Power Flow Control in Multi-Active-Bridge Converters: Theories and Applications

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Abstract—This paper investigates the theories and applications of power flow control in multi-active-bridge (MAB) power converters. Many emerging applications including differential power processing, low voltage power delivery in smart homes, multi-cell battery balancers, and photovoltaic energy systems comprise sophisticated power flow across multiple dc voltage ports. Connecting many dc voltage ports together with a MAB converter reduces the power conversion stress, improves the efficiency and enhances the power density. Fundamentally, the advantages of a MAB design come from merging many standalone magnetic components with simple functions into one single magnetic component that performs sophisticated functions. Three control strategies for MAB converters, including phase-shift (PS) control, time-sharing (TS) control, and hybrid phase-shift and time-sharing (PSTS) control are developed to regulate the voltage and precisely control the power flow. A four-port MAB converter prototype designed for low voltage power delivery applications in future smart homes has been built and tested to compare the performance of the three control methods and verify the effectiveness of the proposed architecture.

Index Terms—dc power delivery, multi-active-bridge converter, power flow control, multiwinding transformer, planar magnetics.

I. INTRODUCTION

Traditionally, power converters are usually designed as single-input single-output converters. For battery energy storage, server racks, and PV strings, a large number of modular cells need to be connected in series and/or parallel and need be coordinated to achieve maximum system performance. In future homes and buildings, more and more devices operate in low voltage dc, have battery storage, and can provide grid support functions. Power converters that can interface with multiple dc voltage domains with high efficiency and high power density are needed in a wide range of applications. Fig. 1 shows the power conversion architecture in four future application scenarios which all need multiport power converters with sophisticated power flow, including 1) energy router for smart homes; 2) multiport battery balancer for grid scale energy storage; 3) differential power processor architecture for series stacked servers; and 4) distributed MPPT for solar photovoltaic systems.

Fig. 1. Four application scenarios of multiport power converters: 1) dc energy router for smart homes; 2) multiport battery balancer for grid scale energy storage; 3) differential power processing architecture for series stacked servers; and 4) distributed MPPT for solar photovoltaic systems.
as a controllable voltage source, which behaves similarly as synchronous generators in a traditional power system. Newton-Raphson algorithm was used in [11], [12] to solve the phase-shift angle at each port for a given power flow.

Another method to route the matrix power flow in a MAB converter is time-sharing (TS) control (on-off control) [13]. At each time instance, only two ports are activated and power flows from one to the other. As a result, the MAB converter can be treated as a two-port DAB converter with no cross-coupling across multiple ports. Similar to bursting a single-input single-output converter, time-sharing control enables the system to achieve high efficiency in light load conditions, and reduce the system efficiency in heavy load conditions. As will be discussed in Section IV, time-sharing control can be merged with phase-shift control to create mutual system advantages.

This paper uses a MAB converter designed for low voltage dc power delivery applications as an example to investigate the theories and applications of power flow control in multi-port converters. Compared to a traditional dc power delivery architecture with a fixed dc bus (usually 400 V), a MAB design can eliminate the numerous dc-dc adapters, reduce the power conversion stress, and improve the power density. The conventional dc-dc adapters attached to each low voltage devices will be replaced by a central MAB converter (located at the circuit box of a room or a building) that can create many adjustable dc voltage levels for many smart outlets. A smart outlet has communication and voltage regulation capability. It senses the type of the load, and communicates with the controller of the MAB to synthesize the needed voltage.

The remainder of this paper is organized as follows: Section II presents the operation principles of phase-shift control. Section III presents the operation principles of time-sharing control. Section IV investigates a hybrid phase-shift time-sharing control. The design details of a 400 W MAB converter are presented in Section V and the small signal analysis are presented in Section VI. Section VII discusses the experimental results. Finally, Section VIII concludes the paper.

