

A Digital Robust Control Scheme for Dual Half-Bridge DC-DC Converters

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Abstract— This paper presents a digital control scheme used in the control system of a bi-directional Dual Half-Bridge (DHB) converter over a wide range of operating conditions (load variations, input voltage changes). The proposed control scheme is a nonlinear current controller, where it enforces the current error of the high frequency transformer to converge to zero in a geometric progression. It offers higher stability, improved transient performance and increased robustness compared to the conventional control methods in DHB converters. Moreover, the proposed control scheme is a simple structure technique, which is easy to implement on digital microprocessors (e.g. DSP, FPGA). Simulation and experimental results show the superior performance of the GSC compared to other conventional control techniques.

Keywords—Current control, DC-DC converter, Dual Half-Bridge, Phase-shift modulation, Power conversion.

I. INTRODUCTION

NOWADAYS, the use of bi-directional DC/DC converters is necessary to control the direction of the power flow for many electrical conversion applications. In this context, dual converters are suitable for Vehicle-to-Grid (V2G) applications, line interactive Uninterruptible Power Supply (UPS), Energy Storage Systems (ESSs), etc. [1]-[2]. In those applications, the converter plays a crucial role of managing the energy between the utility grid and the storage system (mainly batteries).

Figure 1 shows the typical control system of dual converters [3]. Parameters from the circuit (current, voltage and/or power) are measured, and delivered to a compensator. This component has an internal control algorithm, which provides to the modulator the four adjustable control parameters: phase-shift between the bridges, duty-cycles of each bridges, and switching frequency. Finally, the modulator provides the switching instants of each bridge based on the given control parameters.

In this paper, the analysis is focusing on a Dual Half-Bridge (DHB) converter [4]. This topology is used for low power applications, because it reduces the number of switching devices by half compared to the most known Dual Active Bridge (DAB). The DHB is further detailed in section II.

In this work, the power flow in DHB is controlled by phase-shift modulation (PSM) [5]-[6]. The principle of PSM is that the duty-cycles of the grid and battery sides are set to 0.5, and the frequency is kept constant. Therefore, the only adjustable parameter to control the power flow is the phase-shift.

The typical control technique for DHB converter is the PI regulator. Indeed, PI regulators work perfectly at a particular operating point, i.e. fixed load and constant input voltage. However, linear PI controllers result in slow transient response and marginal stability of DHB converters when operating over a wide range of running conditions, i.e. load variations and input voltage changes [7]. Thus, in this paper, the use of a novel Geometric-Sequence Control (GSC) approach, which was first introduced by the authors in [8]-[9], is enhanced for DHB converter. Using a non-linear digital current control scheme, the transformer's current error converge to zero in a few geometric-sequence iterations. Compared to other conventional control techniques, this GSC approach offers better efficiency, such as higher stability, improved transient performance and more robustness against system-model uncertainties, allowing the DHB to operate over a wide range of operating conditions.

This paper is organized as follows. In section II, the DHB topology and its phase-shift modulation are introduced. The GSC approach is described in section III and the simulation and experimental results are shown in section IV. Finally, section V concludes this work.

