A DC Power Distribution System in a Data Center using a Triple Active Bridge DC-DC Converter

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In recent years, the demand for high-reliability systems has been on the rise, while DC power distribution systems are widely used in data centers. The authors propose a DC power distribution system that uses a triple active bridge (TAB) DC-DC converter, toward the realization of such higher-reliability systems. The TAB converter is based on an isolated DC-DC converter and can control the DC power flow among the three ports. First, this paper presents a basic power flow control procedure of the TAB converter, using a phase-shift control. Further, two types of higher-reliability DC power distribution systems are proposed using the TAB converter. The experimental design and simulations of a prototype 200-V TAB converter with 500-W power, connected with the single and double loads, are reported. In the experiment, the 200-V TAB converter rated at a power of 500 W was constructed from a three-winding transformer and gallium nitride (GaN) power devices. Smooth output waveforms indicate good controllability of the power flow and good functional performance of the proposed DC power distribution system.

Keywords: data center, DC power distribution, GaN power device, triple active bridge converter, phase shift control

1. Introduction

The rapid advent of global cloud-computing, big data, and cloud provider companies, such as Microsoft and Google, has brought a rapid increase in the demand of data centers; consequently, many large-scale data centers have been built worldwide during the past decade (1). The expansion of these data centers (both in the number and scale of centers) resulted in substantial consumption of energy. According to some estimates, the energy consumption by the servers and infrastructure of data centers had amounted to 7% of the global electrical energy consumption in 2012 (2). Power consumption by the US data centers is estimated to increase by approximately 10% every year (3)-(5). Moreover, these surveys and papers revealed the critical fact that conventional data centers continue to strongly rely on fossil energy sources (such as coal, oil, and natural gas) for their operation, which led to increasing environmental- and pollution-related concerns. Lately, the users of data centers and the providers of cloud services are making efforts to move toward the utilization of renewable power resources, such as wind and solar energy, for the operation of their data centers. Some companies have attempted to build renewable energy facilities to directly utilize the power from these sources for the operation of their data centers. For example, Google has recently reported that over 35% of the power consumed by its data centers is derived from renewable energy resources (6). Moreover, by using renewable energy sources as a replacement for the grid, pollution can be reduced by at least 150 million metric tons annually (7).

However, the adoption and optimization of renewable energy resources for the power distribution operations of data centers remain challenging, due to the desultory and variable characteristics of renewable energy and its generation. For example, the electrical automation company reported that even with the energy supply reliability as high as 99.999%, a typical data center is likely to experience 5 min of breakdown every year (8). Therefore, reliability is one of the most important indices that should be considered while designing data centers; especially considering the loss of electrical power caused by breakdowns. Under these conditions, it becomes necessary to develop a highly efficient DC-DC converter that would provide stable power distribution with high availability and reliability (9).

There is a need of a backup system that would ensure high reliability by maintaining a data center at the time of power interruption, especially during its peak hours of operation. Suggestions have been made to overcome the problem of backup by using an external system, such as a backup energy storage, which might help to ensure stability, especially during peak hours. Specific examples such as the use of various batteries with different lifecycles, control technologies, and storage capacity have been discussed (7)-(9). Two types of batteries have been widely used for these purposes: lead-acid and lithium-ion batteries. Over the past few decades, deep-cycle acid batteries have been used in renewable energy and off-grid applications, due to their low cost. However, highly efficient and non-toxic lithium-ion batteries, which are more expensive than acid batteries, has also been widely used.
Researchers and engineers have been considering reliable power converters for the power distribution control circuits of data centers. This includes the triple active bridge (TAB) converters with an isolation function circuit diagram that can be used for power distribution at data centers, which are attracting significant attention. A TAB converter consists of three active H-bridge cells with external inductances that are connected through a three-winding high-frequency transformer. DC buses on each side provide power flow through the TAB converter. TAB converters have been proposed to be essential for DC distribution systems because they connect not only the DC grids but also a DC energy storage to a DC distribution bus. Moreover, the transformer in a TAB converter can provide power flow control with isolation, which can provide safety between different voltage inputs. In addition, the multiple ports of a TAB converter satisfy the multiple power conversions and users linked into the DC system as a power router. A power distribution system that uses a TAB converter has been introduced and its advantages have been described.