II. PHASE-SHIFT CONTROL OF THE POWER FLOW

In the topology shown in Fig. 2, Port #1 connects the MAB converter to a 400V dc bus synthesized by a central ac-dc converter. Port #2 is designed to charge and discharge a battery system at 48V. Port #3 and Port #4 deliver power to low voltage consumer electronics (e.g., cellphones and laptops) at 15V and 5V, respectively. $N_1$–$N_4$ are the number of turns of the multi-winding transformer. Branch inductors $L_1$–$L_4$ represent the summation of the leakage inductance of the transformer and external discrete inductors. Depending on the leakage inductance and the switching frequency, external inductors may or may not be needed. In a MAB implementation, the impedance of the dc blocking capacitors, $C_1$–$C_4$, are negligible compared to the impedance of $L_1$–$L_4$.

A. Power Flow Modulation and Large Signal Models

The multi-winding transformer in this 4-port MAB converter can be represented as a Star model (Fig. 3). The Star model can be converted into an equivalent Delta model [4] (Fig. 4) or a Cantilever model [14] to simplify the power flow analysis. The four full-bridge inverters are modeled as four square wave voltage sources $V_{#1}$–$V_{#4}$. An $N$ turn winding in the multi-winding transformer is represented as an ideal transformer with a turns ratio of $N : 1$. The series-connected capacitors $C_1$–$C_4$ are neglected in this analysis. A power flow calculation method considering the impact of these capacitors is provided in [11]. The equivalent inductance between Port $i$ and Port $j$ in the Delta model can be calculated as a function of the equivalent port inductance in the Star model:

$$L_{ij} = L_i' L_j' \left( \frac{1}{L_m} + \sum_{k=1}^{4} \frac{1}{L_k'} \right),$$

where $L_1'$–$L_4'$ are the normalized inductance per-turn of $L_1$–$L_4$ in the Star model (e.g. $L_i' = L_i / N_i^2$). $L_m$ is the magnetizing inductance.

As derived in [11], the average injected power from the transformer in one switching cycle at Port $i$ is:

![Fig. 2. Topology of an example 4-port MAB converter.](image1)

![Fig. 3. Star model of a multi-winding transformer.](image2)

![Fig. 4. Delta model of a multi-winding transformer.](image3)
Based on (2), the dc voltage across Port \( i \) is:

\[
V_i = \frac{R_i}{2\pi f_s N_i} \sum_{j \neq i} \frac{V_j}{N_j L_{ij}} (\Phi_i - \Phi_j) \left( 1 - \frac{|\Phi_i - \Phi_j|}{\pi} \right). \tag{3}
\]

Here \( R_i \) is the equivalent resistance of the load. The small signal transfer function from perturbations in the phase-shift angle of each port \([\phi_1, ..., \phi_n]\) to the voltage of Port \( i \) is:

\[
\dot{V}_i = C_i \frac{R_i}{sR_i C_i + 1} \sum_{j \neq i} \frac{V_j}{N_j L_{ij}} (1 - 2\frac{|\Phi_i - \Phi_j|}{\pi}) - \sum_{j \neq i} \frac{\dot{\phi}_j}{N_j L_{ij}} (1 - 2\frac{|\Phi_i - \Phi_j|}{\pi}) \tag{4}
\]

where \( C_i \) is the bus capacitance of port \( i \). Fig. 6 shows the small signal model of the MAB converter. Note that all the control loops are cross coupled with the phase to current transfer function \( K_{\phi i} \) and the port load impedance \( Z_i \). The small signal dynamic behaviors of the system will be analyzed in detail in Section V.