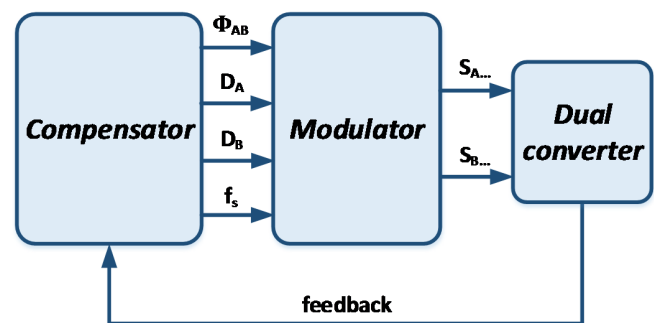


Fig. 1. Typical control system of dual converters

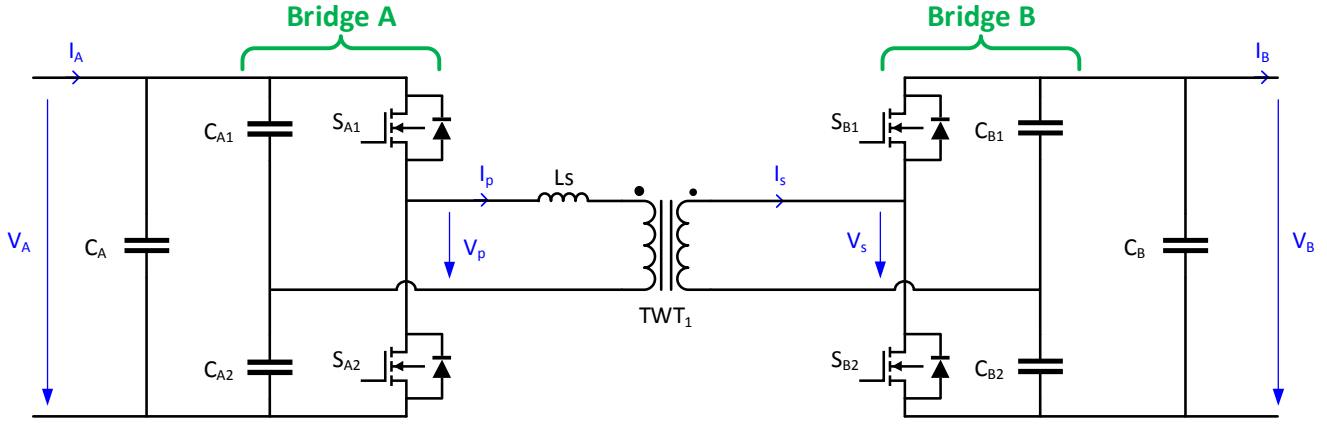


Fig. 2. Dual Half-Bridge (DHB) converter

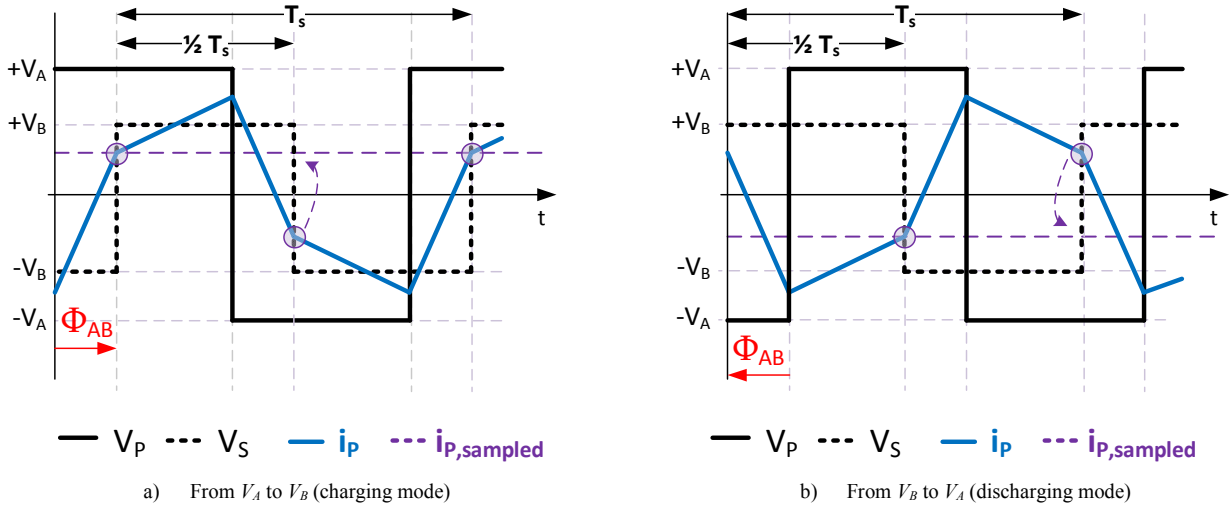


Fig. 3. Steady-state power flow in DHB converters

II. DUAL HALF-BRIDGE TOPOLOGY

A. Dual Half-Bridge

Figure 2 shows the topology of the DHB. For the following explanation, the power is considered flowing from the grid side (left) to the battery side (right). On the primary side, V_A represents the rectified grid voltage, which is inverted by the bridge A. The converted voltage V_p goes through the high-frequency transformer TWT_1 , and the secondary voltage V_s is obtained. Bridge B rectifies V_s in order to get the voltage battery V_B . If the power flows in the other direction, bridge A would work as a rectifier, while bridge B as an inverter. The passive components are listed hereafter:

- C_A is the dead-time capacitor, which works as a snubber capacitor during discharge;
- L_s is the leakage inductance of the transformer TWT_1 ;
- C_B is the energy storage capacitor;
- $C_{A1}, C_{A2}, C_{B1}, C_{B2}$ are the capacitors of the bridge A and B;
- $S_{A1}, S_{A2}, S_{B1}, S_{B2}$ are the switches of the bridge A and B (MOSFETs).

