

Configurable ISOP-IPOP DC-DC Converter for Universal Solid-State Transformer

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Keywords

«Solid-State transformer», «Wide input voltage range», «Dual Active Bridge (DAB)»

Abstract

This paper presents the investigation of configurable DC-DC converter for a Universal Solid-State Transformer with a wide input voltage range. The system design for the combination of the Active Front End (AFE) and the DC-DC converter is analyzed. A DC-DC converter solution with configurable series or parallel input connection is proposed.

Introduction

Universal Solid-State Transformers (USST) are designed to incorporate all typical low voltage (LV) grids. The USST accommodates all the industrial LV grid voltages like 120 V/230 V/277 V/290 V. The system schematic of the USST is shown in Fig. 1. As seen in Fig. 1, the DC-link 1 voltage is variable while the DC-link 2 voltage is set based on the DC grid. For this paper, a DC-link 2 voltage of 800 V is considered. The Active-Front End and the DC-DC converter of the USST are responsible for adjusting the voltage levels between the input AC grid and the output DC grid. Incorporating such a wide input voltage range leads to higher operation losses for certain operating conditions in both the AFE and the DC-DC converter. Different strategies to achieve the wide-gain operation and their pros and cons are explained in Section 1. To tackle wide range operation of the DC-DC converters, the switch is the topological configurations has been previously investigated [1] [2] [3]. In Section 2, this paper introduces a topological solution that uses configurable Input Series Output Parallel (ISOP) and Input Parallel Output Parallel (IPOP) topology for the DC-DC converter. Offline change of the input connection as series or parallel connection for a particular grid connection significantly increases the overall system efficiency without compromising the simplicity of design. A qualitative comparison of this implementation with the conventional implementation is put forward. Finally, the measurement results for a 5 kW DC-DC converter are presented.

Conventional System Implementation

The main objective of the USST is to be able to accommodate all the typical LV grid voltages as input. The conventional two-stage solution to adjust the voltage levels is to simultaneously use the voltage gain

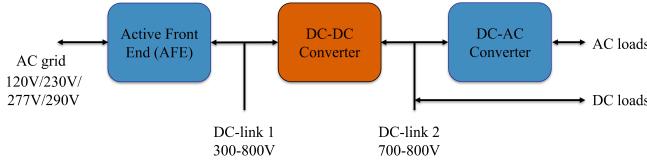


Fig. 1: Universal Solid-State Transformer schematic

Table I: AFE grid input voltage and preferred output voltage levels for low losses

Grid Phase-Neutral RMS Voltage	Preferred DC-link voltage range
120 V	300-350 V
230 V	600-650 V
277 V	700-750 V
290 V	750-800 V

of the AFE (M_{AFE}) and the DC-DC converter ($M_{\text{DC-DC}}$) [4] [5]. The voltage gain of the AFE (M_{AFE}) is the term used in this paper to denote the DC-link voltages due to modulation of the AFE, $M_{\text{AFE}} = V_{\text{DC}1}/(\sqrt{6}V_{\text{AC,rms}})$. This section explains different scenarios of achieving wide-input voltage range by manipulating M_{AFE} and $M_{\text{DC-DC}}$. The variable that separates these scenarios is the DC-link 1 voltage ($V_{\text{DC}1}$). For this project, the DC-link 2 voltage ($V_{\text{DC}2}$) of 800 V is required. Hence, the maximum value of $V_{\text{DC}1}$ voltage is also set to 800 V.

The highest and the lowest input grid voltages will be considered to investigate the system design. The standard North America grid voltage of 120 V at 60 Hz is the lower extreme voltage. The special industrial grid phase voltage of 290 V at 60 Hz is considered the highest input voltage. Other typical grid voltages like 230 V, 50 Hz will not significantly deviate the design of the USST. The adjustment of the voltage levels from input grid to DC link 2 is done by three important parameters: The AFE gain (M_{AFE}), the DC-DC converter gain ($M_{\text{DC-DC}}$) and the transformer ratio (n_r) of the DC-DC converter. The transformer ratio is a fixed hardware parameter while the other two can be varied during operation. By taking into account both the AFE and the DC-DC Converter, to achieve the wide-gain operation for the USST, the following strategies can be used:

