

BAYERO JOURNAL OF ENGINEERING AND TECHNOLOGY (BJET) VOL.17 No.2, MAY, 2022 PP10-17
**SIMULATION AND CONTROL OF DUAL ACTIVE BRIDGE CONVERTER FOR SOLID
 STATE TRANSFORMER APPLICATION**

Nasiru B. Kadandani

Department of Electrical Engineering, Bayero University, PMB 3011, Kano, Nigeria
 Email: nbkadandani.ele@buk.edu.ng

ABSTRACT

Dual active bridge (DAB) converter is a symmetrical converter with identical primary and secondary bridges, capable of providing bidirectional power flow control. It has many advantages, such as electrical isolation, high reliability, ease of realizing soft-switching control and, moreover, having complete symmetry of configuration that allows seamless control for bidirectional power flow, - thus, supporting its candidature for use in the isolation DC-DC conversion stage of solid state transformer (SST). However, the main issue with the cascaded modular DAB converter is the power unbalance across the H-bridges. This occur due to the parameter mismatch, especially the leakage inductance of the transformer, the power may be unequal for each DC-DC converter, and therefore the current stress of them will not be the same. This paper presents a detail analysis, control strategy and simulation of cascaded three module DAB converter for use as DC-DC conversion stage of SST with a dedicated voltage and power balance controller meant to ensure smooth power transfer between the primary and secondary DAB converters, regulation of the low voltage DC (LVDC) link voltages to their reference values and to resolve any parameter variations in the high frequency transformer like leakage inductance. The entire system including the proposed control strategy was simulated in MATLAB[®] using Simulink[®] and other power system toolboxes. The effectiveness of the proposed control method was demonstrated on a three module DAB converter whose transformer leakage inductances were set to different values. The results show that the controller was able to balance both the LVDC link voltage and the power in each DAB.

Keywords: Dual active bridge converter (DAB), solid state transformer (SST), DC-DC converter, power balance controller, phase shift.

1. INTRODUCTION

Solid state transformer (SST) uses power electronics devices and a high frequency transformer to achieve voltage conversion, isolation and other functions. In order to design SST, several architectures can be used. However, this research proposes a feasible architecture of three-stage configuration consisting of AC-DC converter, DC-DC converter and DC-AC converter. The configuration has a DC link on both primary and secondary side and it is highly flexible.

The AC-DC conversion stage of SST converts the AC voltage to DC link voltage and at the same time controls the reactive power at the input side. Possible candidate converters for the AC-DC conversion stage include cascaded H-bridge converter as demonstrated in (Kadandani et al, 2020) and modular multilevel converter (Kadandani, Dahidah, & Ethni, 2021). However, the AC-DC converter may experience voltage unbalance on its DC links due to the device loss mismatching. In fact, this can be worst when the SST operates at no load or light load condition. Hence, a
 Also available on line at <https://www.bayerojet.com>

voltage balance controller is required to resolve the voltage unbalance on the DC links by adjusting the modulating signals (Kadandani et al, 2019).

The DC-DC conversion stage of SST consists of three units (Parreiras et al., 2018), namely; DC-AC converter at the input, high frequency transformer in the middle, and an AC-DC converter at the output. Typically, a dual active bridge (DAB) converter is considered as the most promising converter for the isolation DC-DC conversion stage of SST (Yadeo, Chaturvedi, & Saketi, 2018). However, the main issue with the cascaded modular DAB converter is the power unbalance across the H-bridges. This occur due to the parameter mismatch, especially the leakage inductance of the transformer, the power may be unequal for each DC-DC converter, and therefore the current stress of them will not be the same. As such, when used in the DC-DC conversion stage of SST, a power balance controller is required for the DAB converter to resolve the parameter vari-

ation of the high frequency transformer like leakage inductance and turns ratio(Zhao et al., 2010).

The DC-AC conversion stage of SST will convert DC output of the DAB converter to AC voltage (three-phase line-to-line and line-to-neutral) and will be connected to the grid network. One possible candidate converter for the DC-AC conversion is three phase four leg (3P4L) converter because it can handle unbalanced load, although its control is complex(Tan et al, 2019). However, a dedicated controller is required to ensure that the DC-AC converter regulates

the output AC voltage of the SST to pure sinusoidal one as implemented in (Long et al, 2021).

