DEVELOPMENT AND EXPERIMENTAL SIMULATION OF LABORATORY-SCALE SOLID STATE TRANSFORMER

Electrical Engineering and Computer Science
Power System Engineering

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1. Introduction

In recent years, dispersed power energy system which include Distributed Energy Resources (DERs) and Demand-Side Response (DSR) has been the new focus in power system area. In order to realize this system, a bi-directional power electronics converter that is able to interface between two different AC networks becomes essential. Recent trend shows that three-stage Solid-State-Transformer (SST) which has the ability to perform this function has been the new focus in this research topic. Thus, in order to have more understanding of the SST converter design and converter control system, the development of laboratory scale of three-stage SST becomes necessary.

2. Research Objective

The objective of this research is to design and develop a laboratory-scale of three-stage SST, where the ability of the converter to interface and enable the bi-directional power flow between two different AC networks is proved through several simulations and experimental tests. This research is focusing on the converter design and control system of the three-stage SST.

3. Solid State Transformer Configurations

Figure 1 shows the configuration of three-stage SST. Three-stage SST is formed by the combination of three converters which are active rectifier, dual-active-bridge (DAB) converter, and grid-connected inverter. In SST, three stages of voltage conversions are involved. Active rectifier will transform MV AC voltage to MV DC voltage. While DAB will transform MV DC voltage to LV DC voltage. And grid connected inverter will transform LV DC voltage back to LV AC voltage to be used by the consumer.

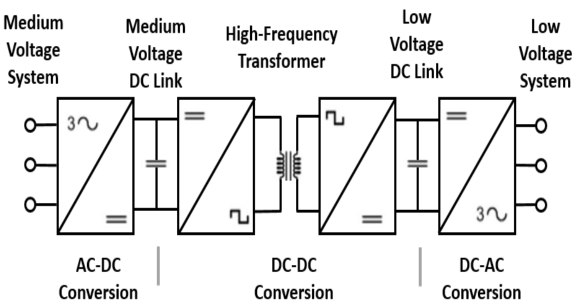


Figure 1. Configuration of three stage SST

3.1 Active rectifier

The control block diagram of the active rectifier is as shown in Figure 2. The function of active rectifier is to convert the AC voltage into DC voltage. The control of active rectifier is done in *dq*-frame, where voltage controller and current controller are being implemented. Desired voltage at the MV DC Link will be regulated by the voltage controller by setting the DC voltage reference value, V_{DC_ref}. Active rectifier also eliminates the reactive power from the AC side as the reference value of current in q-axis, i_{q_ref}, will be constantly set as 0.

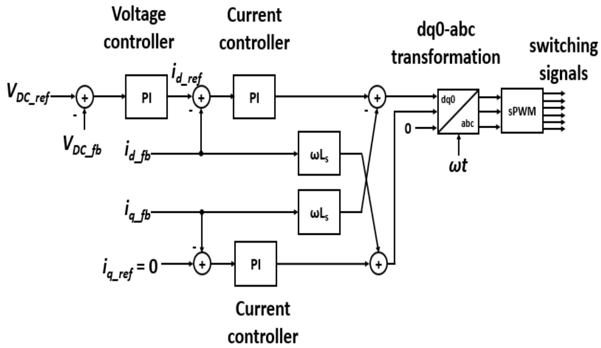


Figure 2. Control block of active rectifier and inverter

3.2 Dual-Active-Bridge (DAB)

Power flow direction of SST is determined by the control of DAB. In DAB, voltage at primary DC link, V_{DC1}, will be transformed to high frequency AC voltage called primary voltage, V_p, as shown in Figure 3. The same transformation is also applied at the voltage at secondary DC link, V_{DC2}, where the DC voltage will be transformed into high frequency AC voltage called the secondary voltage, V_s, as shown in figure 3. Here, the difference of phase angle, δ, between the two high frequency AC voltage will determine the power flow direction. In this research, only open loop control is implemented, where phase-shift values are manually assigned to the control system. When positive phase-shift values are assigned to the control system, AC voltage at primary side of DAB, V_p, is leading compared to the AC voltage at the secondary side, V_s, thus, power flows from MV DC link to LV DC link as shown in Figure 4 (a). On the other hand, when negative values are assigned to the system, AC voltage at secondary side of DAB, V_s, is leading compared to the AC voltage at the primary side, V_p, thus, power flows from LV DC link to MV DC link as shown in Figure 4 (b).

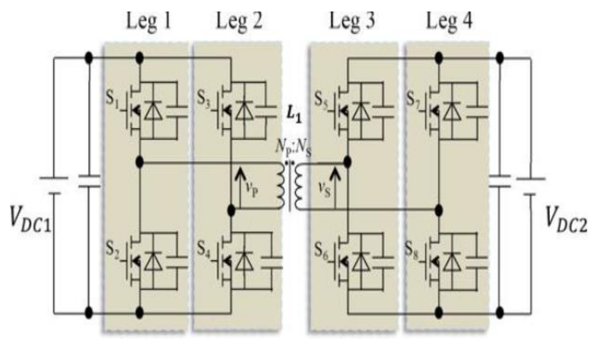
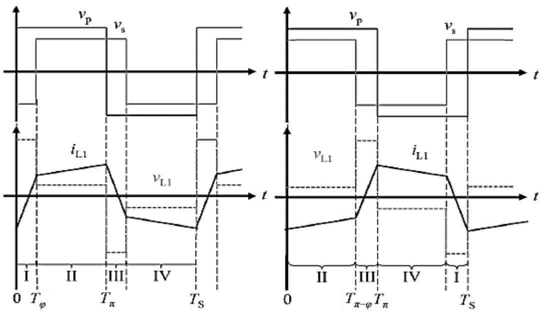


Figure 3. DAB converter circuit



(a) Positive phase-shifted (b) Negative phase-shifted
Figure 4. Phase-shift modulation

3.3 Grid-connected inverter

Grid-connected inverter converts the DC voltage to AC voltage at the second AC side. The control of grid-connected inverter is the same as in active rectifier. Where, the control is done in *dq*-frame and includes voltage controller and current controller. The voltage controller will regulate the LV DC link based on the DC voltage reference value, and current controller will regulate the current flowing at the LV system. Here, the value of current reference value in d-axis, i_{d_ref}, generated by current controller will be in negative values, and the current will flow from LV DC link back to the LV AC system.