- 1. Operate the AFE near unity gain. This leads to a highly efficient operation of the AFE [6]. $V_{\text{DC}1}$ is set close to $\sqrt{6}V_{\text{AC,rms}}$ where $V_{\text{AC,rms}}$ is the rms phase-neutral voltage of the input grid. This leads to $V_{\text{DC}1}$ between 294-710 V for the grid voltage range. Set the transformer ratio such that the DC-DC converter has symmetric buck and boost range. A wide-range operation of the DC-DC converter leads to high losses especially at the ends of the gain range. Additionally, most DC-DC converter topologies lose soft switching which often leads to worse EMI performance. Higher gain range also leads to higher current stress on active and passive components as well as larger magnetic components.
- 2. Operate the AFE with a constant output voltage of 800 V. This leads to an efficient performance for the higher grid voltage of 290 V as suggested in Table I. On the other hand, it leads to very high losses for low grid voltage of 120 V. Also, it leads to a larger volume of the inductors and bulkier filter design. Use $n_r = 1$ to operate the DC-DC converter with unity gain. A compact and efficient design of the DC-DC converter is possible in this region of operation.
- 3. With a variable DC link 1 voltage, optimize the transformer ratio n_r and distribute the losses between the AFE and the DC-DC converter. The range of DC link 1 voltage is set within 450-800 V. The AFE works near unity gain operation for 290 V, while the DC-DC converter needs to operate in step-down mode because of $n_r > 1$. For 120 V input grid voltage, $V_{\text{DC}1}$ is set between 450-600 V. A detailed optimization is required to determine this voltage. The DC-DC converter components have lower peak ratings compared to strategy 1 but losses are high nevertheless. Similar to Strategy 1, deterioration in EMI performance occurs as the converter loses soft switching for buck and boost operation. Although this strategy leads to lower peak losses for the combined system of the AFE and the DC-DC converter compared to strategy 1, it still suffers from high losses for the lowest and the highest input grid voltages.

Table II: Loss trends for the AFE and DC-DC converter for different operational strategies

Input Grid Voltage	120 V		290 V	
	AFE	DC-DC	AFE	DC-DC
Strategy 1	Low	High	Low	High
Strategy 2	Very High	Low	High	Low
Strategy 3	Moderate	Moderate	Low	Moderate
Proposed Strategy	Moderate	Low	Low	Low

Configurable DC-DC Converter

All the above discussed strategies have their pros and cons. Overall, all the strategies suffer from significant losses in certain operating conditions than desired. For the USST application, once the input grid is connected, the voltage range is smaller compared to the design requirements as shown in Table I. The configurable ISOP-IPOP converter takes advantage of this detail. For the lower voltage grid (120 V), the AFE sets V_{DC1} to a fixed voltage of 400 V, while for the other higher voltage grids, V_{DC1} is set to 800 V. V_{DC1} is thus limited to two values, 400 V and 800 V. Fig. 2 shows the topology of the configurable DC-DC converter. The DC-DC converter for the designed USST consists of two individual dual-bridge converter modules which can either be connected in ISOP or IPOP configuration. When the switches S1 and S2 are ON and S3 is OFF, the configuration is IPOP whereas when S1 and S2 are OFF and S3 is ON the configuration is ISOP.