This paper presents a detail analysis, control strategy and simulation of cascaded three-module DAB converter for use as DC-DC conversion stage of SST.

The remaining parts of this article is organised as follows. Section 2 presents basic theory and analysis of DAB converter. Section 3 presents the power balance control strategy of DAB converter in a typical three stage SST. In section 4, simulation results are presented. Lastly, conclusion is drawn in section 5.

2. AN OVERVIEW OF DUAL ACTIVE BRIDGE CONVERTER

2.1. An Overview of Dual Active Bridge Converter

Figure 1 shows a schematic of a typical DAB converter with high frequency transformer, energy transfer inductor, and dc-link capacitors. The converter can be more simply described as a more common full-bridge with a controllable rectifier. Due to the symmetry of this converter, with identical primary and secondary bridges, it is capable of bidirectional power flow control. It has many advantages, such as electrical isolation, high reliability, ease of realizing soft-switching control and, moreover, having complete symmetry of configuration that allows seamless control for bidirectional power flow(Shah & Bhattacharya, 2019), - a qualification supporting its candidature for isolation DC-DC conversion stage of SST. Some of these attributes are due to a high frequency AC conversion stage (Mueller & Kimball, 2018).

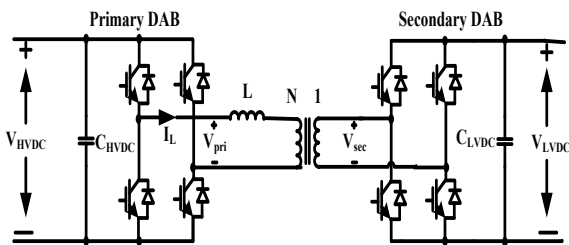


Figure 1:A typical dual active bridge converter

2.2. Analysis of DAB Converter as DC-DC Converter in SST

Figure 2 shows the block diagram of DAB converter as the DC-DC conversion stage of a typical three stage SST. A DAB converter with high frequency transformer is selected for the isolation DC-DC conversion stage of the SST in order to step down the output DC voltage of the rectifier input. As Also available on line at <https://www.bayerojet.com>

can be seen in figure 2, a DAB is chosen for the isolation DC-DC conversion stage of the SST because it is a bidirectional, controllable, and has high power capabilities.

Figure 3 shows the theoretical voltage and current waveform of the DAB converter (Chen et al., 2020).

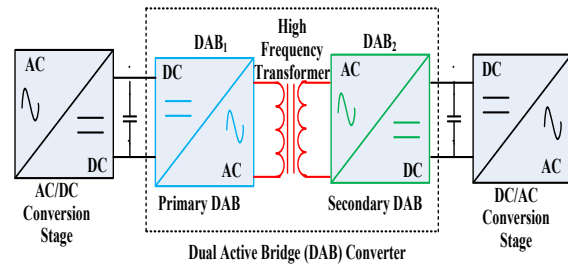


Figure 2:Block diagram of SST highlighting DAB converter as DC-DC conversion stage

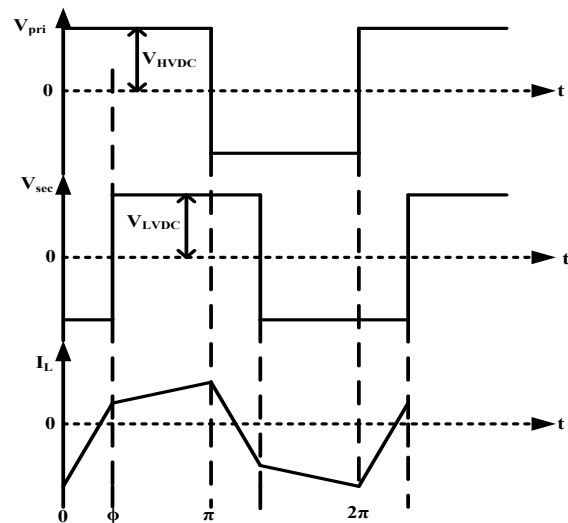


Figure 3:Voltage and current waveform of conceptual transformer of DAB converter

$$P_{DAB1} = \frac{n_{Tr} v_{DAB1} v_{DAB2}}{2f_{DAB} L_{DAB}} d_{DAB} (1 - d_{DAB}) \quad (3)$$