C. Split Power Point Tracking (SPPT)

The power flow needs to be precisely merged or splitted among multiple ports in many applications. A Split Power Point Tracking (SPPT) algorithm, which is similar to the Maximum Power Point Tracking (MPPT) algorithm in photovoltaic systems, is needed in the control loop to determine the power splitting ratio. Based on (2), if the phase difference between two ports is smaller than \( \pi/2 \), the power transferred from one port to the other is monotonically determined by the phase difference – a larger phase difference pushes more power from the leading ports to the lagging ports. One can delay the phase of Port \#1 and maintain all other phases if more power needs to be delivered to Port \#1. Using the 4-port MAB converter shown in Fig. 2 as an example, assuming the phase of Port \#1 is zero, Port \#1 and Port \#2 are input ports, and Port \#3 and Port \#4 are output ports. The total input power is \( P_1 + P_2 \), and the total output power is \( P_3 + P_4 \). Fig. 7 shows the control diagram if one wants to feed \( K(P_3 + P_4) \) from Port \#2, and \((1 - K)(P_3 + P_4)\) from Port \#1. \( K \) is the power dividing ratio between \( P_1 \) and \( P_2 \). \( \Delta P \) is a hysteresis margin to avoid oscillation. \( \Delta \Phi \) is the incremental phase step. \( \Phi_2 \) is increased or reduced by \( \Delta \Phi \) in every tracking step until the difference between \( P_2 \) and its control target \( K(P_3 + P_4) \) is smaller than \( \Delta P \).

For a MAB system with many input ports and output ports, the power combining and splitting ratios are multi-variable vectors and are cross-coupled. A multi-variable SPPT algorithm which can systematically track many splitting ratios is an interesting topic and is beyond the scope of this paper.

III. TIME-SHARING CONTROL OF THE POWER FLOW

Another method to control the power flow in a MAB converter is time-sharing control. With time-sharing control, only two ports are activated at one instance; all other ports are

\[
\dot{V}_i = \frac{R_i}{sR_i C_i + 1} \sum_{j \neq i} \frac{V_j}{N_j L_{ij}} (1 - 2\frac{|\Phi_i - \Phi_j|}{\pi}) \tag{4}
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deactivated as diode rectifiers. With time-sharing control, the MAB converter functions as a DAB converter with a single input port, a single output port with straightforward power flow. Fig. 8 illustrates the principles of time-sharing control, when Port #1 delivers power to Port #2 during $D_2$, delivers power to Port #3 during $D_3$, and delivers power to Port #4 during $D_4$. The time-sharing period is $T_m$, which is much longer than the switching period $T_s$. $D_2-D_4$ are the time-sharing ratios and $D_2 + D_3 + D_4 \leq 1$. The instantaneous power delivered in $D_2-D_4$ may or may not be the same. With time-sharing control, the average port power in one switching cycle when the port is activated is:

$$P_i = \frac{V_i V_i \Phi_i (\pi - |\Phi_i|)}{2\pi^2 f_s N_1 N_i (L_i' + L_i')}.$$ (5)

The average port power in one time-sharing period is:

$$\langle P_i \rangle_{T_m} = D_i P_i = D_i \frac{V_i V_i \Phi_i (\pi - |\Phi_i|)}{2\pi^2 f_s N_1 N_i (L_i' + L_i')}.$$ (6)

Fixing all phase angles and use the time-sharing duty cycle as the only control variables, the transfer function from the time-sharing duty ratio to the port voltage is:

$$\hat{v}_i = \frac{V_i V_i \Phi_i (\pi - |\Phi_i|)}{2\pi^2 f_s N_1 N_i (L_i' + L_i')} \frac{R_i}{sR_i C_i + \frac{1}{G_{di di}}} \hat{d}_i = G_{di di} \hat{d}_i.$$ (7)

Time-sharing control decouples the sophisticated power flow in a MAB system and greatly simplifies the control. The duty ratios of each period should be closely monitored to avoid operation overlapping. In fact, time-sharing control modulates the port voltage and power by adjusting the number of power pulses in one control period, which is similar to the Discrete Pulse Modulation (DPM) concept in dc-dc or grid-interface power converters.

Similiary to burst-mode control, time-sharing control can be used to improve the efficiency of a MAB converter operating in light load. On the other hand, the maximum power rating of time-sharing control is usually limited by the time-sharing duty ratio. Time-sharing control also requires larger filtering capacitors at the ports. The discontinuous operation of the transformer may also make audible noise if the time-sharing modulation frequency locates in the audible range.

IV. HYBRID PHASE-SHIFT TIME-SHARING CONTROL

There is a fundamental tradeoff between time-sharing control and phase-shift control: time-sharing control decouples the complex power flow and is easy to implement, but the device stress and voltage ripple are usually higher; phase-shift control is sophisticated with cross-coupled power flow, but the power conversion stress and energy storage requirements are usually lower. To leverage the advantages of the two power flow methods, we explore the possibility of merging the two power flow control methods to create mutual advantages.

