A Hybrid Voltage Regulation Transformer Based on Interline Power Converters

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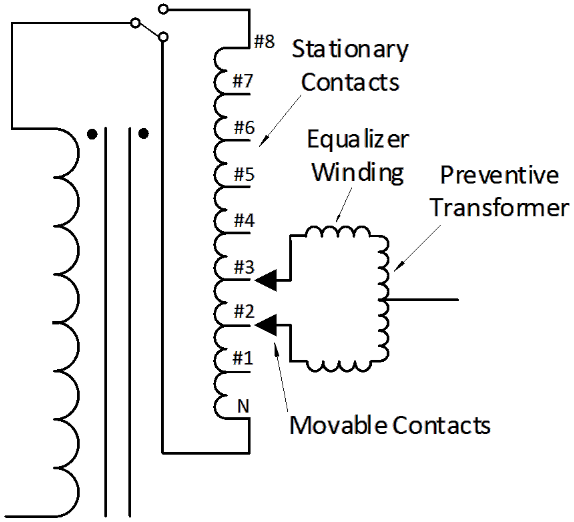
Introduction

- 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



Conventional SVR

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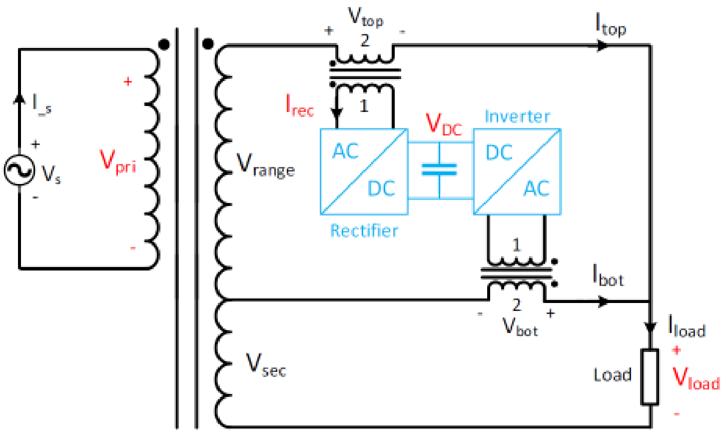
Proposed Hybrid Voltage Regulation Transformer

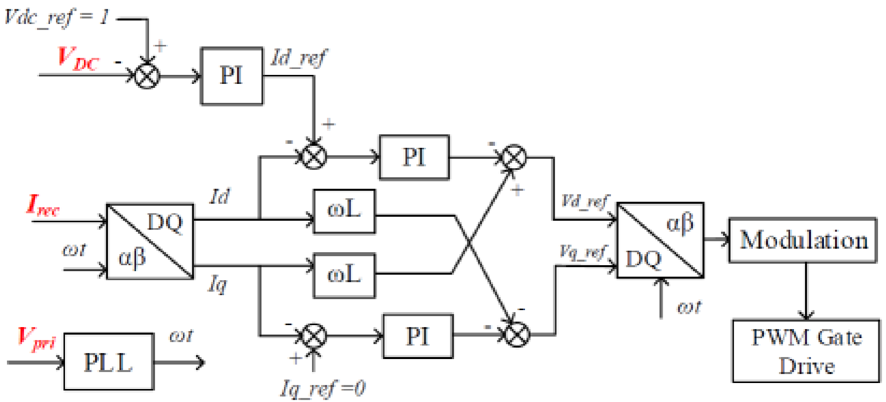
- Circuit Topology
  - Additional winding placed in series with the secondary winding
  - Two series transformers are connected in series with top and bottom branches
  - An interline back-to-back power converter connects two series transformers
- Operation Principle
  - Rectifier regulates the DC bus 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