The input and output power of the DAB converter are equal provided the DAB is lossless.

$$P_{DAB1} = P_{DAB2} \quad (1)$$

$$v_{DAB1} i_{DAB1} = v_{DAB2} i_{DAB2} \quad (2)$$

Where;

P_{DAB1} = Power of the primary DAB

P_{DAB2} = Power of the secondary DAB

v_{DAB1} = High DC link voltage of the DAB

v_{DAB2} = Low DC link voltage of the DAB

i_{DAB1} = Input current of the DAB

i_{DAB2} = Output current of the DAB

The power supplied to the DAB is given by equation 3 (Shi et al, 2011) and (Liu et al, 2018).

Where;

n_{Tr} is the transformer turns ratio,

d_{DAB} is the duty cycle of the DAB converter,

f_{DAB} is the switching frequency of the DAB converter

From equations (1) to (3), the input and output currents of the DAB converter can be expressed as:

$$i_{DAB1} = \frac{n_{Tr} v_{DAB2}}{2f_{DAB} L_{DAB}} d_{DAB} (1 - d_{DAB}) \quad (4)$$

$$i_{DAB2} = \frac{n_{Tr} v_{DAB1}}{2f_{DAB} L_{DAB}} d_{DAB} (1 - d_{DAB}) \quad (5)$$

3. CONTROL STRATEGY OF DAB CONVERTER IN SST APPLICATION

Figure 4 shows a three-module DAB converter used as DC-DC conversion stage in building a modular SST. However, the main issue with the cascaded modular DAB converters used in SST application is the power unbalance across the H-bridges. This occurs due to the parameter mismatch, especially the leakage inductance of the transformer, the power may be unequal for each DC-DC converter, and therefore the current stress of them will not be the same if only the voltage balance controller is adopted for the rectifier (AC-DC) stage. As such, for proper operation of the SST, a power balance controller is necessary for the isolation DC-DC conversion stage, in addition to the voltage balance controller for the input AC-DC rectifier stage. The two controllers working together will ensure the best voltage balance performance in both dynamic and steady state operation.

