Virtual Port Isolation Control of Triple-Active-Bridge Converter for EVs

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1. Introduction

Regulations of vehicle's exhaust gases are gradually becoming strict around the world. To achieve the target, in the automobile industry, the movement to apply more electrical components is accelerating. However, in the conventional 12V system, the power consumption of the automobile has reached about 3kW which is close to the limit value. Thus the application of a 48V system has attracted attention [1]. Since the current value can be lowered by quadrupling the voltage, it is possible to utilize the larger assist force and energy regeneration, and it is possible to reduce CO_2 emissions. Therefore, as a 12V system and a new 48V system will be applied in an automobile, attention is being paid to the Triple-Active-Bridge (TAB) DC/DC converter for EVs, which can combine three different voltages terminal (12V/48V/HV) in a single unit [2].

In this study, a prototype of TAB DC/DC converter is developed. If two ports of the transformer are engaged in operation, another remaining port is idling. The idling port should be isolated, to avoid causing damage to the switches and capacitors by high voltage. Consequently, there are losses when a certain port is isolated with mechanical switches. Therefore, electrical isolation with voltage phase-shift by switching actions called virtual isolation control is studied [3].

2. System Configuration

2.1 Design of TAB DC/DC Converter

Figure 1 shows the model circuit of TAB converter. For safety purposes, the TAB converter consists of three inverters and a three-wiring transformer which achieves a galvanic isolation. Considered the experiment scale, a voltage of HV port is set to 72V.

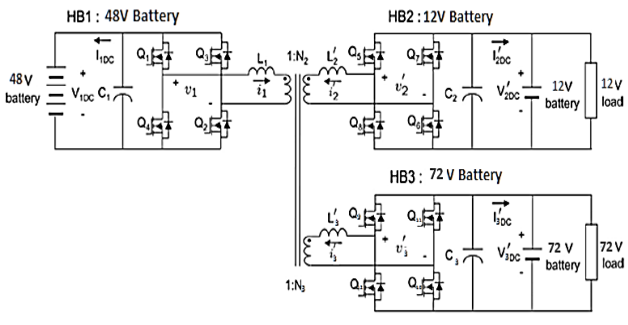

Figure 1. Model circuit of TAB converter

2.2 Virtual Port Isolation

Consider the case that port3 is isolated as an example. Figure 2 shows the Δ-equivalent circuit, Figure 3 shows the phasor diagram. When $I_3 = 0$, port3 will be electrically isolated. In this case, given the following equation from the equivalent circuit:

$$|V_{f3}| = \frac{\sqrt{(L_{\Delta 23}|V_{f1}|+L_{\Delta 31}|V_{f2}|\cos(\varphi_2))^2+(L_{\Delta 31}|V_{f2}|\sin(\varphi_2))^2}}{L_{\Delta 23}+L_{\Delta 31}}$$

$$\varphi_3 = \tan^{-1}\left(\frac{L_{\Delta 31}|V_{f2}|\sin(\varphi_2)}{L_{\Delta 23}|V_{f1}|+L_{\Delta 31}|V_{f2}|\cos(\varphi_2)}\right)$$

From above equations, I3 can be controlled by changing $|V_{f3}|$ and φ_3, and can achieve the virtual isolation of port3 (HB3). [3]

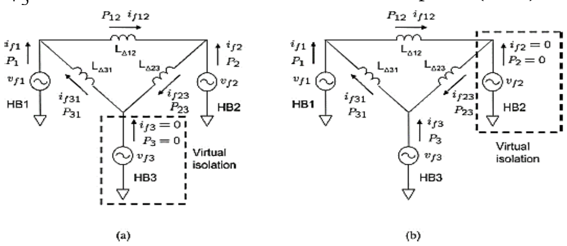

Figure 2. Δ-equivalent circuit for HB3 and HB2 isolation

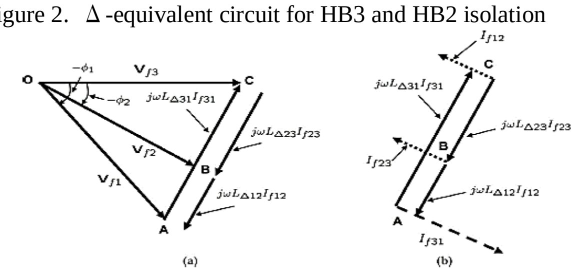

Figure 3. Phasor diagram for HB3 isolation

3. Results and Discussions

3.1 Simulation Test Result

Figure 4 shows the simulation circuit when port3 is isolated, and Table 1 and Figure 5 shows the results.

