A Hybrid Voltage Regulation Transformer Based on Interline Power Converters

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***Abstract*— The hybrid transformer is mostly used for voltage regulation and var control with a fractionally rated power converter, which reduces the device cost and increases the overall efficiency compared with the Solid-State Transformer (SST). Conventionally, the voltage is compensated by injecting voltage in series with the load. This paper proposed a hybrid transformer based on interline power converters for voltage regulation. The maximum power delivered by converters is reduced by half compared with the conventional series compensation configuration for the same voltage regulation range. Therefore, the proposed hybrid transformer exhibits a higher overall efficiency covering a wide range of voltage regulation. Comparison between the conventional series voltage compensation method and the proposed interline power converter-based method is presented based on the operation principle, the converter power, and the overall system efficiency. Hardware test results are presented for further validation of the proposed hybrid transformer.**

Keywords*— *Converter, hybrid transformer, interline, voltage regulation

I. Introduction

In power distribution systems, distribution transformers are widely applied to provide isolation between different voltage levels. The voltage drop across distribution lines and power delivery variation can be frequently observed in distribution systems. Therefore, some voltage regulation devices are implemented to regulate the load voltage. Step voltage regulator (SVR), as shown in Fig. 1, has been utilized in power distribution systems for decades to regulate the voltage step by step while the voltage regulation speed is limited by the tap changer mechanism. In recent years, voltage variation can be observed more frequently due to renewable energy penetration and the power generation variation from distributed energy resources (DERs). Arcless tap change technologies and other accurate voltage regulation methods are discussed in [1] and [2]. However, distribution transformers are expected to achieve fast voltage regulation with cost-efficient solutions. Dynamic voltage restorer (DVR) at medium voltage level is discussed in [3] and [4] to compensate voltage sag and swell for transient voltage variation. Solid state transformer is an advanced technology rated at the feeder's full power [5]. [6] and [7] present the advantages of high efficiency and low cost for the hybrid transformer solutions. The study in [8] discusses the distributed var control considerations for the hybrid distribution transformer. Conventional hybrid transformer with series voltage compensation configuration is shown in Fig. 2. The controllable network transformer in [9] and the interline power flow controller in [10] provide new configurations for voltage regulation.

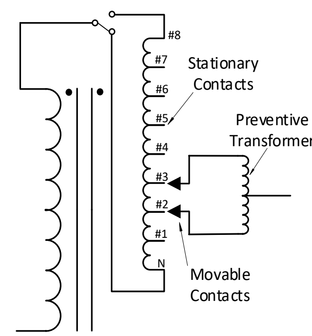

Fig. 1. Conventional voltage regulator

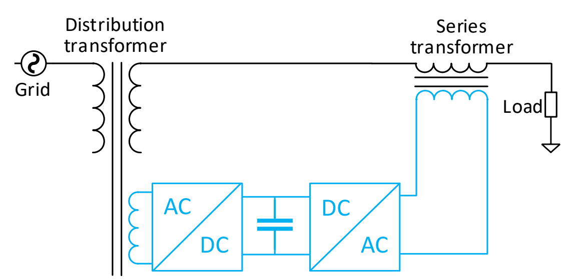

Fig. 2. Conventional hybrid transformer with series voltage compensation

This paper proposes a hybrid transformer based on interline power converters for voltage regulation. Section II introduces the hybrid transformer topology and operation principles. The top and bottom winding voltage and current curves are also illustrated for different source voltage deviations. In Section III, a comprehensive comparison between the proposed hybrid transformer and the conventional series voltage compensation method is presented. Section IV provides the control algorithms and the simulation results for function validation and efficiency comparison. Based on the PLECS simulation results, 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. A prototype is developed in the lab and hardware test results are presented in Section V. Section VI provides the conclusion and future work discussion.

II. Proposed Hybrid Transformer

A. Hybrid Transformer Topology

The configuration of the proposed hybrid transformer is shown in Fig. 3. An additional winding placed in series with the secondary winding covers the complete load voltage regulation range. Two series transformers are connected in series with top and bottom branches, respectively. An interline back-to-back power converter connects two series transformers in the middle. The converter regulates the DC bus voltage while the inverter controls the bottom winding voltage V_{bot}, so the load voltage can be regulated and the top winding voltage V_{top} changes accordingly. The current distribution in the top and bottom branches changes accordingly as the top and bottom winding voltage changes. But the total current of the top and bottom branches is the same as the load current.