The authors have also proposed a power router based on a TAB converter. Further, a power distribution system using the 400-V TAB converter with lithium-ion battery is used to explain the principle and operation of applications using a TAB converter.

This paper proposes DC power distribution systems using a TAB converter for data centers, which are under the situation of faults that may occur in data centers. By using the TAB converter, the downtime of power distribution systems is reduced, therefore, higher-reliability DC distribution systems are realized. Fig. 1 shows power distribution systems with single and double loads. Fig. 1(a) shows the conventional power distribution systems with single and double loads at data centers, while Fig. 1(b) shows the proposed power distribution systems using the TAB converter. The load on data centers is contributed by equipment such as switches, routers, servers, and storage devices; which are the conventional DC-supplied loads. A backup supply, such as batteries, is required to address the critical situations, such as interruption and breakdown. Compared with the conventional distribution system, the proposed structure can utilize the TAB converter to precisely distribute the power from the backup batteries during power interruptions, while the multiple ports enable the use of different batteries on demand. This makes the system more suitable for dealing with multiple loads and helping to reduce the distribution volume without using bulky batteries. Further, it is feasible to connect the TAB converter for DC power distribution at a data center and achieve a higher reliability for the DC distribution function. In section 2, the modeling and the structure of the power distribution system using the TAB converter for data centers with single load and double loads, have been described. In section 3, the authors describe the topology, operation, and basic theories of the TAB converter. Section 4 shows the simulations results for the power distribution in data centers with single and double loads, using the open-loop TAB converters. The simulations describe the operation of the power flow control for DC power distribution systems with interruptions that happen in a data center, and the behavior of the proposed structure. In section 5, the circuit configuration of a TAB converter for an experimental system is described, and the performance tests of a DC power distribution system with a double loads, under the power flow control, are discussed in detail.

2. Modeling a DC Distribution System for a Data Center

A DC distribution system connected to DC power sources and resistive loads was constructed for a data center. The resistive loads (the single and double loads) were similar to the ones shown in Figs. 2 and 3, and the distribution structure employed the TAB converter as a power router. In the DC distribution system, the voltage $V_{DC}$ on the TAB converter was supplied by DC sources, such as a DC grid. The voltage $V_{bat}$ can be assumed to be a peripheral power storage device, such as a battery.

In the single-load system, the TAB converter was connected to the power branch with a user in the terminal. In the normal operation of a data center, the input DC source, $V_{DC}$, provides power to be used by the users, as well as the power to be stored in the backup batteries. When the DC transmission associated with the DC source fails, the backup batteries provide power flow to the load through the TAB converter. In the double-load system, two loads in the terminal of the DC branches, $P_{S2}$ and $P_{S3}$, represent the double users in the DC power distribution system. The battery storage ensures the power reliability of the data center. The TAB converter can react to the power flow changes in the DC power distribution system using the power flow control, thus ensuring a stable operation.
3. Configuration and Power Flow Control of the TAB Converter

3.1 Topology of the TAB Converter

Fig. 4 shows the circuit diagram of the TAB DC-DC converter. The TAB converter is composed of three active H-bridge cells that are connected through a three-winding high-frequency transformer. The primary, secondary, and tertiary ports can be connected to the DC sources, such as batteries or DC grids. The power flow is ensured by the transformer. In the converter model, \( f_{sw} \) represents the switching frequency and \( L_{e1}, L_{e2}, \) and \( L_{e3} \) describe the external inductances that are connected to the different ports.

3.2 Power Flow Control

The power flow control method that is utilized in the power control of the TAB converter is a phase-shift control. The phase-shift pattern is shown in Fig. 5. When the phase shift of the primary side full-bridge cell is regulated as the reference value, the phase shift of the control signals between the primary and secondary sides is represented by \( \delta_2 \) [rad] and the signal between the primary and tertiary sides is represented by \( \delta_3 \) [rad].

Fig. 6 also shows the voltage waveforms (\( u_1, u_2, \) and \( u_3 \)) as well as the current waveforms (\( i_1, i_2, \) and \( i_3 \)) of the transformers in each side under the phase-shift control, where \( \delta_2 \) and \( \delta_3 \) can be rectified to control the power flows among the other ports.