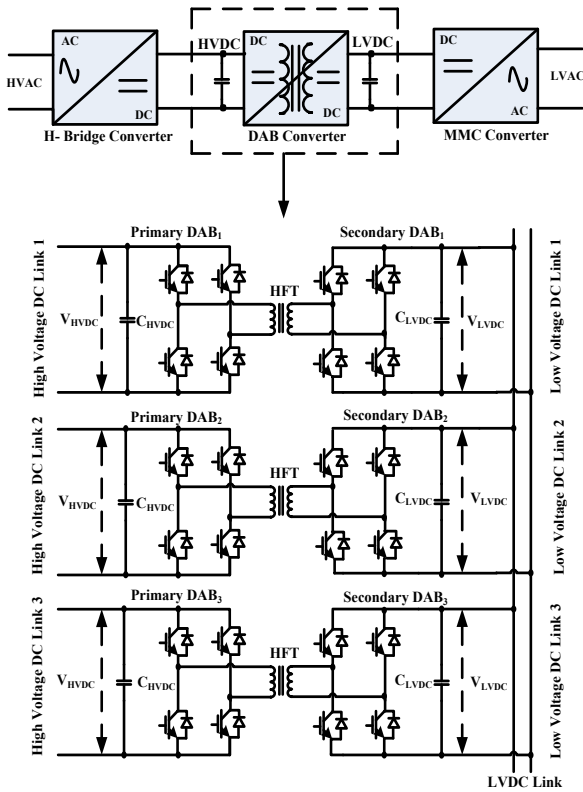


Figure 4:Block diagram of 3-module DAB converter used in building modular SST

3.1. Power Balance Controller for DAB Converter

Figure 5 shows the block diagram of SST with control strategy. The SST comprises of three power converters, namely AC-DC converter for absorbing active power from the high voltage grid, DC-DC converter (DAB converter in this case) for providing galvanic isolation between the high voltage side and the low voltage side and DC-AC converter which is located on the low voltage side. The control aspect consist of a voltage balance controller for the AC-DC converter and a power balance controller for the DC-DC converter. The voltage balancing controller is meant to regulate the high voltage DC link and also to control the power factor of the AC-DC converter. The power balance controller is specifically meant for the DAB converter in order to regulate the low voltage DC link and also to control the flow of power between the primary and secondary DAB converter.

The power transferred by the DAB converter, P is defined in

Also available on line at <https://www.bayerojet.com>

terms of the phase-shift angle, ϕ between the primary side H-bridge and the secondary side H-bridges as(She, Huang, & Ni, 2014) and(Cupelli et al., 2019):

$$P_{DAB1} = P_{DAB2} = \frac{V_{DAB1}V_{DAB2}}{2\pi f_{DAB}n_{Tr}L_{DAB}}\phi\left(1 - \frac{\phi}{\pi}\right) \quad (6)$$

It can be seen from equation 6 that if the same phase shift is adopted for all DAB converters, the mismatch of the parameters, such as transformer leakage inductance, will cause the unbalanced power sharing among them. Therefore, different phase shift may be needed for the each DAB converter as shown in figure 5.

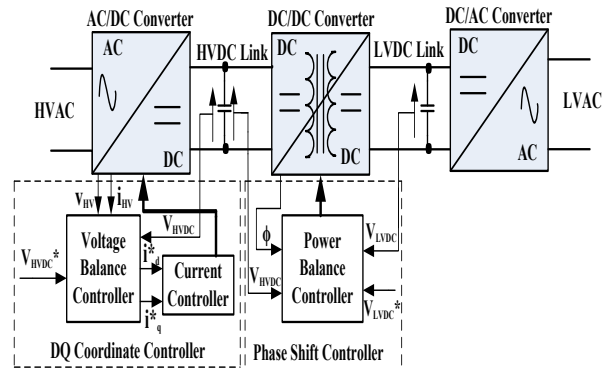


Figure 5:Block diagram of SST control strategy showing power balance controller of DAB converter

The main system controller generates the common phase shift ϕ for regulating the low voltage DC bus. When there is parameter mismatch (such as variation in the transformer leakage inductance), the additional current balance controller will come into action so as to generate a modified phase shift for each DAB converter in order to balance any current stress that may arise. The active power of each H-bridge rectifier input is calculated as (She et al., 2014):

$$P_i = I_s d_{di} V_{dci} \quad (i = 1 \dots n) \quad (7)$$

3.2. Overall Controller for DAB Converter

The proposed current power balance controller for the parallel operated DAB converters is shown in figure 6.

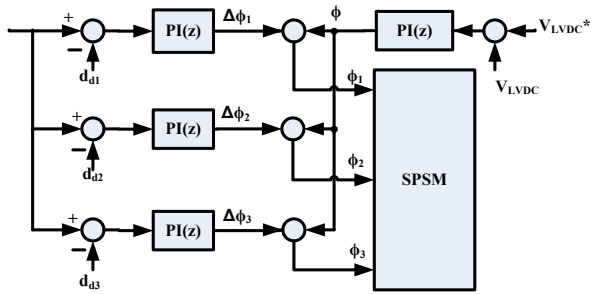


Figure 6:Block diagram of power balance controller for DAB converter

A common phase shift, ϕ is generated by the DC voltage regulation loop. The active power component of duty cycle

for each H-bridge cell in the rectifier stage is adopted as the feedback signal for the power balance controller, the reference of which is set to the average value of them. By using this power balance controller, the modification of the phase shift for each DAB converter is generated, which is denoted as $\Delta\phi_1, \Delta\phi_2, \dots, \Delta\phi_N$. These modifications are added to the common phase shift to compose the individual phase shift for each DAB converter. In this passion, the active component of the duty cycles d_{di} ($i=1 \dots N$) will be identical, and the power flows through the DAB converters will be the same.