B. Operation Principle and Equations

The load voltage can be expressed by equation (1) and the nominal load voltage, in equation (2), is acquired when V_{top} and V_{bot} are both half of the additional winding voltage V_{range}. Equation (3) and (4) shows the current and voltage distribution relationships in the top and bottom branches where I_{top} and I_{bot} are top and bottom branch current, respectively. Rectifier power P_{rec} and inverter power P_{inv} can be calculated by equation (5).

For the same source voltage variation between $\pm\Delta V$, the top and bottom branch voltage and current curves are illustrated in Fig. 4. As the regulation voltage changes from $-\Delta V$ to $+\Delta V$, the branch winding voltage and current change at different slopes. However, for the conventional series voltage compensation strategy in Fig. 2, the series transformer winding current is constant as the load current but the series winding voltage varies linearly with the regulation voltage ΔV.

For the conventional series voltage compensation strategy, the maximum converter and inverter active power can be expressed as equation (6). However, in the proposed interline voltage regulation transformer topology, the regulation range at the load side needs to cover $+\Delta V$ and $-\Delta V$. Therefore, the regulation winding turns ratio or the voltage regulation range should be designed to be double of the series regulation range, as described in equation (7). Based on equation (1)-(7), the maximum active power rating of the converter in the interline voltage regulation transformer can be derived as equation (8), which is half of the series voltage regulation solution. The converter and inverter only need to operate at half of the load current and half of the voltage across the regulation winding voltage ΔV. As reflected in the equations, the maximum power in the interline voltage regulation topology is half of which in the conventional series voltage regulation configuration for the same load voltage regulation range.

$$V_{load} = V_{sec} + V_{bot} \tag{1}$$

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

$$I_{top} + I_{bot} = I_{load} \tag{3}$$

$$V_{range} = V_{top} + V_{bot} \tag{4}$$

$$P_{rec} = V_{top} I_{top} = P_{inv} = V_{bot} I_{bot} \tag{5}$$

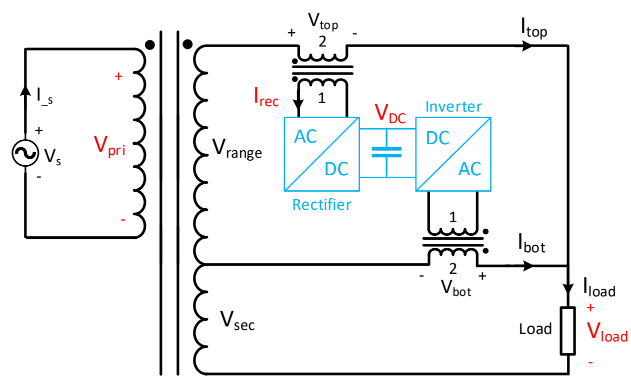

Fig. 3. Proposed hybrid transformer

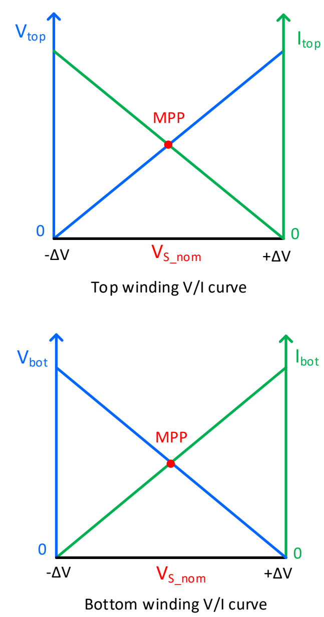

Fig. 4. Top and bottom winding V/I curve (MPP: maximum power point)

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

$$V_{range} = 2 \cdot \Delta V \tag{7}$$

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

III. Comparison Between The Proposed Hybrid Transformer and The Conventional Method

To compare the proposed hybrid transformer and the conventional hybrid transformer based on series voltage compensation, a reference distribution load model is provided in Table I. Both systems target on 10% load voltage regulation range for the 4 kV/20 A nominal loading condition.

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%

Based on the same reference load model, the hybrid transformer parameters of the two solutions are listed in Table II and Table III. For the conventional series regulation solution, the maximum converter power is proportional to the voltage regulation range. In the proposed interline-based hybrid transformer, the nominal branch current is just half of the load current. And the secondary winding and addition voltage regulation winding voltages are specifically designed for the referred distribution load model and the corresponding voltage regulation range. The series transformer turns ratio is 1:2. The converter switching frequency is 10 kHz for both solutions, which helps evaluate the efficiency model comparison in the following section. Based on equation (6)-(8), the maximum converter power of the interline hybrid solution is 4 kW which is half of the conventional series solution.

