Efficient and scalable power control in multi-port active-bridge converters

Soleiman Galeshi, David Frey, Yves Lembeye

► To cite this version:

Soleiman Galeshi, David Frey, Yves Lembeye. Efficient and scalable power control in multi-port active-bridge converters. The 22nd European Conference on Power Electronics and Applications EPE'20 ECCE Europe, Sep 2020, Lyon, France. 10.23919/EPE20ECCEEurope43536.2020.9215905 . hal-03145571

HAL Id: hal-03145571

<https://hal.science/hal-03145571>

Submitted on 18 Feb 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Efficient and scalable power control in multi-port active-bridge converters

Soleiman Galeshi, David Frey, Yves Lembeye
UNIV. GRENOBLE ALPES, CNRS, GRENOBLE INP*, G2ELAB
21 avenue des Martyrs, 38031
Grenoble, France
Tel.: +33 (0)4 76 82 62 99
E-Mail: soleiman.galeshi-mooziraji@g2elab.grenoble-inp.fr
URL: <http://g2elab.grenoble-inp.fr>

Acknowledgements

This work has been partially supported by the CDP Eco-SESA receiving fund from the French National Research Agency in the framework of the "Investissements d'avenir" program (ANR-15-IDEX-02). The authors also thank the Carnot Institute Energies du Futur for supporting this work.

Keywords

«Converter control», «Modelling», «Estimation technique», «Power converters for EV», «Scalable control».

Abstract

Application of multi-port active-bridge converters is constantly increasing due to their advantages such as bidirectional power transfer, high efficiency, and intrinsic electrical isolation. However, controlling the flow of power in these converters becomes more and more complex as the number of ports increases. Power flow in a multi-port active-bridge converter is controlled through phase shifts and duty cycles. Analytical and Numerical methods, when suitable, often require huge amounts of processing and memory resources for real-time control of the power in converters with three or more ports. This work proposes a method that is computational cost efficient and can be employed for real-time control purposes. It is scalable and can be applied to any number of ports. Simulation and experimental results are provided to validate correct operation of the proposed method.

Introduction

Application of multi-port active-bridge converter (MAB) in energy systems is increasing due to several advantages of this type of converters. The multi-port transformer in MAB provides galvanic isolation and voltage level compatibility. Soft switching of active-bridges allows for increasing the switching frequency and reducing the size of magnetic components. Another advantage is that MAB converters exchange energy between several sources and loads at the same time through the same medium, which is the magnetic core of the transformer. Many researches and experiments have been done on application of triple port active-bridge converter (TAB) [1,2]. Quad-active-bridge converters (QAB) have also been studied and designed for several applications such as interfacing three-phase and dc networks [3,4], electric vehicles [5,6], and micro-grids [7,8]. Two main challenges of MAB converters are the complexity of their design and the associated control. As the number of ports increases, control and design parameters increase as fast and power transfer equations become more and more complex. Considering the complex calculations and high number of parameters in control and switching of a MAB, closed-form analytical solutions become almost impossible to find. Therefore, numerical optimization methods are required to find the optimum possible solution for each power flow. The problem is that not only numerical optimizations take a long time to find a solution, but also, it is not possible to implement them on industrial control chips with limited processing power and memory. Some researches consider special constraints or scenarios that lead to direct solution of the power flow problem [3]. Although they manage to efficiently solve the problem, they still miss the

ability to put forward a general control scheme for MAB. Other works employ voltage or current feed-back loops to adjust the phase shifts of each active bridge [5,6]. Employing feed-back loops alone, brings about challenges such as stability issues and the need for correct adjustment of speed and accuracy. Another problem is that large dynamics may occur in those systems, because the flow of power between every two ports are intertwined and the feed-back control loops could affect each other.

Considering the above-mentioned challenges in control of a MAB, this work seeks to propose a method that has acceptable accuracy and dynamic behavior in finding an optimum operating point, while being compatible with limited resources of an industrial control target and assuring stability.