The relationship among \( P_1, P_2, P_3, \delta_2, \) and \( \delta_3 \) can be obtained from (1) and yields the following equations:

When \( 0 \leq \delta_2 \leq \delta_3 \):

\[
\begin{align*}
P_1 &= V_1V_2\delta_2 (\pi - \delta_2) L_{e3} + V_1V_3\delta_1 (\pi - \delta_1) L_{e2} \\
&\quad - \frac{2\pi f_{sw}(L_{e1}L_{e2} + L_{e2}L_{e3} + L_{e3}L_{e1})}{L_{e1}L_{e2}L_{e3}} \delta_1^2 \\
P_2 &= \frac{V_1V_2\delta_2 (\pi - \delta_2) L_{e3} + V_2V_3 (\delta_2 - \delta_1) L_{e3}}{2\pi f_{sw}(L_{e1}L_{e2} + L_{e2}L_{e3} + L_{e3}L_{e1})} \\
P_3 &= \frac{V_1V_3\delta_1 (\pi - \delta_1) L_{e2} + V_3V_2 (\delta_3 - \delta_1) L_{e2}}{2\pi f_{sw}(L_{e1}L_{e2} + L_{e2}L_{e3} + L_{e3}L_{e1})} \\
\end{align*}
\]

(1)

When \( 0 \leq \delta_3 \leq \delta_2 \):

\[
\begin{align*}
P_1 &= V_1V_2\delta_2 (\pi - \delta_2) L_{e3} + V_1V_3\delta_1 (\pi - \delta_1) L_{e2} \\
&\quad - \frac{2\pi f_{sw}(L_{e1}L_{e2} + L_{e2}L_{e3} + L_{e3}L_{e1})}{L_{e1}L_{e2}L_{e3}} \delta_1^2 \\
P_2 &= \frac{V_1V_2\delta_2 (\pi - \delta_2) L_{e3} + V_2V_3 (\delta_2 - \delta_1) L_{e3}}{2\pi f_{sw}(L_{e1}L_{e2} + L_{e2}L_{e3} + L_{e3}L_{e1})} \\
P_3 &= \frac{V_1V_3\delta_1 (\pi - \delta_1) L_{e2} + V_3V_2 (\delta_3 - \delta_1) L_{e2}}{2\pi f_{sw}(L_{e1}L_{e2} + L_{e2}L_{e3} + L_{e3}L_{e1})} \\
\end{align*}
\]

(2)

For the same input voltage and inductance, the relationship between the power flow and the phase-shift angle can be simplified with the following equations:
When $0 \leq \delta_2 \leq \delta_3$: 
\[
\begin{align*}
P_1 &= \frac{V^2 \delta_2 (\pi - \delta_2) + \delta_3 (\pi - \delta_3)}{6\pi^2 f_{sw} L_e} \\
P_2 &= \frac{V^2 \delta_2 (\delta_2 - \pi) + (\delta_3 - \delta_2) (\pi - \delta_3 + \delta_2)}{6\pi^2 f_{sw} L_e} \\
P_3 &= \frac{V^2 \delta_3 (\delta_3 - \pi) + (\delta_2 - \delta_3) (\pi - \delta_2 + \delta_3)}{6\pi^2 f_{sw} L_e}
\end{align*}
\]

When $0 \leq \delta_3 \leq \delta_2$: 
\[
\begin{align*}
P_1 &= \frac{V^2 \delta_2 (\pi - \delta_2) + \delta_3 (\pi - \delta_3)}{6\pi^2 f_{sw} L_e} \\
P_2 &= \frac{V^2 \delta_2 (\delta_2 - \pi) + (\delta_3 - \delta_2) (\delta_2 - \pi)}{6\pi^2 f_{sw} L_e} \\
P_3 &= \frac{V^2 \delta_3 (\delta_3 - \pi) + (\delta_2 - \delta_3) (\pi - \delta_2 + \delta_3)}{6\pi^2 f_{sw} L_e}
\end{align*}
\]

As shown in Eqs. (3) and (4), when certain parameters of the TAB converter are fixed, the power flows of the TAB converter can be controlled.