4. Experimental Test and Results

(a) Rectifier-DAB experiment

Experimental set up for rectifier-DAB test is shown in Figure 5. In this experiment, rectifier is assigned to regulate the DC link voltage 1, V_{DC1}, of DAB to 50V. The DC link voltage 2, V_{DC2}, of DAB will be kept constant to 50V by the DC electronic load. Here, several phase shift is assigned to DAB. The power flow from DC link voltage 1, V_{DC1}, to DC link voltage 2, V_{DC2}, will be recorded and the efficiency of the DAB converter will be analysed.

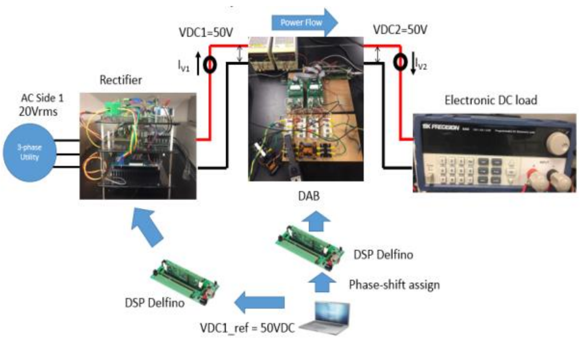


Figure 5. Experimental set up for Rectifier-DAB test

(b) DAB-Inverter experiment

Experimental set up for inverter-DAB test is shown in Figure 6. DC link voltage 1, V_{DC1}, is set constant to 50V by a DC power supply and DC link voltage 2, V_{DC1}, is regulated by the inverter. Here, several phase-shift values were assigned and the power flow from DC link voltage 1, V_{DC1}, to DC link voltage 2, V_{DC2}, were recorded and the efficiency of DAB is recorded and analysed.

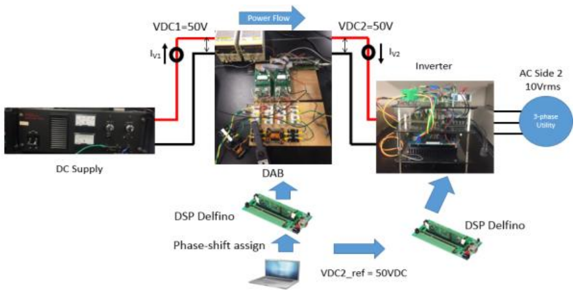


Figure 6. Experimental set-up for inverter-DAB test

5. Results & Discussions

Table 1 and Table 2 show the results of rectifier-DAB experimental test results and DAB-inverter experimental test results respectively. Assigned phase-shift values are varied between 23° to 27°. Power flow between DC link voltage 1, V_{DC1}, and DC link voltage 2, V_{DC2}, were analysed.

Table 1. Rectifier-DAB experimental test results

Phase-shift (°)	I_{V1}(A)	I_{V2}(A)	P primary (W)	P secondary (W)	Efficiency (%)
24	0.62	0.5	31	25	80.6
24.5	0.74	0.61	37	30.5	82.4
25	0.87	0.72	43.5	36	82.8
25.5	0.99	0.85	49.5	42.5	85.9
26	1.14	0.97	57	48.5	85.1
26.5	1.28	1.1	64	55	85.9
27	1.43	1.24	71.5	62	86.7

Table 2. DAB-inverter experimental test results

Phase-shift (°)	I_{V1}(A)	I_{V2}(A)	P primary (W)	P secondary (W)	Efficiency (%)
23	0.27	0.196	13.5	9.8	72.6
23.5	0.35	0.271	17.5	13.55	77.4
24	0.44	0.356	22	17.8	80.9
24.5	0.56	0.455	28	22.75	81.3
25	0.67	0.555	33.5	27.75	82.8
25.5	0.8	0.668	40	33.4	83.5
26	0.91	0.785	45.5	39.25	86.3

Based on the results gained from both experiments, power flow increases when higher phase-shift values are assigned to the DAB control. The trend also shows that the efficiency of DAB system increases when power flow increases.

6. Conclusions & Future Works

This paper presented about the development and experimental simulation of three stage SST. Before combining the active rectifier, DAB and grid connected inverter, two preliminary tests were conducted to verify the control system of each converter. In the future, all three converters will be combined to form laboratory-scale three stage SST and experimental simulations need to be done.

References

[1] M. S. Turiman, G. Fujita: Droop Control Implementation in Solid State Transformer, 12th South East Asian Technical University Consortium Symposium (SEATUC) Jogjakarta, 13th March 2018.

Research Achievements

① M. S. Turiman, G. Fujita: Droop Control Implementation in Solid State Transformer, 12th South East Asian Technical University Consortium Symposium (SEATUC) Jogjakarta, 13th March 2018.
② F.I. Jefri, M.S. Turiman, N.D. Dinh, G. Fujita; Development of Active Rectifier In Solid State Transformer By Using Embedded Coder Toolbox, The 11th Vietnam-Japan Scientific Exchange Meeting (VJSE 2018), Sendai, 15th September 2018