Power flow problem in MAB converters

A multi-port converter, whatever its application is, connects several generators and consumers of energy in one place. The role of the converter is to flow power between its different ports, i.e., the generators and the consumers, with a certain direction and amount. Energy system of a smart building, as a common application of multi-port converters, includes several resources such as photovoltaic panels, wind turbines, storage devices, and several consumers on ac and dc networks [8]. There is a higher-level controller in these systems, which takes into account several inputs (such as solar irradiance, wind speed, state of charge of the batteries, instantaneous demand, and electricity tariffs), and based on predefined strategies, determines how the power must flow in the energy system. The power flow indicates how much power should be fed to or drawn from each port and the converter is responsible for its realization.

The power flow between ports of a MAB can be controlled through applying phase shifts between switching of different legs. Two types of phase shifts can be defined in an active-bridge converter: internal phase shift, which is the phase shift between switching of two legs of a single active-bridge; and external phase shift, which is the phase shift between first harmonics of output voltages of two active-bridges. Fig. 1 shows internal and external phase shifts in a dual-active-bridge converter (DAB). It can be concluded that the control system has two domains of freedom for realization of the desired power flow: internal phase shifts, and external phase shifts. In this study, square-wave voltages (Fig. 2-a) are approximated by their first harmonics, and represented by phasors (Fig. 2-b). Magnitudes of first harmonics of output voltages are controlled through adjusting the internal phase shifts, so they can be considered equivalent to internal phase shifts. In this regard, solving the power flow problem means determining a set of magnitudes (internal phase shifts) of voltage phasors and angles between them (external phase shifts) for of every port, which corresponds to the desired power flow.

Fig. 1: internal and external phase shifts in switching of a DAB. Switches on the same arm are switched complementarily.

Fig. 2: voltages and phase shifts in a quad-active-bridge converter: (a) output voltages of active bridges; (b) phasor-space representation.

Using modular matrixes to solve power flow problem

As explained in the previous section, power flow controller must determine magnitude of voltage phasors of every port and the phase difference between them. In an active bridge converter with n active bridges, there are n magnitudes and $n-1$ phase shifts (one phasor is considered as phase reference) to be determined. Complexity of the power flow problem increases quickly with the number of ports, and there is no direct analytical solution for more than two ports. This work proposes a modular method of solving power flow problem in MAB with any number of ports. Application of modular matrixes for solving power flow problem of a MAB was previously presented in [9] for a special structure of MAB. The current paper presents the solution for a general structure.

A QAB based on general MAB structure is displayed in Fig. 3-a. The first step to determine power transfer is to distribute the inductors between ports. The star-delta transform illustrated in Fig. 3-b is employed to do this. This transform can be generalized for n ports, as

$$L_{i,j} = L_i L_j \sum_{k=1}^n \left(\frac{1}{L_k} \right) \quad (1)$$

It is calculated based on superposition theorem. For example, L_{12} in Fig. 3-b would be

$$L_{1,2} = \frac{L_1 L_2 L_3 + L_1 L_2 L_4 + L_1 L_3 L_4 + L_2 L_3 L_4}{L_1 L_2 L_3 L_4} L_1 L_2 = \frac{L_1 L_2 L_3 + L_1 L_2 L_4 + L_1 L_3 L_4 + L_2 L_3 L_4}{L_3 L_4} \quad (2)$$

Through generalizing power transfer of DAB for a MAB with n ports, the power output of port k would be

$$P_k = \frac{V_1 \cdot V_k}{L_{1,k} \cdot \omega} \cdot \sin(\varphi_1 - \varphi_k) + \frac{V_2 \cdot V_k}{L_{2,k} \cdot \omega} \cdot \sin(\varphi_2 - \varphi_k) + \dots + \frac{V_n \cdot V_k}{L_{n,k} \cdot \omega} \cdot \sin(\varphi_n - \varphi_k) \quad (3)$$

where, V_k and φ_k are magnitude and phase of first harmonic voltage phasor of port k , respectively; and ω is the angular frequency, $2\pi f$, f being the switching frequency. The equation for power transfer can be simplified using approximate assumption of $\sin(\varphi) = \varphi$ as

$$P_k = \frac{V_1 \cdot V_k}{L_{1,k} \cdot \omega} (\varphi_1 - \varphi_k) + \frac{V_2 \cdot V_k}{L_{2,k} \cdot \omega} (\varphi_2 - \varphi_k) + \dots + \frac{V_n \cdot V_k}{L_{n,k} \cdot \omega} (\varphi_n - \varphi_k) \quad (4)$$