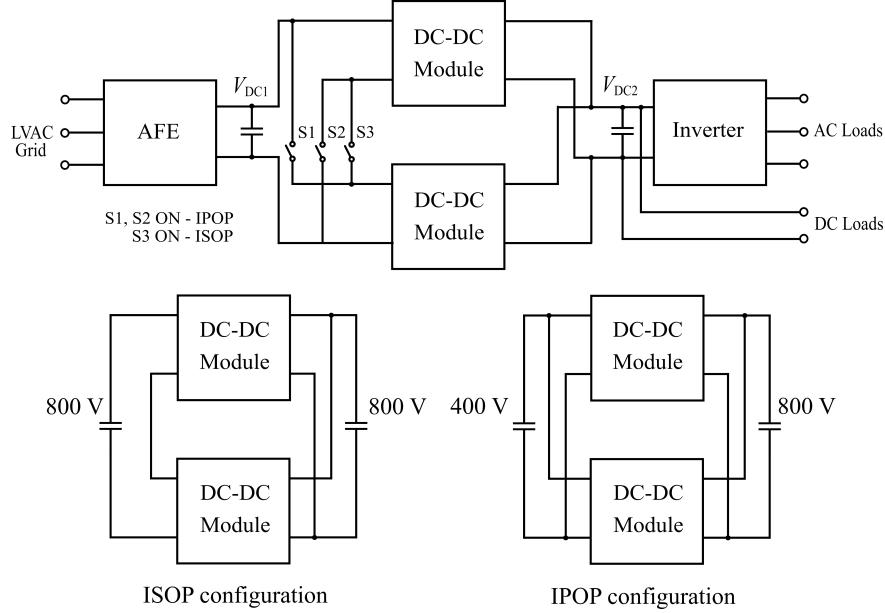


Fig. 2: Configurable ISOP-IPOP DC-DC converter and its two configurations

For low and high input grid voltages, V_{DC1} is set to 400 V and 800 V respectively by the AFE. V_{DC2} is fixed at 800 V and the n_r for the dual-bridge converter is set to 2. The combination of these DC-DC converters is then operated in IPOP and ISOP configurations for V_{DC1} of 400 V and 800 V respectively. Fig. 2 shows that, for both the configurations, each DC-DC converter is operated with fixed voltage ratio operation with input voltage of 400 V and output voltage of 800 V. For most of the DC-DC converter topologies, a fixed voltage ratio operation ensures high efficiency and low stresses on the components. Additionally, the AFE has significantly less losses compared to the conventional solutions discussed before. As an offline switch in configurations is possible, the switches S1, S2 and S3 can be realized using contactors, mechanical relays or even jumpers. Use of contactors or relays is simpler and more efficient compared to the use of bidirectional switches which add to the complexity of the converter. Use of jumpers is the most efficient and cheap solution, but needs human intervention which is often undesirable.

DC-DC Converter Module Topology

The DC-DC converter modules for the USST must exhibit galvanic isolation and bidirectional power transfer capability. For the ISOP/IPOP configuration, the DC-DC converter operates at unity gain. There are many DC-DC converter topologies relevant for this application. The Dual Active bridge (DAB) converter first introduced in [7] is one of the most popular topologies for SSTs. It features Zero Voltage Switching (ZVS) for both the full-bridges at fixed voltage ratio operation. It is also capable of buck and boost operation in both directions of power flow. Another popular topology is the Series Resonant Converter (SRC). SRC is one of most efficient converters for fixed voltage ratio operation especially when operated in sub-resonant or HC-DCM mode [8]. LLC converter is another often considered topology for soft switching and buck-boost capability. Also, it only works in buck mode in reverse direction when the resonant tank is placed on one side of the transformer. This loses a degree of freedom during non-ideal voltage conditions. The Series Resonant Dual-Active Bridge (SRC-DAB) is a resonant version of the DAB converter. It ensures ZVS on the primary bridge and ZCS with partial ZVS on the secondary bridge for unity gain operation [9]. The resonant topologies have added costs and volume because of the resonant capacitors. Additionally, the resonant topologies have a slower transition speed for bidirectional power. [10]. Overall, it is a practical choice dependent on the application, especially the voltage and power levels required for the USST. Although the resonant converters provide excellent efficiency, for high power applications, the costs far outweigh the benefits compared to the non-resonant DAB. Hence, for this project the DAB converter is considered.