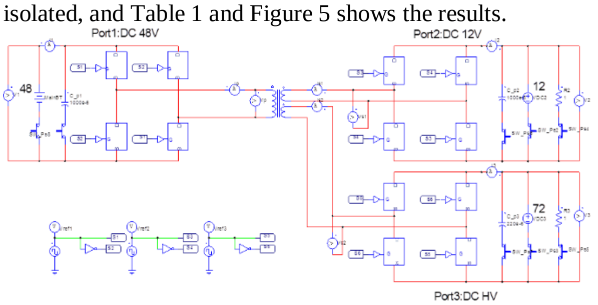

Figure 4. Simulation circuit

Table 1. Phase shift and Simulation results

	Phase shift [°]	DC Voltage [V]	DC Current [A]
Port1	0	48	2.74
Port2	90	12	-10.3
Port3	0	72	0.107

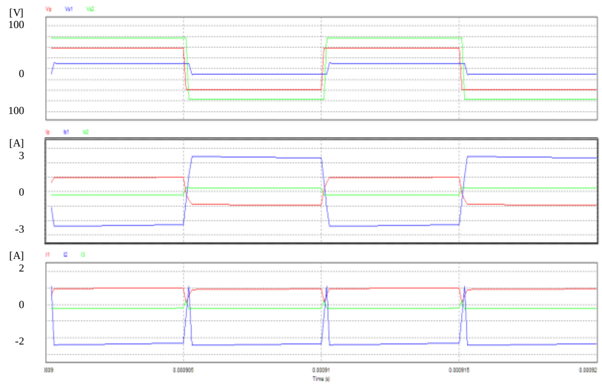

Figure 5. Waveform ([v_p, v_{s1}, v_{s2}], [i_p, i_{s1}, i_{s2}], [I_1, I_2, I_3])

In Figure 5, I_3 is 0.08A and loss ratio is 5.86% considering input 131.5W. Regarding to the current value, virtual isolation control is valid. However, this current value can be small since the phase isolation does not suit perfectly because of errors relating to the no uniformity leakage inductances and turn ratio of the three-winding transformer.

3.2 Experimental Test Result

Figure 6 shows the experimental equipment of TAB converter, Table 2 and Figure 7 show the experimental result.

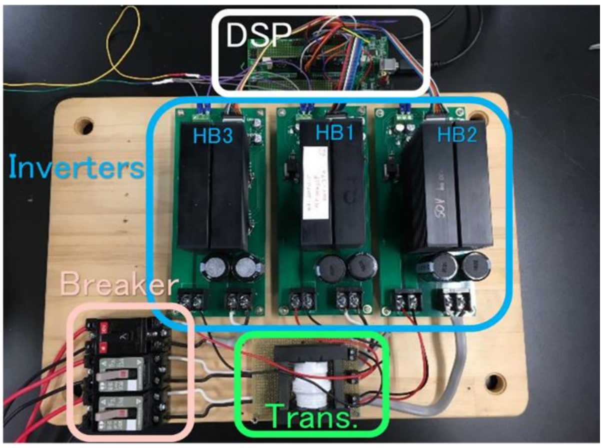

Figure 6. Experimental equipment of TAB converter

Table 2. Phase shift and Experimental results

	Phase shift [°]	DC Voltage [V]	DC Current [A]
Port1	0	12.0	1.22
Port2	90	3.74	1.86
Port3	0	18.00	0.04

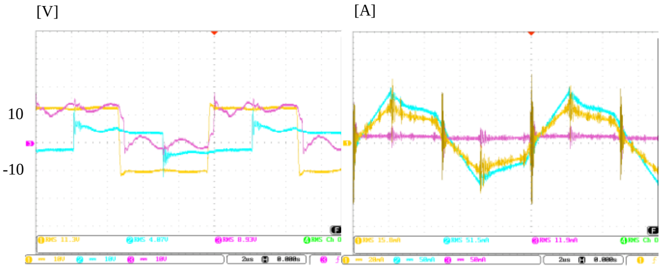

Figure 7. Waveform (Left: [v_p, v_{s2}, v_{s2}], Right: [i_p, i_{s2}, i_{s2}])

In Table 2, the current value of port3 is 0.04A. Consequently, the virtual isolation of port3 is achieved. In terms of the losses of HB3 against input power, the loss ratio becomes 4.92%. It is still possible to reduce this power losses by modifying the phase shift with closed loop controller system.

4. Conclusion and Future Works

In this study, the validity of the theory is confirmed by the simulation on PSIM software under the conditions: port3 isolation and port2 isolation, respectively. Then experiments with developed TAB DC/DC converter are conducted with low voltages. In both simulation and experiments, the virtual port isolation of a certain port is verified. By applying this virtual isolation control for the TAB converter, it is expected that the downsized multi-port converter with high efficiency is developed, and it can be replaced with conventional Dual-Active-Bridge DC/DC converters in the automobiles.

However, there are still possibilities to improve the power transmission efficiency, since there are some errors regarding the turn ratio and the non-unified leakage inductances of the single-phase three-winding transformer, and also the value of the phase-shift which is controlled with an open-loop. Therefore, it is required to improve the topology and quality of three-winding transformer and develop the suitable closed-loop system with PI controller for the precise phase-shift modulation for future works.

References

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[3] Zhao, Chuanhong, Simon D. Round, and Johann W. Kolar. "An isolated three-port bidirectional DC-DC converter with decoupled power flow management." *IEEE transactions on power electronics* 23.5 (2008): 2443-2453.