Fig. 3: a quad-active-bridge converter: (a) the structure, with a four-port transformer (the red box), four active bridges (green box), and four inductors (blue box); (b) ac representation and star-delta transform.

Maximum power each port can transfer, P_{max} (the maximum value for power transfer when $\sin(\varphi) = 1$), is an important factor in design of MAB and depends inversely on the size of the inductors [10]. If inductors are large, i.e., P_{max} is relatively small, the instantaneous transferred power might often get close to P_{max} and current magnitudes will increase nonlinearly, leading to large losses. Choosing a very small inductor, on the other hand, has its own challenges such as sharp changes in current waveform, higher voltages across the transformer windings, and limited range of soft switching. Considering this trade-off, active-bridge converters are usually designed in a way that their nominal power transfer is around 60% of P_{max} [10]. Under this design condition, the phase shift between the ports will be in the range of ± 37 degrees, and assumption of $\sin(\varphi) = \varphi$ in (4) will have maximum 7.3% error, which is acceptable. Rearranging (4) gives

$$P_k = \frac{V_1 \cdot V_k}{L_{1,k} \cdot \omega} \cdot (\varphi_1) + \frac{V_2 \cdot V_k}{L_{2,k} \cdot \omega} \cdot (\varphi_2) + \dots + \frac{V_k \cdot V_k}{L_{k,k} \cdot \omega} \cdot (\varphi_k) \dots + \frac{V_n \cdot V_k}{L_{n,k} \cdot \omega} \cdot (\varphi_n) - \frac{V_k \varphi_k}{\omega} \sum_{i=1}^n \frac{V_i}{L_{n,i}} \quad (5)$$

where, $L_{k,k}$ does not have a real representation and is only added for keeping symmetry in the equation. It will be omitted from calculations in each line of the final matrix. All the power equations can be put into one matrix equation as (6).

$$\omega \begin{bmatrix} P_1 \\ P_2 \\ \dots \\ P_n \end{bmatrix} = \begin{bmatrix} \frac{V_1 \cdot V_1}{L_{1,1}} - V_1 \sum_{i=1}^n \frac{V_i}{L_{1,i}} & \frac{V_1 \cdot V_2}{L_{1,2}} & \dots & \frac{V_1 \cdot V_n}{L_{1,n}} \\ \frac{V_2 \cdot V_1}{L_{2,1}} & \frac{V_2 \cdot V_2}{L_{2,2}} - V_2 \sum_{i=1}^n \frac{V_i}{L_{2,i}} & \dots & \frac{V_2 \cdot V_n}{L_{2,n}} \\ \dots & \dots & \dots & \dots \\ \frac{V_n \cdot V_1}{L_{n,1}} & \frac{V_n \cdot V_2}{L_{n,2}} & \dots & \frac{V_n \cdot V_n}{L_{n,n}} - V_n \sum_{i=1}^n \frac{V_i}{L_{n,i}} \end{bmatrix} \times \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \dots \\ \varphi_n \end{bmatrix} \quad (6)$$