4. SIMULATION RESULTS AND DISCUSSION

In order to verify the effectiveness of the power balance controller, a cascaded three module DAB converter was simulated in MATLAB[®] using Simulink[®] based on system parameters of Table 1. The results obtained are presented in Figure 7 through 12.

As can be seen in figure 7, the LVDC link voltages of the three module DAB converter were unable to follow the reference value because the controller was disabled and different leakage inductance values were used for the transformers of the DAB modules. The variation in the leakage inductance of the DAB modules further result in variation in the current stress in both primary and secondary DABs. This can be seen in figure 8 (for the primary DAB) and figure 9 (for the secondary DAB). The implication of the current stress variation is power unbalance across the three DAB modules.

Table 1: System parameters for simulation

HVDC capacitor reference	1.4mF for each DAB module
HVDC voltage reference	400V for each DAB module
Transformer magnetizing inductance	28mH for each DAB module
Transformer leakage inductance	23.9mH for each DAB ₁ 24.9mH for each DAB ₂ 25.9mH for each DAB ₃
Switching frequency	3kHz for each DAB module

4.1. Simulation Results without the Power Balance Controller

The system was first simulated without the power balance controller. Figures 7, 8 and 9 show the DC link voltage on the low voltage, primary DAB currents and secondary DAB currents respectively.

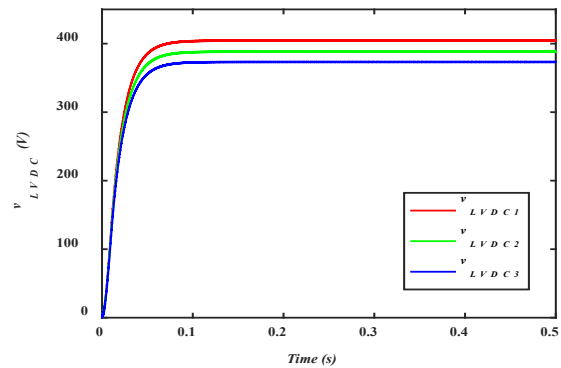


Figure 7:DAB LVDC link voltages without the power balance controller

of the power balance controller.