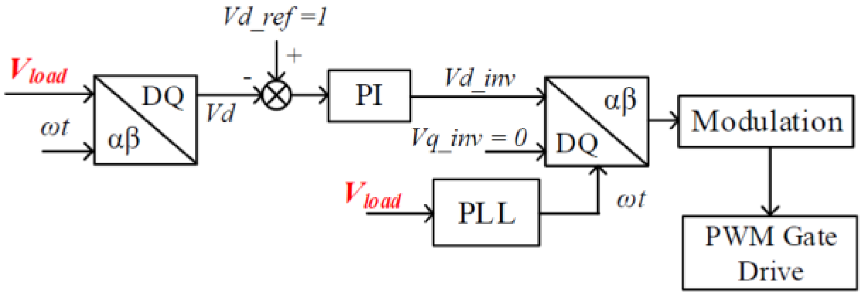
Proposed Hybrid Voltage Regulation Transformer

Proposed Hybrid Voltage Regulation Transformer

- Converter Control
  - Rectifier regulates the DC bus voltage with unity power factor
  - Inverter regulates the load voltage



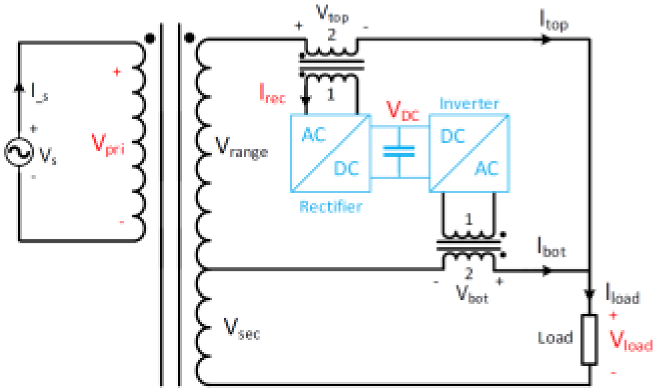
Rectifier Control Algorithm



Inverter Control Algorithm

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



$$V_{load} = V_{sec} + V_{bot} \quad (1)$$

$$V_{load(nominal)} = V_{sec} + 0.5\,V_{range} \quad (2)$$

$$I_{top} + I_{bot} = I_{load} \quad (3)$$

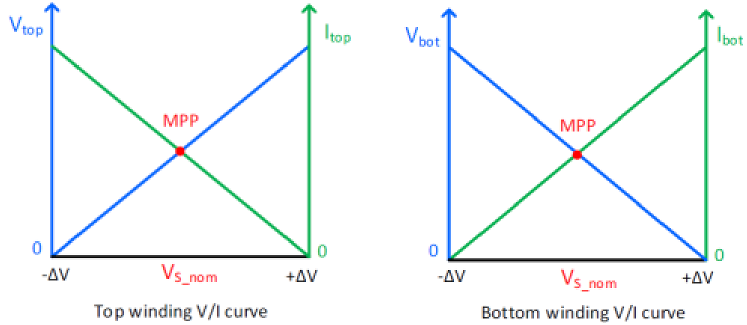
$$V_{range} = V_{top} + V_{bot} \quad (4)$$

$$P_{rec} = V_{top} I_{top} = P_{inv} = V_{bot} I_{bot} \quad (5)$$

$$P_{series(max)} = \Delta V \cdot I_{load} \quad (6)$$

$$V_{range} = 2 \cdot \Delta V \quad (7)$$

$$\begin{aligned} P_{interline(max)} &= 0.5 V_{range} \cdot 0.5 I_{load} \\ &= 0.5 P_{series(max)} \end{aligned} \quad (8)$$



Top and bottom winding V/I curve
(MPP: maximum power point)

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Simulation Results

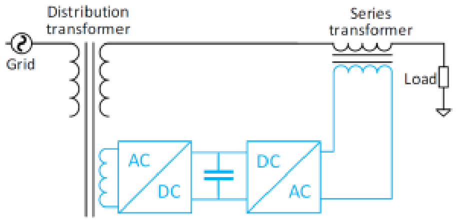
- Simulation for Function Validation
  - The simulation specifications are listed in Table I, II and III for comcomparison.
  - The proposed interline solution requires half of the maximum converter power than the series solution.