For the conventional series solution, the rectifier only provides power for the inverter to regulate the load voltage. However, for the proposed interline solution, the rectifier participates in the top branch voltage control as well to change the voltage distribution in the top and bottom branch loop, which contributes to the lower maximum converter power and the higher overall transformer efficiency.

IV. Simulation Results

A. Voltage Regulation Function Validation

The proposed hybrid transformer based on interline power converters is developed in MATLAB Simulink to verify the operation principles. The system parameters are the same as Table I and Table II. In the simulation, the load voltage closed-loop control is implemented. The rectifier and inverter control algorithms are illustrated in Fig. 5 and Fig. 6, respectively. The required analog sensing signals are marked in red correspondingly in Fig. 3. Since the winding voltage phases in the proposed hybrid transformer are the same, the phase lock loop (PLL) voltage can use primary winding voltage, load voltage, or secondary winding voltages. The rectifier is controlled to regulate stable DC bus voltage for the inverter. And the inverter control is implemented to compensate the load voltage deviation to regulate the load voltage to a fixed value of 4 kV.

TABLE II. Proposed Hybird 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 Hybird 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

The simulation results are shown in Fig. 7. From 1s to 2s, the source voltage increases from 3.6 kV to 4 kV, and the load voltage is regulated to 4 kVrms nominal voltage. The top winding voltage increases while its current decreases. On the