Qualitative Comparison of Configurable DC-DC Converter with Single Wide-Input Voltage DC-DC Converter

There are multiple advantages to using the configurable DC-DC converter compared to a single wide-input voltage DC-DC converter. Due to the fixed voltage ratio operation of each module, the semiconductor losses are significantly lower due to lower peak currents and ubiquitous soft switching. Total losses in the semiconductors are usually limited by the cooling effort. Higher $R_{DS(on)}$ often co-relates to lower switching energy of the MOSFET. Soft-switching provides additional freedom to choose SiC MOSFETs with higher $R_{DS(on)}$ which further reduces the costs. As the DAB undergoes hard turn-off, lower switching energies would lead to lower losses. Due to the low switching losses, an increase in the switching frequency is possible. A larger switching frequency leads to smaller transformer volume as well as low current ripple on the DC-link. As shown in [11] use of DC-link capacitor for each module is better than for the complete DC-link irrespective of the configuration. Lower current ripple, lower voltage rating reduces the capacitor volume and cost. Additionally, the primary side of the DAB uses low voltage devices for half the power rating of the full converter. Lower voltage class switches are often cheaper. Lower peak currents also lead to lower conduction losses in the transformer. Soft switching for the whole power range leads to a much superior EMI performance too.

On the other hand, the number of semiconductor devices is doubled for this converter. Even though the transformer is small, the overall volume of two transformers is still higher than that of a single wide-input DC-DC converter. Although, the modules operate with fixed voltage ratio, additional control effort

Table III: Hardware prototype components

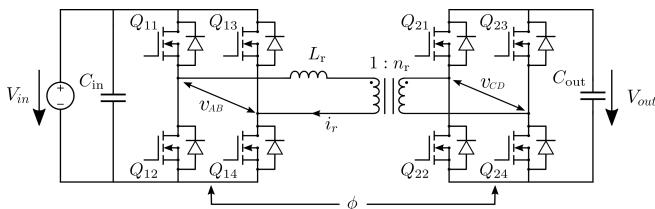


Fig. 3: Dual Active Bridge topology

Component	Type
MOSFETs	Infineon IMZA65R027M1H (Prim) Infineon IMZ120R030M1H (Sec)
Transformer	E55/28/21 (2 sets), turns ratio 7:14 $L_\sigma = 12.4 \mu\text{H}$, $L_m = 400 \mu\text{H}$
Litz Wire	1400 x 0.05 mm (Prim) 200 x 0.1 mm (Sec)
Controller	Texas Instruments F28379D
Power Analyzer	Yokogawa WT1800

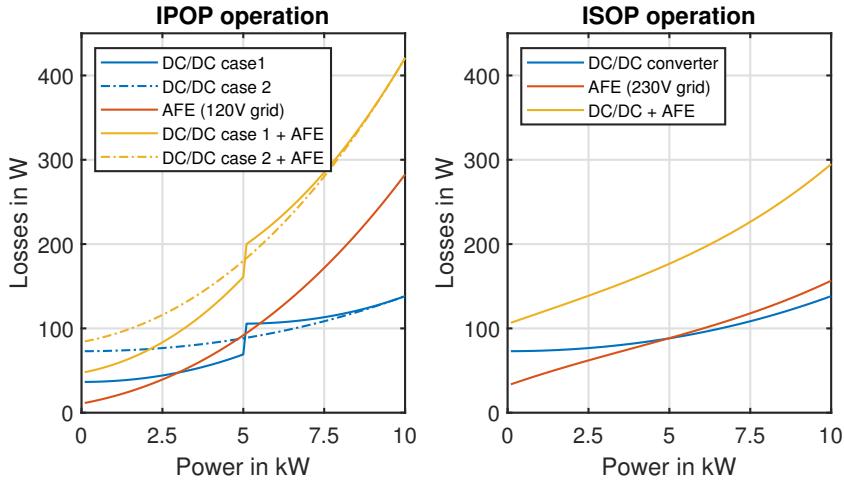


Fig. 4: Calculated losses for DC-DC converter and AFE for IPOP and ISOP configurations

is required to achieve power and voltage balance for the modules. However, a fixed input DC-link voltage reduces the complexity of control.

Design of Dual-Active Bridge Module

To analyze the performance of the configurable ISOP-IPOP converter, a fixed voltage ratio DAB module is designed. For a 10 kW SST, each DAB module is rated for 5 kW with input voltage of 400 V and output voltage 800 V. The primary bridge consists of 650 V SiC switches while the secondary consists of 1200 V SiC switches. For a fixed voltage ratio operation, all the switches undergo ZVS for the entire power range. The conduction losses and the turn-off losses are mainly influenced by the peak transformer current. A small leakage inductance is thus preferred as it results in lower peak currents and eventually lower semiconductor losses. Additionally, to reduce the volume of the converter only the leakage inductance of the transformer is used.