TABLE II. PROPOSED HYBRID TRANSFORMER SPECIFICATIONS

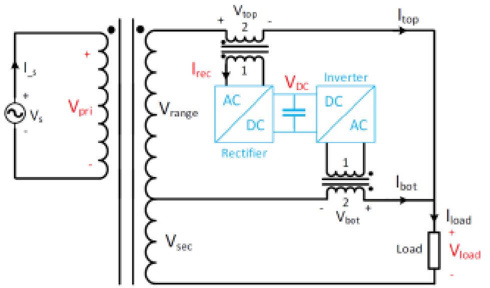
Parameter	Value
Primary winding voltage V_{pri}	4 kV
Secondary winding voltage V_{sec}	3.6 kV
Additional winding voltage V_{range}	800 V
Nominal branch current I_{top}/ I_{bot}	10 A
Nominal branch voltage V_{top}/ V_{bot}	400 V
Maximum converter power	4 kW
DC bus voltage	800 V
Series transformer turns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

TABLE III. CONVENTIONAL SERIES HYBRID TRANSFORMER SPECIFICATIONS

Parameter	Value
Primary winding voltage V_{pri}	4 kV
Secondary winding voltage V_{sec}	4 kV
Nominal load current I_{load}	20 A
Regulation voltage range ΔV	400 V
Maximum converter power	8 kW
DC bus voltage	800 V
Series transformer turns ratio (N)	1:1
Converter switching frequency	10 kHz