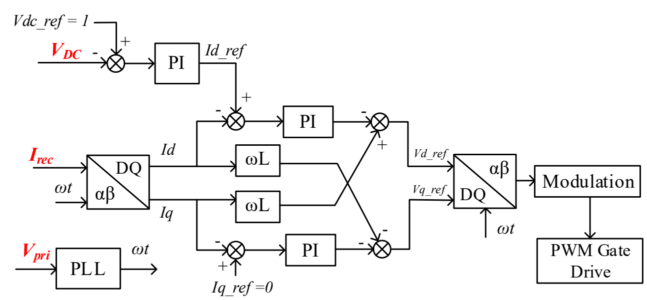

Fig. 5. Rectifier control algorithm

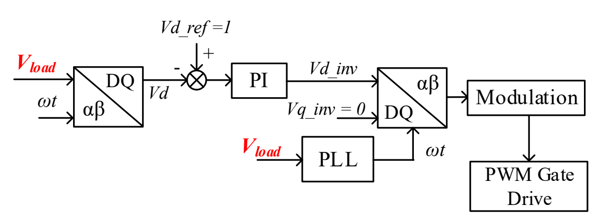

Fig. 6. Inverter control algorithm

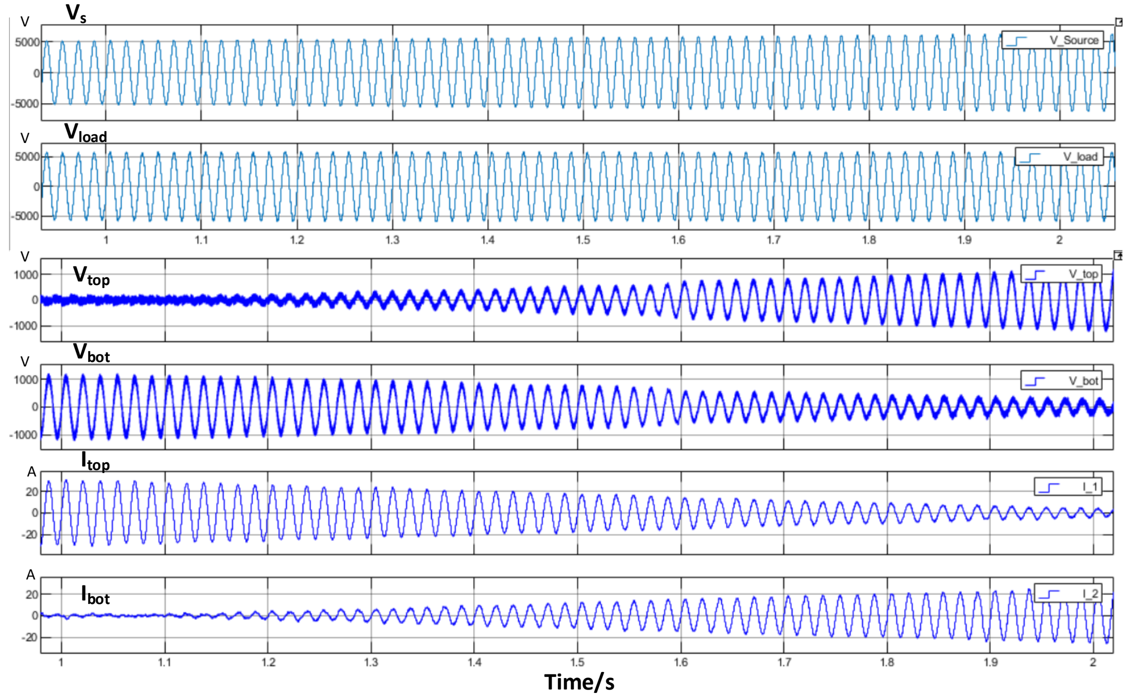

Fig. 7. Voltage regulation waveforms of the proposed hybrid transformer. (From top to bottom: source voltage, load voltage, top winding voltage, bottom winding voltage, top branch current and bottom winding current.)

contrary, the bottom winding voltage and current change in a reverse pattern. With the proposed control algorithms, the top and bottom winding voltage and current change accordingly based on different primary winding voltage deviations. The proposed control method adapts to different current and voltage distributions in the top and bottom windings. And the simulation results match the previous model analysis in Fig. 4. The operation principles and control algorithms are verified by the simulation results.

B. Converter Power Loss and Overall Efficiency Comparison

To further investigate the converter power loss and the overall transformer efficiency, reference simulation models are developed in PLECS. The power loss in the PLECS simulation tool is calculated based on the look-up table of different switching device PLECS models related to the devices' current and voltage. Based on the converter ratings, Infineon IGBT IGW60T120 rated at 1200V and 60A is selected as the switching devices in the rectifier and inverter [11]. The operation temperature is 70 degrees Celsius. The converter's total power loss and the loss breakdown are shown in Fig. 8 based on different source voltages while the load voltage is regulated to 4 kV. It is observed that the rectifier and inverter switching loss and conduction loss are highly related to the current flowing through the converter. Therefore, in the conventional series solution, the inverter power loss remains high through the entire voltage regulation range since the inverter current is constant as the load current while the rectifier power loss increases when the source voltage deviates from the nominal voltage. For the proposed interline solution, the rectifier loss decreases, and the inverter loss increases when the source voltage increases from 3.6 kV to 4.4 kV, which is also related to the top and bottom branch current distribution. The absolute 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, so the voltage regulation transformer overall efficiency of the interline solution is also higher than the series solution as shown in Fig. 9. Meanwhile, the maximum converter power of the interline solution is half of which of the conventional series solution.

To summarize the advantages of the proposed hybrid transformer, 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. Considering the distribution feeder voltage profile that most voltage deviation happens within a narrow range around the nominal voltage, e.g., < 5%, and the primary winding voltage rarely deviates to 10% from the nominal voltage, the proposed hybrid transformer can exhibit a higher overall efficiency in the practical application.

V. PROTOTYPE TEST RESULTS

To verify the operation principle and the top and bottom winding V/I curve analysis, a scaled-down prototype is developed in the lab as shown in Fig. 10. An interface board is designed to communicate between sensing circuits, DSP controller, and the back-to-back power converter. The prototype design specifications are listed in Table IV. And hardware tests are conducted with 72V nominal load voltage and 6A load current. The source voltage steps down from 72V nominal voltage to 60V which is at the regulation limit. As observed from the prototype voltage regulation waveform in Fig. 11, the load voltage remains being regulated at 72V. The top branch current I_{top} increases while the bottom branch

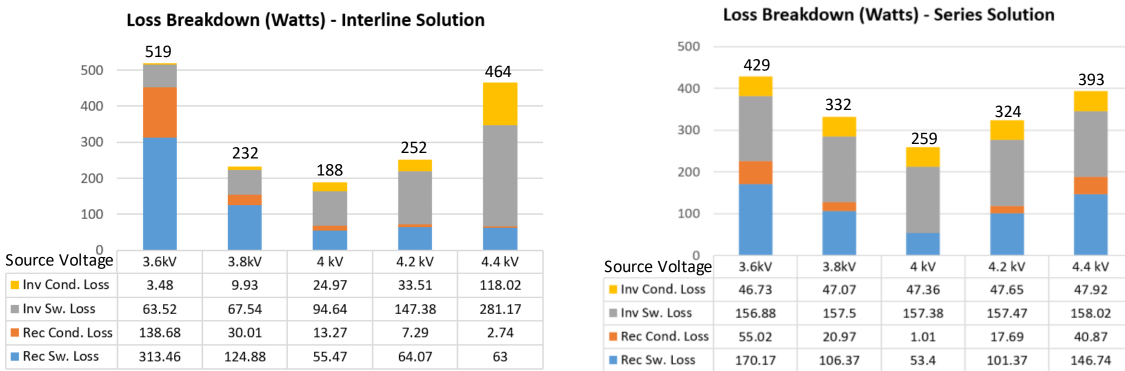

Fig. 8. Converter loss breakdown. (Left: proposed interline solution, right: conventional series solution.)