We use the following example to explain the principles of hybrid phase-shift time-sharing control. The MAB system is delivering power from Port #1 to Port #2–#4. $D_3$ and $D_4$ are modulated by time-sharing control with fixed phases $\Phi_3$ and $\Phi_4$. $D_2$ is set to be exactly $1 - D_3 - D_4$, and $\Phi_2$ is determined by phase-shift control. The small signal model linking the phase of Port #2, $\phi_2$ and the port ac voltage, $v_2$, is:

$$\hat{v}_2 = \frac{V_1 (\pi - 2|\Phi_2|)}{2\pi^2 f_s N_1 N_2 (L_1' + L_2')} \frac{R_2}{sR_2 C_2 + 1} D_2 \phi_2.$$ (8)

The voltage control loops of the three output ports are all decoupled with hybrid phase-shift time-sharing control. Hybrid phase-shift time-sharing control reduces the instantaneous power of Port #1 and Port #2 during $D_2$ due to the extended operating period. The efficiencies of Port #1 and Port #2 are higher than phase-shift control, but not higher than time-sharing control. The efficiencies of Port #3 and Port #2 maintain the same. The low frequency voltage ripple of Port #2 is usually smaller than its voltage ripple with time-sharing control due to smaller energy buffering requirement on the filter capacitors. That audible noise also disappears because the transformer operates continuously in one time-sharing modulation cycle.

Fig. 7. Split power point tracking of MAB converters. This diagram shows a SPPT tracking algorithm to modulate the phase of Port #2 while keeping the phases of all other ports fixed.

Fig. 8. Time-sharing control of the 4-port MAB converter. Port #1 is an input port and Port #2-4 are output ports.
maximum flux density in the core, of the transformer is 80:10:3:1. If all ports are in phase, the rated power for Port #1–Port #4 are 400 W, 300 W, 150 W, and 75 W, respectively. The turn ratio of this prototype. The rated power for Port #1–Port #4 are 400 W, 300 W, 150 W, and 75 W, respectively. The turn ratio of this prototype. Table I lists the design details of this prototype. Port #1 Switches GS66508T 650 V/30 A/50 mΩ Port #2–#4 Switches GS61008P 100 V/90 A/7 mΩ Transformer Ferroxcube E38/8/25, 3F36: 80:10:3:1, 4×4-layer PCB Leakage Inductance: $L_{i1k1} - L_{i4k4}$, all measured at each port. The magnetizing inductance is 39.08 mH referred to Port #1. The maximum power that Port #1 can carry is:

$$B_{\text{max}} = \frac{V_i T_s}{4 N_1 A_e}. \quad (9)$$

Here $A_e$ is the effective area of the core, $T_s$ is the switching period, and $V_i/N_1$ is the voltage per turn. The PCB transformer is implemented as a E38/8/25 core with 3F36 material. $B_{\text{max}}$ is 64.4 mT at 100 kHz. The transformer windings are implemented as four vertically stacked 4-layer PCBs. The leakage inductance $L_{i1k1}-L_{i4k4}$ are 18.2 $\mu$H, 0.81 $\mu$H, 84.1 nH, 26.4 nH, all measured at each port. The magnetizing inductance is 39.08 mH referred to Port #1. The maximum power that Port #1 can carry is:

$$P_{\text{max}} = \frac{V_i}{8 f_s N_1} \sum_{j \neq i} \frac{V_j}{N_j L_{ij}} \approx \frac{V_o^2}{8 f_s} \sum_{j \neq i} \frac{1}{L_{ij}}. \quad (10)$$

