/V_{bot}$</td>
<td>400 V</td>
</tr>
<tr>
<td>Maximum converter power</td>
<td>4 kW</td>
</tr>
<tr>
<td>DC bus voltage</td>
<td>800 V</td>
</tr>
<tr>
<td>Series transformer turns ratio (N)</td>
<td>1:2</td>
</tr>
<tr>
<td>Converter switching frequency</td>
<td>10 kHz</td>
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</tbody>
</table>

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<thead>
<tr>
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<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary winding voltage $V_{pri}$</td>
<td>4 kV</td>
</tr>
<tr>
<td>Secondary winding voltage $V_{sec}$</td>
<td>4 kV</td>
</tr>
<tr>
<td>Nominal load current $I_{load}$</td>
<td>20 A</td>
</tr>
<tr>
<td>Regulation voltage range $\Delta V$</td>
<td>400 V</td>
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<tr>
<td>Maximum converter power</td>
<td>8 kW</td>
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<tr>
<td>DC bus voltage</td>
<td>800 V</td>
</tr>
<tr>
<td>Series transformer turns ratio (N)</td>
<td>1:1</td>
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<tr>
<td>Converter switching frequency</td>
<td>10 kHz</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source voltage</td>
<td>4 kV</td>
</tr>
<tr>
<td>Nominal load voltage</td>
<td>4 kV</td>
</tr>
<tr>
<td>Load current</td>
<td>20 A</td>
</tr>
<tr>
<td>Resistive load power</td>
<td>80 kW</td>
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<tr>
<td>Voltage regulation range</td>
<td>±400 V</td>
</tr>
<tr>
<td>Voltage regulation percentage</td>
<td>±10%</td>
</tr>
</tbody>
</table>
Simulation Results

- Simulation for Function Validation
  - With the proposed control algorithms, the top and bottom winding voltage and current change accordingly based on different primary winding voltage deviations.
  - The operation principles and control algorithms are verified by the simulation results.

Voltage regulation waveforms of the proposed hybrid transformer. (From top to bottom: source voltage $V_s$, load voltage $V_{load}$, top winding voltage $V_{top}$, bottom winding voltage $V_{bot}$, top branch current $I_{top}$, and bottom winding current $I_{bot}$)
Simulation Results

- Converter Power Loss and Overall Efficiency Comparison
  - In PLECS simulation, IGBT (IGW60T120) rated at 1200V and 60A is selected.
  - The rectifier and inverter losses are highly related to the current flowing through the converter. So, the converter power loss of the proposed interline solution is lower than that of the conventional series solution across a wide range of the load voltage regulation.
Simulation Results

- Converter Power Loss and Overall Efficiency Comparison
  - The rectifier and inverter power capacity can be lowered to half compared to the conventional series voltage compensation solution, which saves the cost of the converter module.
  - The voltage regulation transformer overall efficiency of the interline solution is higher than the series solution across a wide range of the load voltage regulation.
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Prototype Test Results

• Prototype and Specifications
  – A scaled-down prototype is developed in the lab to verify the operation principle.
  – The prototype design specifications are listed in Table IV.

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>Source voltage</td>
<td>72 V</td>
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<tr>
<td>Nominal load voltage</td>
<td>72V</td>
</tr>
<tr>
<td>Load current</td>
<td>6 A</td>
</tr>
<tr>
<td>Primary winding voltage $V_{pri}$</td>
<td>72 V</td>
</tr>
<tr>
<td>Secondary winding voltage $V_{sec}$</td>
<td>60 V</td>
</tr>
<tr>
<td>Additional winding voltage $V_{range}$</td>
<td>24 V</td>
</tr>
<tr>
<td>DC bus voltage</td>
<td>100 V</td>
</tr>
<tr>
<td>Series transformer turns ratio (N)</td>
<td>4:1</td>
</tr>
<tr>
<td>Converter switching frequency</td>
<td>10 kHz</td>
</tr>
</tbody>
</table>
Prototype Test Results

• **Prototype Test**
  - Test condition: the source voltage steps down from 72V nominal voltage to 60V which is at the regulation limit.
  - Test result: the load voltage remains being regulated at 72V.
  - The top branch current $I_{top}$ increases while the bottom branch current $I_{bot}$ decreases to almost zero.
  - The current distribution in the branch changes accordingly, which matches the simulation results.
  - The hardware test results validate the operation principle of the proposed voltage regulation hybrid transformer.

![Prototype voltage regulation test waveform](image)
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Conclusion

• A hybrid transformer based on interline power converters is proposed for voltage regulation.

• The operation principles are analyzed and validated by the simulation results. A scale-down prototype is developed, and the operation principle is validated by the hardware test results.

• The new operation pattern illustrates the feasibility of implementing both rectifier and inverter for the voltage regulation, which differs from the conventional series voltage compensation solution.

• The proposed hybrid transformer presents a higher overall efficiency covering a wide range of voltage regulation and requires half maximum converter power compared with the conventional series voltage compensation configuration for the same voltage regulation range.

• The new current and voltage distribution pattern between top and bottom branches helps reduce the size and cost of the power converter and improves the system overall efficiency.
Thanks!