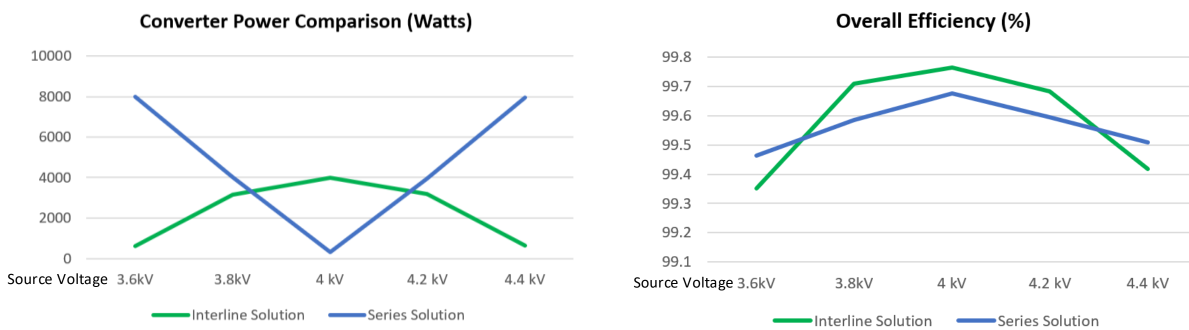

Fig. 9. Left: converter power comparison, right: transformer overall efficiency.

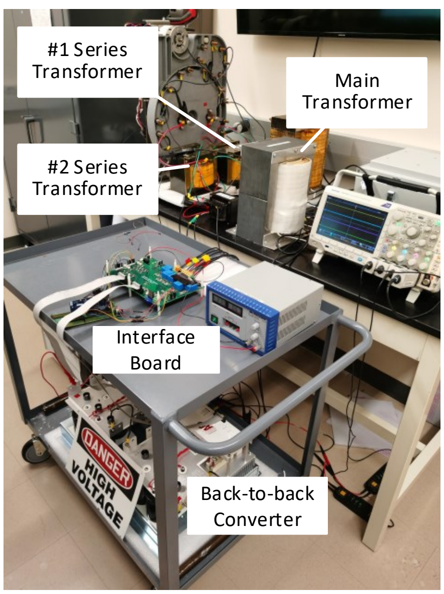

Fig. 10. Hybrid transformer scale-down prototype

current I_{bot} decreases to almost zero. The entire load current flows through the top branch and the power transferred between rectifier and inverter is almost zero. The current distribution in the branch changes accordingly, which matches the simulation results. And the top and bottom winding V/I curves also comply with the previous analysis for different source voltage deviation. In the interline configuration, both rectifier and inverter participate in voltage regulation. The hardware test results validate the operation principle of the proposed voltage regulation hybrid transformer.

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

VI. CONCLUSION

In this paper, a hybrid transformer based on interline power converters is proposed for voltage regulation. The operation principles are analyzed and validated by the simulation 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 control algorithms are validated by

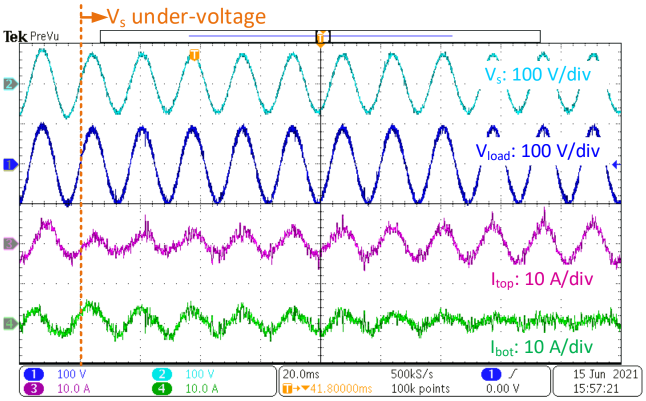

Fig. 11. Prototype voltage regulation test waveform

simulation. Power loss breakdown and efficiency analysis are presented based on the PLECS simulation results. A scale-down prototype is developed, and the operation principle is validated by the hardware test results. 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. 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. For further verification and prototype efficiency comparison, a full-scale medium-voltage prototype is expected to be developed. And the switching device rating can be selected for specific application senario, hence facilitating the efficiency measurement and justification.

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