Conventional Series Solution



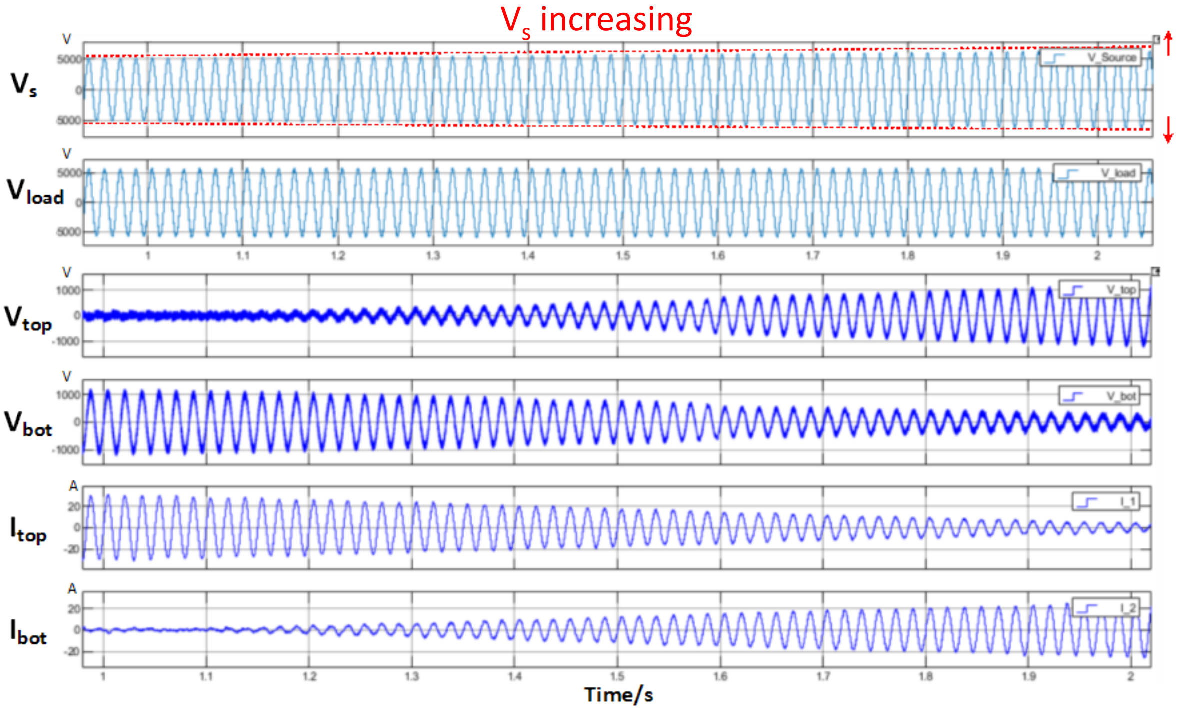
Proposed Interline Solution

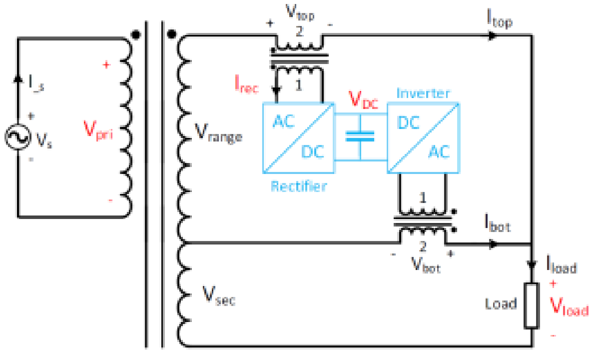
TABLE I. REFERENCE LOAD MODEL SPECIFICATIONS

Parameter	Value
Source voltage	4 kV
Nominal load voltage	4 kV
Load current	20 A
Resistive load power	80 kW
Voltage regulation range	±400 V
Voltage regulation percentage	±10%

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.

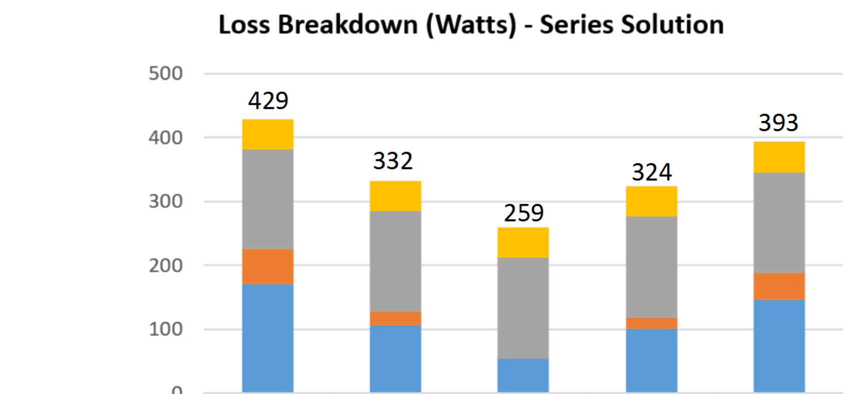




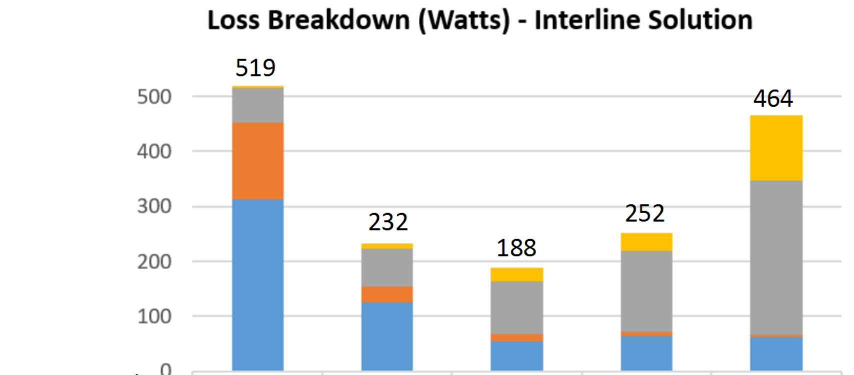
Voltage regulation waveforms of the proposed hybrid transformer. (From top to bottom: source voltage V_s, load voltage V_{load}, top winding voltage V_{top}, bottom winding voltage V_{bot}, top branch current I_{top} and bottom winding current I_{bot})