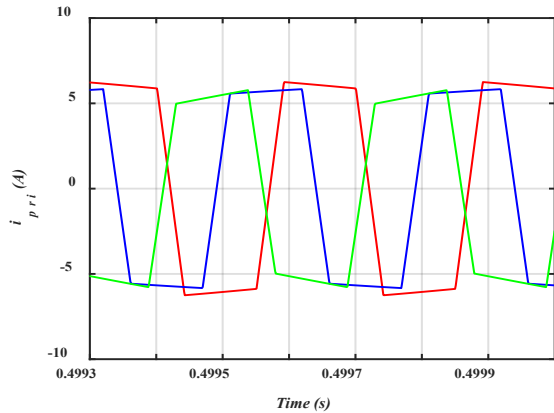


Figure 8:DAB primary current without the power balance controller

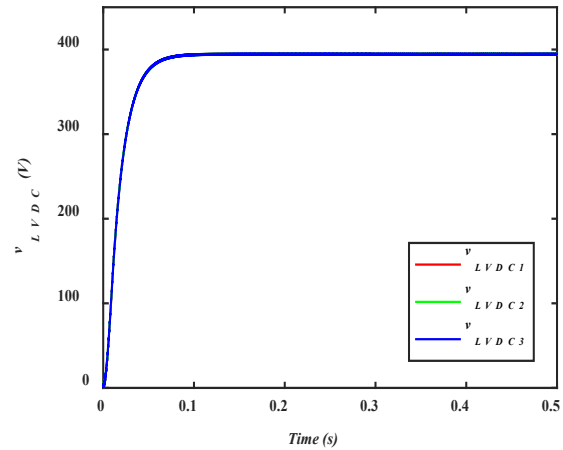


Figure 10:DAB LVDC link voltages when the power bal-

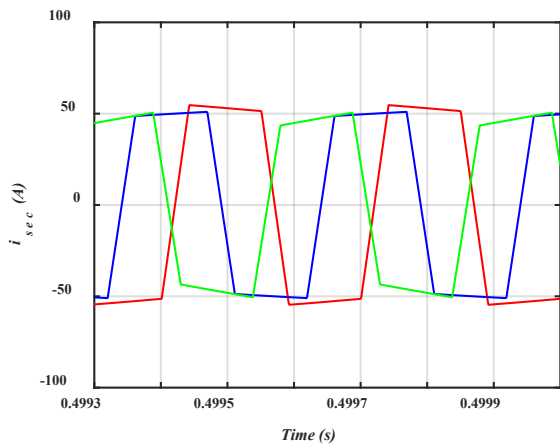


Figure 9:DAB secondary current without the power balance controller

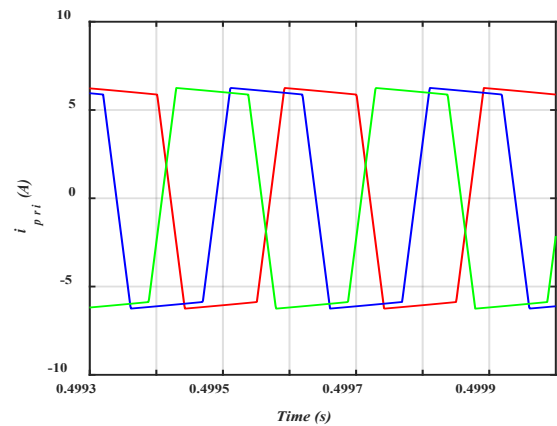


Figure 11:DAB primary current when the power balance controller was enabled

4.2. Simulation Results with the Power Balance Controller Enabled

Figure 10 shows the LVDC link voltage when the controller was enabled. It can be seen that the power balance controller was able to regulate the LVDC link voltages of the three modules DAB to their reference value. Figures 11 and 12 show the DAB currents at primary and secondary sides respectively. In both figures, the peak values of the current remained the same, thus, confirming equal current stress which is required for guaranteeing balanced power transfer through each DAB module. This confirms the effectiveness

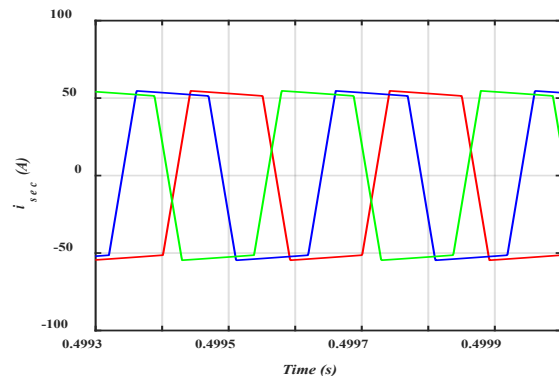


Figure 12:DAB secondary current when the power balance controller was enabled

5. CONCLUSION

The paper presented a detail analysis, control strategy and simulation of cascaded three module dual active bridge converter for use as DC-DC conversion stage of solid state transformer. The analysis reveals that the power transferred by the DAB converter, P is determined by the phase-shift angle, ϕ between the primary side H-bridge and the secondary side H-bridge converters. In the control strategy, a power balance controller is proposed for the DAB converter in order to regulate the low voltage DC link and also

to control the flow of real power through the DAB parallel modules and between the primary and secondary DAB converters. The controller works in such a way that when there is parameter mismatch (such as variation in the transformer leakage inductance), the current balance controller will come into action so as to generate a modified phase shift for each DAB converter in order to achieve the current balance among them.