The matrix of coefficients in (6) may not be reversible under some conditions; for instance, when all inductances and voltage magnitudes are equal. In order to modify this matrix and make it reversible, V_1 can be considered as the reference for phase; therefore, φ_1 will be zero. The first column of the matrix of coefficients can be omitted without changing the outcome, because all of its elements will be multiplied by φ_1 , which is zero. Additionally, the last row can be omitted because P_n can be determined as $P_n = -\sum_{i=1}^{n-1} P_i$, based on conservation of power. The final equation would be

$$\omega \begin{bmatrix} P_1 \\ P_2 \\ \dots \\ P_{n-1} \end{bmatrix} = \begin{bmatrix} \frac{V_1 \cdot V_2}{L_{1,2}} & \frac{V_1 \cdot V_3}{L_{1,3}} & \dots & \frac{V_1 \cdot V_n}{L_{1,n}} \\ \frac{V_2 \cdot V_2}{L_{2,2}} - V_2 \sum_{i=1}^n \frac{V_i}{L_{2,i}} & \frac{V_2 \cdot V_3}{L_{2,3}} & \dots & \frac{V_2 \cdot V_n}{L_{2,n}} \\ \dots & \dots & \dots & \dots \\ \frac{V_{n-1} \cdot V_2}{L_{n-1,2}} & \frac{V_{n-1} \cdot V_3}{L_{n-1,3}} & \dots & \frac{V_{n-1} \cdot V_n}{L_{n-1,n}} \end{bmatrix} \begin{bmatrix} \varphi_2 \\ \varphi_3 \\ \dots \\ \varphi_n \end{bmatrix} \quad (7)$$

It is now possible to determine phase shifts as

$$\begin{bmatrix} \varphi_2 \\ \varphi_3 \\ \vdots \\ \varphi_n \end{bmatrix} = \omega[A]^{-1} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_{n-1} \end{bmatrix} \quad (8)$$

where, $[A]$ is the matrix of coefficients in (7). Equation (8) gives an approximate solution for the power flow problem, i.e., given a desired value of power transfer on each port, (8) can determine a set of phase shifts that if applied to switching of the active bridges, leads approximately to the desired power flow. It should be noted that voltage magnitudes (internal phase shifts) have to be determined before this step. This is usually done by another part of the converter control scheme, whose task is to maintain soft switching conditions. Depending on the variations in dc link voltages and the amount of power on each port, the soft switching control determines the internal phase shifts, and the method proposed in this work uses them for its calculations.

Simulation and experimental results

Fig. 4 shows simulation results of open-loop control of power flow in a QAB. The thick lines are the reference values of powers, changing at 0.2 ms and 0.4 ms moments, and thin lines represent the actual measured powers. The actual powers follow the changes in reference values but with some steady state error. The coupling of powers can be seen on the second port at 0.2 ms and 0.4 ms, where its reference value ($P2^*$) does not change but the actual power ($P2$) varies. The steady state errors, that are large in some cases, are due to the approximations in the control scheme, the fact that the control is open-loop, and the losses that were not considered in the calculations.

Fig. 4: performance of the proposed power controller when in a QAB. Thick lines show the reference values, and thin lines show actual powers.

Fig. 5 shows the lab-scale prototype that was used to validate the proposed control system experimentally. The details of the converter are provided in Table I. Several experimental tests were performed to validate correct operation of the proposed method. Closed-loop control scheme with PI controllers was employed to validate effective elimination of steady state errors. It should be noted that the reference values of the power sum up to zero due to conservation of power, ignoring the losses in the converter. In other words, it not possible to have all the actual powers equal to their reference value. Therefore, control of one port is always open-loop to allow it to provide the losses.

Fig. 6 shows experimental results. The open-loop results show that the proposed power controller is able to realize the desired power but with some steady state error. The closed-loop results show that the steady state error can be effectively eliminated using PI feedback loops. Due to the limited number of input ports of the oscilloscope and analog outputs of the controller, it was not possible to capture and show all the powers. Measurement of powers on the other ports also showed effective elimination of steady state error, similar to that of the second port in Fig. 6.

Fig. 5: The quad active-bridge converter that was built in G2ELab for experimental validation of the proposed power control method. The black boxes, numbered 1 and 2, indicate the controller and signal conditioning circuit, respectively. The green and the blue boxes indicate four active bridges and inductors, respectively. The red box is a four-winding transformer. Colors of the boxes correspond to the ones in Fig. 3-a.