The modules are assumed to be identical and all parasitic components are neglected. The DAB modules are operated with a fixed frequency of 100 kHz using single phase shift (SPS) modulation. The power equation of the DAB converter for the SPS modulation is given by Eq. 1.

$$P_{12} = \frac{nV_1V_2\phi(\pi - |\phi|)}{2\pi^2 f_s L} \quad \text{where } \phi \text{ is the phase difference between } V_{AB} \text{ and } V_{CD} \quad (1)$$

In the IPOP configuration the individual DAB modules have the same operating conditions as the ISOP configuration if they equally share the power. Fig. 4 shows the calculated losses for the DAB modules for ISOP and IPOP configurations. In IPOP operation, case 1 implies that the second module is switched ON after 5 kW and case 2 implies equally power distribution for complete power range. In case of ISOP configuration, there is no added advantage to operate the two modules with different output power. On the other hand, it can be seen from Fig. 4 that for the IPOP configuration, use of a single module for partial load conditions significantly reduces the losses. The least loss operation involves use of a single module up to 5 kW and then equal power sharing after that.

Performance of the Combined DC-DC Converter and AFE System

To analyze the performance of the AFE, two different grid voltages of 120 V and 230 V are considered. Fig. 4 shows the loss plots for the AFE. The AFE has higher losses with the 120 V grid operation. This is primarily due to high currents which lead to higher conduction losses for the semiconductors. On the other hand, the benefits of lower grid voltage are seen for lower power values. As discussed in the previous sections, the losses from the DC-DC converter are nearly the same for both the configurations. The combined losses plots for the DC-DC converter and the AFE are also shown in Fig. 4. The IPOP configuration has the higher peak losses compared to ISOP. The difference in peak losses is not extreme

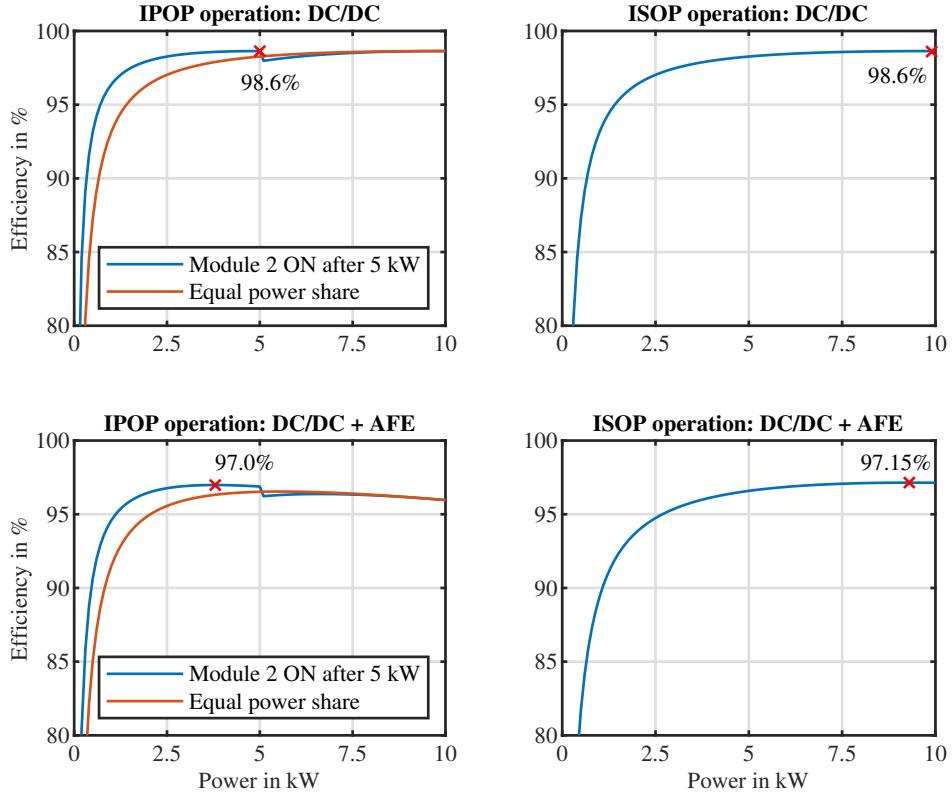


Fig. 5: Calculated efficiency plots and maximum efficiency for 10 kW DC-DC converter and combination of DC-DC converter and AFE for ISOP and IPOP configurations