B. Phase-shift modulation

Conventionally, the power flow in DHB converters is controlled by phase-shift modulation, based on the phase-shift between the bridge A and B at fixed frequency and with both duty-cycles set to 0.5. The phase-shift Φ_{AB} is defined as the phase-shift of the bridge B relative to the phase-shift of the bridge A, i.e.:

$$\Phi_{AB} = \Phi_B - \Phi_A. \quad (1)$$

Figure 3 depicts the steady-state power flow of the DHB, based on the phase-shift Φ_{AB} . Thus, the operating mode is determined by the value of Φ_{AB} . If $0^\circ < \Phi_{AB} < 90^\circ$, the power will flow from V_A to V_B (charging mode). If $-90^\circ < \Phi_{AB} < 0^\circ$, the power will flow from V_B to V_A (discharging mode).

C. Sampling of the inductor current

According to Figure 3, the primary current of the transformer i_p , called inductor current, and the primary and secondary voltages of the transformer (V_p and V_s) are symmetric in each half-cycle ($\frac{1}{2}T_s$) if the phase-shift Φ_{AB} and the voltages V_A and V_B are constant. When it is the case, the converter operates in steady-state, and the inductor current i_p can be sampled ($i_{p,sampled}$) at a certain value. The sampling instants are chosen as

the beginning of each half-period (purple dots on Figure 3), i.e. when S_{B1} turns on resp. off, which corresponds to the instants when V_s reaches $+V_B$ resp. $-V_B$. This sampled current $i_{p,sampled}$ can be determined by the following equation:

$$i_{p,sampled} = \frac{1}{2L_s f_s} [(\Phi_{AB} - 0.5)kV_B + 0.5V_A] \quad (2)$$

where:

- L_s is the leakage inductance of the transformer,
- f_s is the switching frequency,
- Φ_{AB} is the phase-shift between the two bridges,
- k is the transformer turn's ratio,
- V_A, V_B are the DC-side voltages.

This sampled current $i_{p,sampled}$ is then used as feedback signal in the control system, which is explained in Section III.

III. PROPOSED CONTROL APPROACH

A. Global control system

As the goal of this application is to regulate the output current of the battery i_B , two cascaded loops are used for the control system. First, the outer control loop for i_B can be achieved by using any conventional regulator. Given that, the transient response of the output current i_B is limited by the value of the energy storage capacitor C_B , and the transient behavior of i_B could not be improved significantly by using an innovative control system. Thus, for this paper, a PI regulator has been chosen for the outer loop. Then, as shown in the previous section, the sampling of the inductor current i_p at every half-

cycle ($i_{p,sampled}$) is a good representation of the dynamic state of the converter. Therefore, the inner loop will affect the inductor current i_p , and it will be implemented with the Geometric-Sequence Control (GSC) approach. Figure 4 depicts the block diagram of the global control system, with the outer and inner loop.

The purpose of the inner loop is to determine the control variable, here the phase-shift Φ_{AB} , for every half-cycle interval $\frac{1}{2}T_s$, until the sampled current error Δi_p is zero. However, the phase-shift calculated from (2) cannot be changed directly in only one half-cycle because of a possible oscillatory behavior. Therefore, a suitable control approach like Geometric-Sequence Control is required in order to change the control variable between two steady-state operations without causing oscillation.

B. Control Scheme

The control variable Φ_{AB} at a certain half-cycle n can be determined by the following equation:

$$\Phi_{AB}(n) = \Phi_{AB}(n-1) + \Delta\Phi_{AB}(n-1) + \Delta\Phi_{AB}(n) \quad (3)$$

where:

- $\Phi_{AB}(n-1)$ is the previous phase-shift (one half-cycle before);
- $\Delta\Phi_{AB}(n-1)$ is the calculated difference to add to the previous phase-shift;
- $\Delta\Phi_{AB}(n)$ is the calculated difference to add to the actual phase-shift.