REFERENCES

- Chen, L., Shao, S., Xiao, Q., Tarisciotti, L., Wheeler, P. W., & Dragicevic, T. (2020). Model Predictive Control for Dual-Active-Bridge Converters Supplying Pulsed Power Loads in Naval DC Micro-Grids. *IEEE Transactions on Power Electronics, Vol. 35, No. 2*, pp. 1957 - 1966.
- Cupelli, M., Gurumurthy, S. K., Bhandari, S. K., Yang, Z., Joebges, P., Monti, A., & Doncker, R. W. D. (2019). Port Controlled Hamiltonian Modelling and IDA-PBC Control of Dual Active Bridge Converters for DC Microgrids. *IEEE Transactions on Industrial Electronics, Vol. 66, No. 11*, pp. 9065 - 9075.
- Kadandani, N. B., Dahidah, M., & Ethni, S. (2021). Design and Development of Modular Multilevel Converter for Solid State Transformer Application. *Bayero Journal of Engineering and Technology (BJET), Vol. 16, No. 1*, pp. 31-41.
- Kadandani, N. B., Dahidah, M., Ethni, S., & Alharbi, M. A. (2020). Overloading Scenario in Solid State Transformer. *Proceedings of 2020 IEEE 11th International Renewable Energy Congress (IREC), Hammamet, Tunisia*, pp. 1-6.
- Kadandani, N. B., Ethni, S., Dahidah, M., & Khalfalla, H. (2019). Modelling, Design and Control of Cascaded H-Bridge Single Phase Rectifier. *Proceedings of 2019 10th International Renewable Energy Congress (IREC), Sousse, Tunisia*, pp. 1-6.
- Liu, J., Yang, J., Zhang, J., Nan, Z., & Zheng, Q. (2018). Voltage Balance Control Based on Dual Active Bridge DC/DC Converters in a Power Electronic Traction Transformer. *IEEE Transactions on Power Electronics, Vol. 33, No. 2*, pp. 1696 - 1714.
- Long, B., Cao, T., Fang, W., Chong, K. T., & Guerrero, J. M. (2021). Model Predictive Control of a Three-Phase Two-Level Four-Leg Grid-Connected Converter Based on Sphere Decoding Method. *IEEE Transactions on Power Electronics, Vol. 36, No. 2*, pp. 2283 - 2297.
- Mueller, J. A., & Kimball, J. W. (2018). An Improved Generalized Average Model of DC-DC Dual Active Bridge Converters. *IEEE Transactions on Power Electronics, Vol. 33, No. 11*, pp. 9975 - 9988.
- Parreiras, T. M., Machado, A. P., Amaral, F. V., Lobato, G. C., Brito, J. A. S., & Filho, B. C. (2018). Forward Dual-Active-Bridge Solid-State Transformer for a SiC-Based Cascaded Multilevel Converter Cell in

- Solar Applications. *IEEE Transactions on Industry Applications*, Vol. 54, No. 6, pp. 6353 - 6363.
- Shah, S. S., & Bhattacharya, S. (2019). A Simple Unified Model for Generic Operation of Dual Active Bridge Converter. *IEEE Transactions on Industrial Electronics*, Vol. 66, No. 5, pp. 3486 - 3495.
- She, X., Huang, A. Q., & Ni, X. (2014). Current Sensorless Power Balance Strategy for DC/DC Converters in a Cascaded Multilevel Converter Based Solid State Transformer. *IEEE Transactions on Power Electronics*, Vol. 29, No. 1, pp. 17 - 22.
- Shi, J., Gou, W., Yuan, H., Zhao, T., & Huang, A. Q. (2011). Research on Voltage and Power Balance Control for Cascaded Modular Solid-State Transformer. *IEEE Transactions on Power Electronics*, Vol. 26, No. 4, pp. 1154 - 1166.
- Tan, C., Chen, Q., Zhao, K., & Zhang, L. (2019). A Simple High-Performance Current Control Strategy for V2G Three-Phase Four-Leg Inverter With LCL Filter. *IEEE Transactions on Transportation Electrification*, Vol. 5, No. 3, pp. 695 - 701.
- Yadeo, D., Chaturvedi, P., & Saketi, S. K. (2018). *A New Five Level Dual Active Bridge DC-DC Converter for Solid State Transformer*. Paper presented at the 2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES).
- Zhao, T., Wang, G., Zeng, J., Dutta, S., Bhattacharya, S., & Huang, A. Q. (2010). Voltage and power balance control for a cascaded multilevel solid state transformer. *Proceedings of 2010 Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 761-767.