as would have been the case for other SST strategies. Fig. 5 shows the efficiency of the DC-DC converter and the combined efficiency of the AFE and DC-DC Converter system. For both the grid voltages of 120 V and 230 V, the system has a peak efficiency of greater than 97 %. The higher grid voltages like 277 V and 290 V which were not considered for calculations actually lead to better efficiencies as the AFE would have a smaller boost gain to reach V_{DC1} of 800 V. In summary, for all the possible grid voltages, the AFE + DC-DC converter system has an excellent efficiency performance.

Measurement Results

Fig. 6 shows the 5 kW DAB module prototype with rated input voltage of 400 V and output voltage of 800 V. The hardware specifications of the prototype are mentioned in Table III. It consists of a single power PCB with both the full bridges of the DAB. The PWM signals and the SPS modulation are facilitated by the Texas Instruments F28379D Launchpad. The measurement waveforms at rated voltage and power are shown in Fig. 7. This prototype reached a peak efficiency of 97.95 % near full load which is very close to the calculated efficiency. More tests need to be conducted to validate the efficiency for the ISOP/IPOP configurations.

Conclusion

In this paper, different strategies to realize the USST were analyzed. A configurable DC-DC Converter is proposed as a solution for efficient operation of the USST. In contrast to a wide-input voltage DC-DC converter, a converter with two unique input voltages enables achieving high efficiency. A qualitative comparison of the configurable converter and a conventional wide-input voltage converter is presented. The performance of the AFE and DC-DC converter system is analyzed. A 5 kW DAB prototype with voltage ratio of 1:2 is built and tested for rated voltage and power to prove the high efficiency of the DC-DC converter.

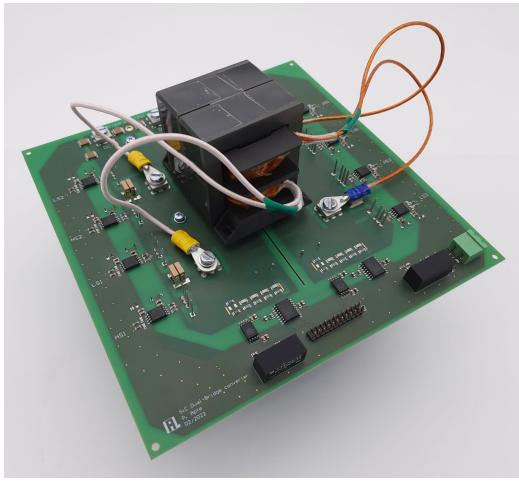


Fig. 6: 5 kW DAB module prototype

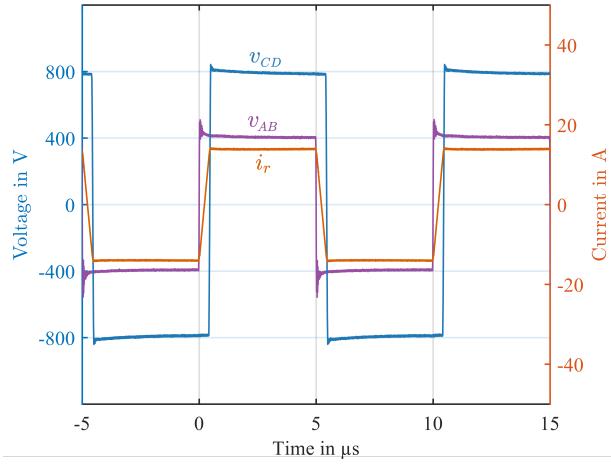


Fig. 7: Measurement waveforms for the DAB prototype with SPS modulation at $V_{in} = 400\text{ V}$, $V_{out} = 798\text{ V}$ and $P_{out} = 4985\text{ W}$

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