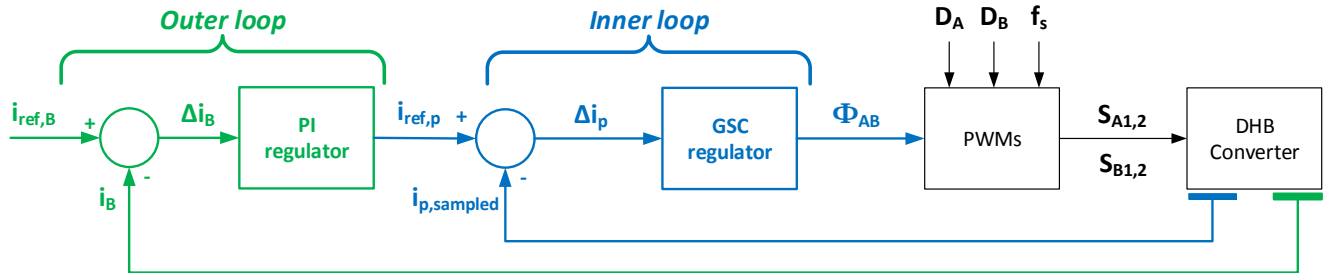


Fig. 4. Block diagram of the global control system with outer and inner loop

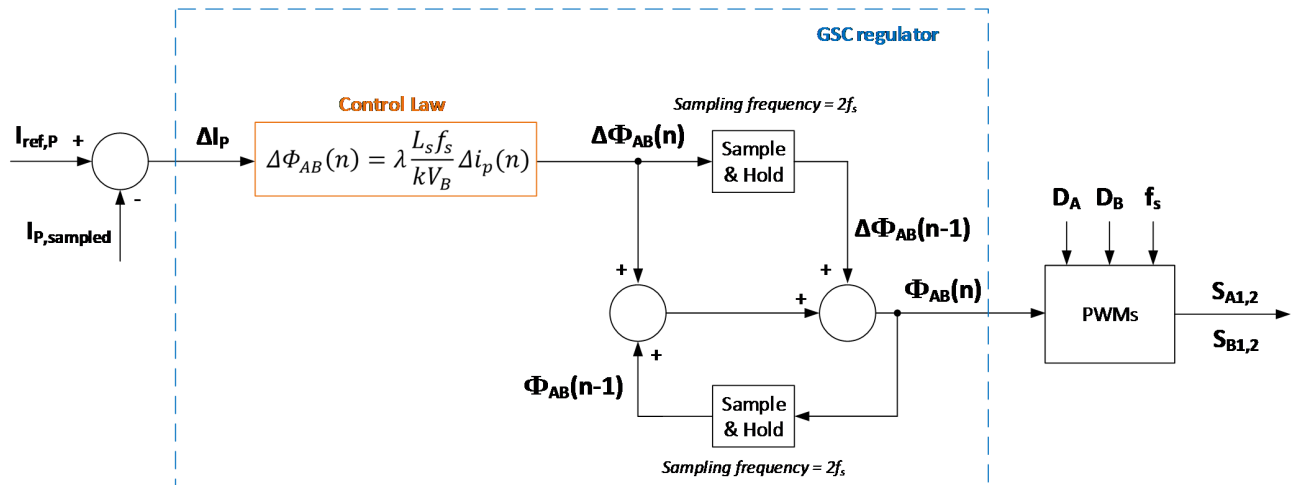


Fig. 5. Inner loop with the Geometric-Sequence Control (GSC) approach

The control signal $\Delta\Phi_{AB}(n)$ is related to the error signal $\Delta i_p(n)$ with the following linear equation, chosen as the control law:

$$\Delta\Phi_{AB}(n) = \lambda \frac{L_s f_s}{k V_B} \Delta i_p(n) \quad (4)$$

where:

$$0 < \lambda < 2 \quad (\lambda \in \Re) \quad (5)$$

$$\Delta i_p(n) = i_{ref,p}(n) - i_{p,sampled}(n) \quad (6)$$

The addition of (3) and (4) gives the inner loop depicted in Figure 5.

Depending on the value of λ , the control algorithm reduces the sampled current error $\Delta i_p(n)$ with a geometric-sequence trend in every half-cycle $\frac{1}{2}T_s$, hence the name Geometric-Sequence Control. A geometric sequence is a set of values, where each term is obtained by always multiplying (or dividing) the previous value in the series by a common ratio r . With the GSC approach, r corresponds to $(1 - \lambda)$. Mathematically, after n half-cycles, with an initial value of $\Delta i_p(0)$, $\Delta i_p(n)$ can be calculated with the following formula:

$$\Delta i_p(n) = \Delta i_p(0) r^{n-1} \quad (7)$$

where:

$$r = \lambda - 1 \quad (8)$$

In order to have the most efficient dynamic response, without damaging the entire system, the error needs to be equal to zero ($\Delta i_p(n) = 0$) as fast as possible. To achieve this, the optimal value for λ should be $\lambda = 1$. In this case, the control law states that the inductor current i_p will reach its reference value after only two half-periods. During the first interval, the initial conditions are set up for the final steady-state operation, while the second half-cycle modifies the control variable Φ_{AB} in order to reach its steady value.