The control schematic of the power distribution system, when the interruption occurs, is shown in Fig. 6. The information of the input sources from the DC source (battery), the load power information, and the power demand of power distribution system will be analyzed. In addition, the power flow amplitude of each port can be obtained. Further, the phase-shift analysis can change the phase shift of the TAB converter switches according to Eqs. (3) and (4). When the phase-shift $\delta_2$ and $\delta_3$ of the TAB converter are controlled accordingly, the power transmitted in the power distribution system can be verified with the help of the TAB converter.

4. Simulation of the TAB Converter

To analyze the power distribution function of the TAB converter for the DC power distribution at data centers, the simulations conducted are of DC power distribution systems with single and double loads, rated at 500 W and 200 V. The TAB converters with single and double loads are the same as those shown in Figs. 2 and 3. The resistors at the end of the distribution system represent the resistive loads, such as servers in the network system, constantly consuming a certain amount of power, linked via the DC energy sources, $V_{in}$ and $V_{DC}$. Hence, the ideal batteries are applied in the simulation with a constant DC voltage. The parameters of the 500 W TAB converter are listed in Table 1, and the Powersim (PSIM) simulation model was constructed based on Figs. 2 and 3.

4.1 Power Distribution of the TAB Converter with Single Load

The open-loop phase-shift control in the TAB converter regulates the phase-shift angles in the secondary and tertiary sides.

A performance test of the 500 W TAB converter, with a single load for power distribution, was conducted using the phase-shift control.

The conditions for the simulation of the 500 W TAB converter with single load are listed in Table 2. Fig. 7 shows the simulation results for the 500 W TAB converter with the single load for a DC distribution system. The test was designed based on the three scenarios of power distribution. The duration of the simulation was 0.7 s, and the simulation was divided into three time periods. During each period, the open-loop phase-shift control was employed in the power flow control. The waveforms of $P_1$, $P_2$, and $P_3$ in Fig. 7 show that during the three periods, the power flow was verified by the phase-shift control in amplitude, while the power distribution of $P_{S1}$ was ensured. During the first period, the power flow in $P_{S1}$ directly fed 500 W into the load, while at the same time no powerflowed through the TAB converter. During the second period, when the abnormal condition occurred in $P_{S1}$, decreased the power from 500 W to 250 W, the branch of $P_2$ provided 250 W to the load through the TAB converter, while no power flow in $P_3$. During the third period, when an interruption occurred in $P_{S1}$, cut off the power flow, both $P_2$ and $P_3$ react to the interruption and transmitted 250 W feed to the load, which ensured that a constant amount of power was taken from the load in $P_{S1}$.

4.2 Power Distribution of the TAB Converter with Double Loads

The open-loop phase-shift control in the
TAB converter controlled the power distribution in the TAB converter in the double-load system. A performance test of the 500 W TAB converter with double loads for power distribution was conducted using the phase-shift control. The simulation is designed considering the abnormal situation and interruptions that may occur in the system. The simulation conditions for this test of the 500 W TAB converter with double loads are listed in Table 3.

Fig. 8 shows the power distribution system scheme with double loads during the three periods. The simulation is designed with three periods. When the abnormal situation happens in the power distribution system, the TAB converter can verify the power flow according to the demand with the changing phase shift.

Fig. 9 shows the simulation results for the 500 W TAB converter with double loads for a DC distribution system. The waveforms of $P_1$, $P_2$, and $P_3$ in Fig. 9 show that, by controlling the phase shift, the amplitude of the power transmitted among the three ports can be regulated according to the reference power. During the first period, the power that flowed in $P_{S2}$ and $P_{S3}$ fed 500 W into the double loads, while at the same time no power flowed through the TAB converter. During the second period, when the abnormal condition in the branch of $P_{S2}$ reduced the power flow from 500 W to 250 W, $P_{S1}$ provided 250 W through the TAB converter to the load. During the last period, when the interruption in $P_{S3}$ cut off the DC source, $P_{S2}$ transmitted 500 W to the load, while 250 W were distributed through the TAB converter. Further, $P_{S1}$ delivered 250 W to the load, ensuring that a constant amount of power was taken from the load in $P_{S3}$. Additionally, the waveforms clearly show that the power $P_R$ consumed by the users is guaranteed to be 500 W. Finally, Fig. 10 shows the current and voltage waveforms of each port, in the steady-state condition $\delta_2 = \delta_3 = 30^\circ$.
5. Experimental Studies of the TAB Converter