Here $V_o$ is the voltage per turn, $f_s$ is the switching frequency. $V_o$, $f_s$, and $L_{ij}$ should be carefully selected such that all ports provide 12V-48V voltage rails to home appliances. As shown in Fig. 9, the MAB converter interface with a roof-top PV system at 400V, with a battery energy storage system at 48V, and provide 12V-48V voltage rails to home appliances. Fig. 10 shows a picture of this prototype. The prototype of 4-port MAB converter has been built and tested for dc power delivery in smart homes. As shown in Fig. 9, the MAB converter interface with a roof-top PV system at 400V, with a battery energy storage system at 48V, and provide 12V-48V voltage rails to home appliances. Fig. 10 shows a picture of this prototype. Table I lists the design details of this prototype. Port #1 Switches GS66508T 650 V/30 A/50 mΩ Port #2–#4 Switches GS61008P 100 V/90 A/7 mΩ Transformer Ferroxcube E38/8/25, 3F36: 80:10:3:1, 4×4-layer PCB Leakage Inductance: $L_{i1k1} - L_{i4k4}$, all measured at each port. The magnetizing inductance is 39.08 mH referred to Port #1. The maximum power that Port #1 can carry is:

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Here $V_o$ is the voltage per turn, $f_s$ is the switching frequency. $V_o$, $f_s$, and $L_{ij}$ should be carefully selected such that all ports can carry sufficient power. The MAB converter is controlled by a microcontroller (TI F28069 DSP).

The size of the filtering capacitor at each port is determined by the time-sharing control. The bus voltage ripple of each port in time-sharing control is:

$$\Delta v_i = \frac{P_i D_i (1 - D_i) T_m}{C_i V_i} \leq \frac{P_i T_m}{4 C_i V_i}. \quad (11)$$

Here $V_i$ is the port voltage and $T_m$ is the time-sharing period. With the parameters listed in Table I, for a time-sharing frequency of 1 kHz, the maximum voltage ripple ratio from Port #1 to Port #4 is 0.52%, 1.63%, 0.83%, and 1.875%, respectively.

V. PROTOTYPE DESIGN

A prototype of 4-port MAB converter has been built and tested for dc power delivery in smart homes. As shown in Fig. 9, the MAB converter interface with a roof-top PV system at 400V, with a battery energy storage system at 48V, and provide 12V-48V voltage rails to home appliances. Fig. 10 shows a picture of this prototype. Table I lists the design details of this prototype. The prototype of 4-port MAB converter has been built and tested for dc power delivery in smart homes. As shown in Fig. 9, the MAB converter interface with a roof-top PV system at 400V, with a battery energy storage system at 48V, and provide 12V-48V voltage rails to home appliances. Fig. 10 shows a picture of this prototype. Table I lists the design details of this prototype. Port #1 Switches GS66508T 650 V/30 A/50 mΩ Port #2–#4 Switches GS61008P 100 V/90 A/7 mΩ Transformer Ferroxcube E38/8/25, 3F36: 80:10:3:1, 4×4-layer PCB Leakage Inductance: $L_{i1k1} - L_{i4k4}$, all measured at each port. The magnetizing inductance is 39.08 mH referred to Port #1. The maximum power that Port #1 can carry is:

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VI. SMALL SIGNAL STABILITY ANALYSIS

With phase-shift control, based on Fig. 6 and (4), the small signal loop gain of the port voltage is:

$$G_{PSi}(s) = H_i(s) G_d(s) G_{\phi vi}(s). \quad (12)$$

Here $H_i(s)$ is the transfer function of the voltage sampling circuit and $G_d(s)$ is the delay of the digital control circuitry. Fig. 11 shows the Bode plot of $G_{PSi}(s)$. The phase-shift difference in $G_{\phi vi2j}(s)$ is set as zero (no perturbation from other ports). The bandwidth of the original loop transfer function is 320 Hz with a phase margin of 26.4°. Fig. 11 shows the Bode plot of PI controller $G_{PI2}(s)$, with which the phase margin is improved to 84° and the bandwidth is decreased to 13.2 Hz.

With time-sharing control, based on (7), the small signal loop gain of the port voltage is:

$$G_{TSi}(s) = H_i(s) G_d(s) G_{dvi}(s). \quad (13)$$

Fig. 12 shows the Bode plot of Port #3 with time-sharing control. With a PI controller the bandwidth of the loop transfer function decreases from 650 Hz to 49 Hz while the phase margin increases from 14.2° to 66.8°.