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



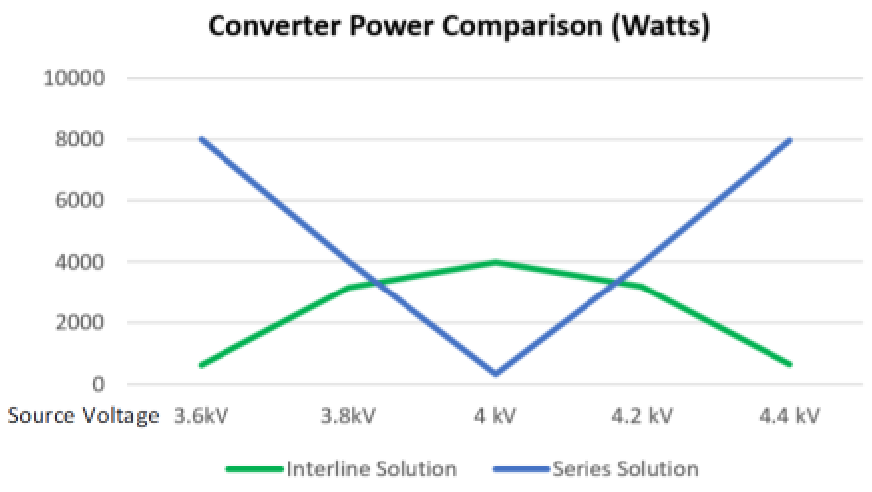
Source Voltage	3.6kV	3.8kV	4 kV	4.2 kV	4.4 kV
Inv Cond. Loss	46.73	47.07	47.36	47.65	47.92
Inv Sw. Loss	156.88	157.5	157.38	157.47	158.02
Rec Cond. Loss	55.02	20.97	1.01	17.69	40.87
Rec Sw. Loss	170.17	106.37	53.4	101.37	146.74

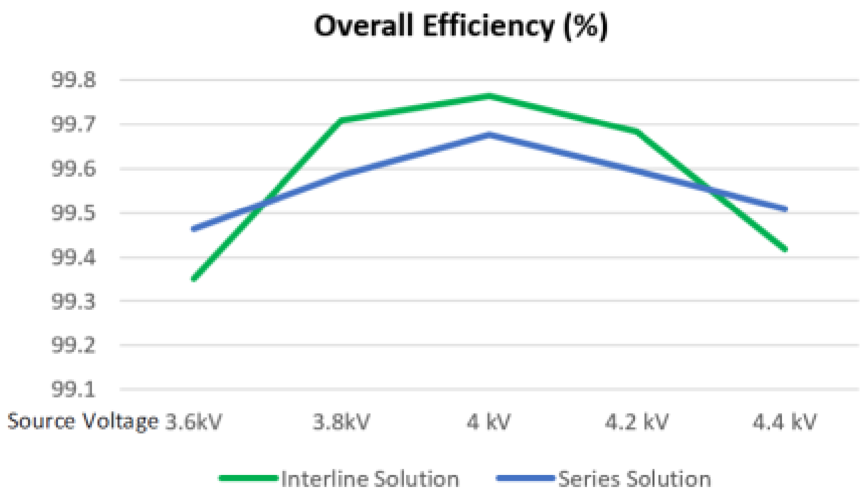


Source Voltage	3.6kV	3.8kV	4 kV	4.2 kV	4.4 kV
Inv Cond. Loss	3.48	9.93	24.97	33.51	118.02
Inv Sw. Loss	63.52	67.54	94.64	147.38	281.17
Rec Cond. Loss	138.68	30.01	13.27	7.29	2.74
Rec Sw. Loss	313.46	124.88	55.47	64.07	63

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.