5.1 Experimental Setup Gallium nitride (GaN) devices are advantageous, because they exhibit low switching loss in high-frequency operations.\(^{(24)}\)\(^{(25)}\)

In this experiment, a prototype 500 W TAB converter using GaN power devices was constructed, consisting of three active H-bridge cells that were mutually connected through a three-winding high-frequency transformer, as shown in Fig. 11. Each active H-bridge cell represents an individual port. Each active H-bridge cell was composed of four GaN semiconductors and one external inductor, and the details of GaN power devices and specifications are listed in Table 4. The parameters of the three-winding high-frequency transformer are revealed in Table 5.

5.2 Basic Operation of the TAB Converter using GaN Power Devices In the experiment of DC power distribution, the open-loop phase-shift control was applied in the 500 W TAB converter by changing the phase-shift angles of different ports. The parameters of the 500 W TAB converter are listed in Table 6.

The phase-shift control was applied to the 200 V TAB converter in the steady-state condition \(\delta_2 = \delta_3 = 30^\circ\). Figure 12 shows the experimental output voltage waveforms \(u_1\), \(u_2\), and \(u_3\), as well as the current waveforms \(i_1\), \(i_2\), and \(i_3\), for transformers of different ports.

Figure 13 shows the efficiency curve by the experiments rated at 500 W. The efficiency results are tested by changing the phase shift \(\delta_2\) and \(\delta_3\) of the secondary and tertiary sides. The selection of the phase shift \(\delta_2\) is from 20° to 40°, while the range of \(\delta_3\) is from 40° to 20°. The difference between the \(\delta_2\) and \(\delta_3\) affected the power flows in the TAB converter. The power flow \(P_2\) is increased from 0 W to 500 W and the power flow \(P_3\) is decreased from 500 W to 0 W during the operation. From Fig. 13, the highest efficiency point of the TAB converter is 97.6%, when the phase shift \(\delta_2\) and \(\delta_3\) has the same value, 30°.

5.3 Experimental Results for the DC Distribution System After connecting the 500-W TAB converter to the double-load DC distribution system, the transient condition was designed as in Table 2. The phase-shift angles for power flow control were also indicated and calculated by (1) and (2) according to the reference power.

Figure 14 shows the experimental results for the 500 W TAB converter under the open-loop transient condition from the first to the second period, and from the second to the third period. During each period, the phase-shift angles for the secondary and tertiary ports were varied in the TAB converter. The power flows in the TAB converter are changed under the phase-shift control. Therefore, the amplitude and direction of the power flows in the double-load DC distribution system are also controlled. The waveforms of \(P_1\), \(P_2\), and \(P_3\) show that by using the phase-shift control, the amplitude of the power transmitted among the three ports instantly changes.
In the first period of the experiment, the power that flowed in $P_{S2}$ and $P_{S3}$ fed 500 W into the double-load system, while at the same time no power flowed through the TAB converter. During the second period, $P_{S2}$ provided 500 W to the load, while $P_{S1}$ and $P_{S3}$ each delivered 250 W at the same time, ensuring power consumption by the user in $P_{S3}$. During the last time period, when the $P_{S2}$ transmitted 500 W to the load, while 250 W were distributed through the TAB converter; $P_{S1}$ delivered 250 W to $P_{S1}$, ensuring that a constant amount of power was taken from the load in $P_{S3}$. Further, from the waveform of $P_{S2}$, it is clear that the power $P_{S2}$ consumed by the users is guaranteed to be 500 W in the experiment.

6. Conclusion

This paper proposed DC power distribution systems with single load and double loads, for realizing a high-reliability data center system using the TAB converter. Further, the basic operation and power flow control characteristics of the TAB converter are presented. The simulation and experimental conditions, considering the interruptions that may occur in a real operation, are designed and conducted. The open-loop simulation models and the experimental models featuring GaN devices were constructed and tested under the critical requirements of the power flow conditions. The satisfactory performance in simulations and experiments validated the feasibility and reliability of the TAB converter in DC power distribution systems for its utilization at data centers.

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