Table I: Details of the prototype converter

Parameter	Value
Maximum DC voltage	40 V
Nominal power	250W each port
External inductors	10 μ H
Transformer turns	7:7:7:7
Switching frequency	40 kHz

Fig. 6: experimental results of power control in a quad active-bridge converter: (a) open-loop results; (b) closed-loop results. The first port (P1) is always open-loop, to be able to provide the losses. The rest are closed-loop, including P2 that is shown here. Due to the limited number of available analog outputs of the controller and inputs on the oscilloscope, the reference and measured powers of the third and fourth port are not shown.

Performance of the proposed method

An iterative method of solving the problem is presented in [11]. It begins with finding a first approximate solution by assuming the currents to be zero. The solution found this way could be far from the correct solution, but through performing some iterative calculations and updating magnitudes of the current, this method can get very close to the desired power flow. The method presented in [11] and the method presented in this work do the same task: given the desired power flow and voltage

magnitudes as inputs, these methods determine a set of phase shifts that, if applied as external phase shifts between switching of the active bridges, will correspond to the desired power flow. The major difference between these methods is the approximations they use for solving the problem. These two methods will be compared in terms of accuracy of their final solution and amount of calculations they require on a controller chip.

Since the reference control signal is the power transfer of each port, a good parameter for comparison of accuracy is the average difference between the desired power transfer and the one measured after applying the phase shifts. Fig. 7 shows the defined error of consecutive iterations of the method proposed in [11] (labeled as “zero currents”), and the error from the method proposed in the current work (Labeled as “matrix”). The “zero currents” method starts with a large error in its first guess, but quickly reduces the error after an additional iteration. The “matrix” method leads to a smaller error, but does not include a mechanism to minimize it. It is noticeable that the error of the proposed method is larger when powers are higher (Fig. 7-a) compared to lower powers (Fig. 7-b). This is due to the $\sin(\varphi) = \varphi$ approximation that is used in this method. The phase shifts increase as the powers increase and the difference between $\sin(\varphi)$ and φ becomes larger, reaching up to around 7% at the nominal power, where φ is around 37 degrees. Fig. 7 also shows that two iterations of the “zero currents” method is enough for reaching negligible errors.

Fig. 7: Comparing convergence of different power control methods in a simulated 2 kW quad active-bridge converter: (a) ideal converter with all powers and voltage at their nominal values; (b) non-ideal converter with $\pm 10\%$ voltage variation.

It should be noted that a feedback PI controller is usually present in control systems that depend on models, such as the one presented in this work. The main goal of using a PI feedback is to eliminate the steady state errors that occur due to the mismatch between the values in the model and the real system. This feedback loop can be counted upon for eliminating the steady state error caused by the approximation of the proposed method, too. Performance of the proposed method with a closed-loop control was illustrated in Fig. 6-b. In this regard, the steady state errors of the proposed method, although larger than those of the “zero currents” method, are within acceptable range and can be eliminated using a feedback loop.

The second comparison is the amount of calculations involved with each method. The final goal of designing a MAB is to build and use it in a real energy system. The control system for this converter should be able to work with limited resources of low-end controller chips used in industrial products. In this regard, it is important to assess performance of the presented methods on a controller and validate that they run correctly. NI myRIO 1900 package, with a 40MHz processor and a Xilinx Z-7010 chip, was used as the controller. Both methods were implemented on the target chip and run on its processor. Fig. 8 illustrates the results. The time required to do the calculations of the proposed method is 4 μs , compared to 127 μs for two iterations of the “zero currents” method of [11]. Considering the overhead processing time of 18 μs , the total runtime would be 22 μs for the proposed

method, compared to 145 μs for two iterations of “zero currents”. The comparison shows that the proposed method is computational cost efficient and a good candidate for real-time control and optimization purposes.