With hybrid control, the voltage of Port #2 is still controlled by the phase-shift angle and its loop gain function is similar to (12). Comparing (4) with (8), we can find that the only
difference is the loop gain. The same PI controller is applied to Port #2 with both phase-shift control and hybrid control. As expected, the bandwidth and phase margin in both mode are almost the same with the two control methods.

VII. EXPERIMENTAL RESULTS

The performance of the MAB prototype is measured across a variety of operating conditions. Fig. 13 shows the waveforms of ac input voltage of the 400V winding $V_{#1}$ and the branch inductance current $I_{L1} - I_{L4}$ with phase-shift control. Fig. 14 shows the phase-shift angle of each port. Port #2–Port #4 achieved zero-voltage-switching (ZVS) at this operating point.

Fig. 15 show the measured waveform of the system with two input ports and two output ports. Fig. 16 shows the transient waveform with a step change in the power dividing ratio. The phase of each port is updated every 10 ms. Current spikes are observed on the waveform of $I_{L1}$ in Fig. 15 due to hard-switching of the 400V port switches.

Two example cases of time-sharing control and hybrid control with a control cycle of 1 ms are presented in Fig. 17. The instantaneous power of Port #2–Port #4 with time-sharing control is 100 W, 100 W, 50 W respectively. The time-sharing duty ratio of Port #2–Port #4 can be found in the branch current waveforms, which is close to 60%, 10% and 20%. With hybrid control, the duty ratio of Port #2 is 70% and instantaneous power is approximately 85.7 W.
Fig. 15. Waveforms with phase-shift control: 400V input at 80W, 48V input at 40W, 15V output at 80W, 5V output at 40W.

Fig. 16. Input power regulation with phase-shift control: 400V input change between 20W and 100W, 48V input change between 100W and 20W, 15V output at 75W, 5V output at 45W.

Fig. 17. Time-sharing and Hybrid control: 400V input, 48V output at 60W, 15V output at 10W, 5V output at 10W, control cycle is 1ms.

Fig. 18. Efficiency curves of 400V input DAB operation.

Fig. 19. Efficiency curves of 400V input MAB with phase-shift control.

Fig. 20 shows measured efficiency with the average power $P_2$ changes from 10 W to 300 W, and the average power of $P_3$ and $P_4$ both at 10W. Time-sharing control improves the optimal power for time-sharing control. The efficiency of 400V-48V operation with time-sharing control in light load is also shown in Fig. 18, which is much higher than the efficiency with phase-shift control.

Fig. 19 shows the efficiency of the system with Port #1 as the input and Port #2–#4 as the output, all together. All ports are modulated with phase-shift control. The peak efficiency of the seven groups of test is 97.1% with 400V as the input and delivers 110W to 48V, 50W to 15V and 25W to 5V. The efficiency of the system drops significantly at light load.

Two instantaneous power cases are tested for time sharing control. Case 1 is [110 W, 140 W, 60 W] and Case 2 is [100 W, 100 W, 50 W] for Port #2–Port #4. Same instantaneous power setting is used in hybrid control for Port #3 and Port #4. Fig. 20 shows measured efficiency with the average power $P_2$ changes from 10 W to 300 W, and the average power of $P_3$ and $P_4$ both at 10W. Time-sharing control improves the

Fig. 18 shows the efficiency of the system with Port #1 as the input and Port #2–#4 as the output, individually one-at-a-time. The system operates as a DAB converter with one input and one output. The peak efficiency of 400 V–48 V operation is 98%. The peak efficiency of 400 V–15 V operation is 92%. The peak efficiency of 400 V–5 V operation is about 70%. The measured efficiency with DAB operation is used to select
device utilization ratio and higher voltage ripple; and the hybrid control can merge the advantage of the two methods and create mutual advantages. The small signal behaviors of the three control strategies are investigated in detail. The effectiveness of the three power flow control methods are verified by a 4-port MAB converter prototype.

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