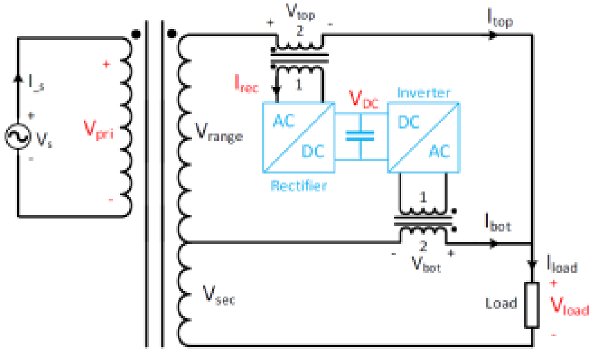
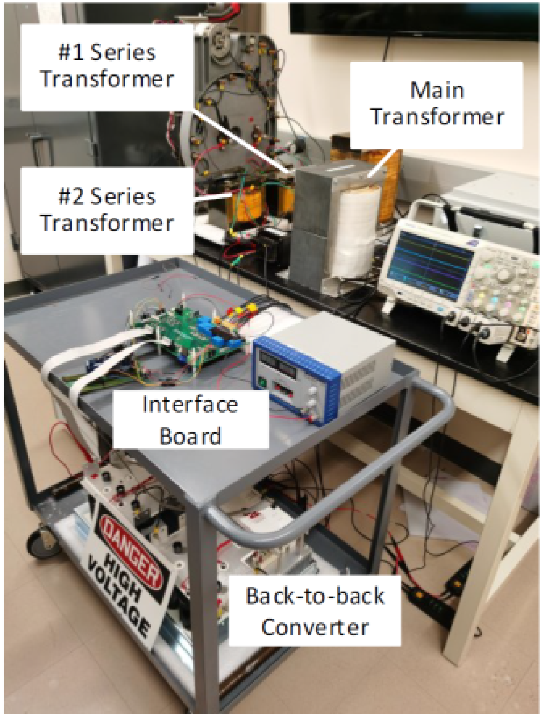


TABLE IV. PROTOTYPE DESIGN SPECIFICATIONS

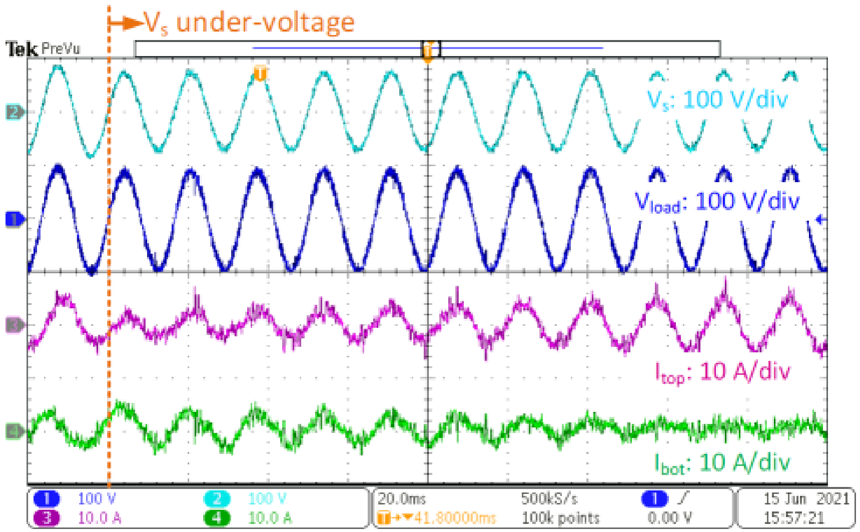
Parameter	Value
Source voltage	72 V
Nominal load voltage	72V
Load current	6 A
Primary winding voltage V_{pri}	72 V
Secondary winding voltage V_{sec}	60 V
Additional winding voltage V_{range}	24 V
DC bus voltage	100 V
Series transformer turns ratio (N)	4:1
Converter switching frequency	10 kHz



Scaled-down hybrid transformer prototype

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

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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!