Fig. 8: comparing the time needed to run the proposed method and the method presented in [11]. The first section on the left corresponds to runtime of an empty program and indicates the overhead processing time, which is 18 μs . The second section corresponds to the proposed method, which requires 4 μs to run plus the additional 18 μs overhead processing time. The third and the fourth sections indicate the runtime of the method presented in [11] for one and two iterations, respectively. The total time required for running two iterations is 145 μs .

Conclusions

A modular method is proposed in this paper for control of power flow in multi-port active-bridge converters. Application of these types of converters is increasing, especially in energy systems based on renewable resources. These converters facilitate simultaneous exchange of energy between multiple resources and loads, with lower costs, smaller size, good efficiency, and isolation. The challenge of these converters is their control, which becomes more and more complex when number of their ports increases. The proposed method solves the power flow control problem using an approximate mathematical model of the converter. Compared to a method previously presented, this method has a larger, yet acceptable error due to its approximation. The proposed method acts as a feed-forward loop and it was shown with experimental results that in combination with a feed-back loop, it can effectively control the power flow with no steady state errors. This method requires less mathematical calculations and runs about 7 times faster, compared to a previously proposed method in the literature. This fact makes it applicable for industrial control systems with limited processing resources. Several simulation and experimental results are presented to validate correct performance of the method.

References

- [1] N. Delmonte, P. Cova, D. Santoro, A. Toscani and G. Buticchi: Development of a GaN Based Triple-Active-Bridge for DC Nanogrid, 2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe), Riga, 2018.
- [2] K. Katagiri, K. Nishimoto, S. Nakagawa, S. Okutani, Y. Kado and K. Wada: Decoupling Power Flow Control of Triple-Active Bridge Converter with Voltage Difference between Each Port for Distributed Power Supply System, 2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe), Riga, 2018.
- [3] L. F. Costa, G. Buticchi and M. Liserre: Quad-Active-Bridge DC–DC Converter as Cross-Link for Medium-Voltage Modular Inverters, IEEE Transactions on Industry Applications, vol. 53, no. 2, pp. 1243-1253, March-April 2017.
- [4] B. J. D. Vermulst, J. L. Duarte, C. G. E. Wijnands and E. A. Lomonova: Quad-Active-Bridge Single-Stage Bidirectional Three-Phase AC–DC Converter With Isolation: Introduction and Optimized Modulation, IEEE Transactions on Power Electronics, vol. 32, no. 4, pp. 2546-2557, April 2017.

- [5] A. Chandrasekharan Nair, M. J. Vishal and B. G. Fernandes: A Quad Active Bridge Based on-Board Power Electronic Interface for an Electric Vehicle, 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 5941-5947.
- [6] M. J. Vishal, A. C. Nair and B. G. Fernandes: Quad-Active-Bridge DC-DC Converter based on-board Power Electronic Interface for Electric Vehicle, 2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Chennai, India, 2018, pp. 1-6.
- [7] S. Falcones and R. Ayyanar: LQR control of a quad-active-bridge converter for renewable integration, 2016 IEEE Ecuador Technical Chapters Meeting (ETCM), Guayaquil, pp. 1-6.
- [8] S. Galeshi, D. Frey, Y. Lembeye and D. Motte-Michellon: Application of Clustered Multi-port Active-bridge Converters in Microgrids, 2019 21st European Conference on Power Electronics and Applications (EPE '19 ECCE Europe), Genova, Italy, 2019.
- [9] B. J. D. Vermulst, J. L. Duarte, E. A. Lomonova and K. G. E. Wijnands: Scalable multi-port active-bridge converters: modelling and optimised control, IET Power Electronics, vol. 10, no. 1, pp. 80-91, 2017.
- [10] S. Galeshi, D. Frey, and Y. Lembeye: Design Procedure of DC-DC Multi-Port Active-Bridge Converters, PCIM Europe conference, 2020, in press.
- [11] S. Galeshi, D. Frey, Y. Lembeye: Modular Modeling and Control of Power Flow in A Multi-Port Active-Bridge Converter, Symposium de Genie Electrique (SGE 2018), 3-5 Jul. 2018, Nancy, France.