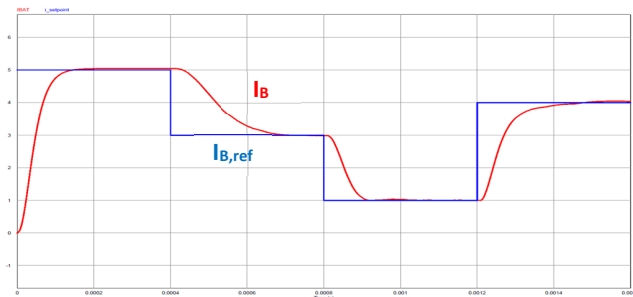
IV. SIMULATION & EXPERIMENTAL RESULTS

The simulations results for the DHB converter are depicted in Figure 6. For this study, a rectified grid voltage $V_A = 400V$ and a battery voltage $V_B = 250V$ are used. The parameter λ has been considered ideal ($\lambda = 1$) and the additional specifications of the DHB are listed in the Table I.

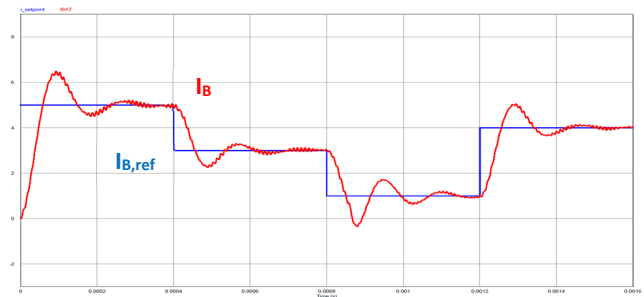
The dynamic improvement and increased stability of the GSC method (Figure 6a) are demonstrated compared to a typical PI control (Figure 6b). The GSC approach allows the converter to operate over a wide range of running conditions, unlike PI control, where oscillations in the battery current i_B can be seen. Figure 6c depicts the speed of the GSC method to reach the necessary phase-shift value Φ_{AB} with only two half-cycles. The geometric sequence at every interval can be clearly noticed. Finally, Figure 6d displays the regulation of the sampled current $i_{p,sampled}$ at the beginning of each half-period. The increase in stability and control speed prove the performance of the GSC approach.

TABLE I
SPECIFICATIONS OF THE DHB CONVERTER

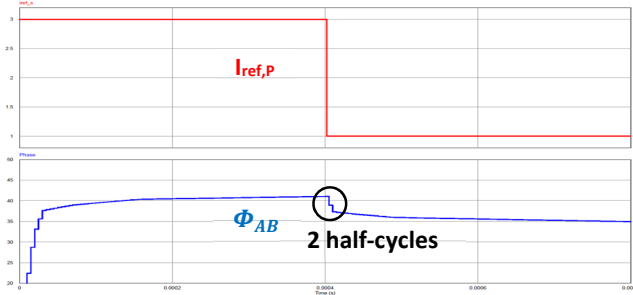
Symbol	Description	Value
V_A	Rectified grid voltage	400 V
V_B	Battery voltage	250 V
λ	Geometric sequence parameter	1
f_s	Switching frequency	100 kHz
C_A	Dead-time capacitor	150 μ F
C_B	Energy storage capacitor	150 μ F
k	Transformer turn's ratio	0.9
L_s	Leakage inductance	10 μ H
C_{A1}, C_{A2} C_{B1}, C_{B2}	Bridge capacitors	100 μ F
S_{A1}, S_{A2} S_{B1}, S_{B2}	MOSFETs	IPB65R110CFD



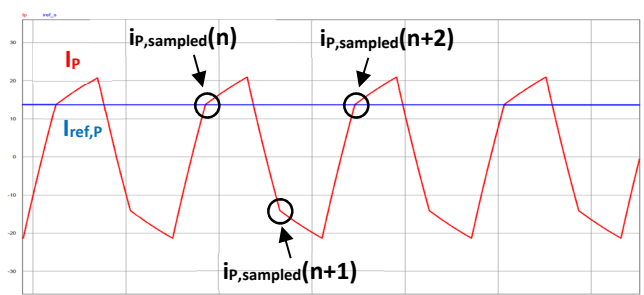
a) GSC approach with $V_A = 400V$ and $V_B = 250V$



b) PI control with $V_A = 400V$ and $V_B = 250V$



c) Speed of the GSC method to reach the necessary phase-shift value Φ_{AB} with two half-cycles

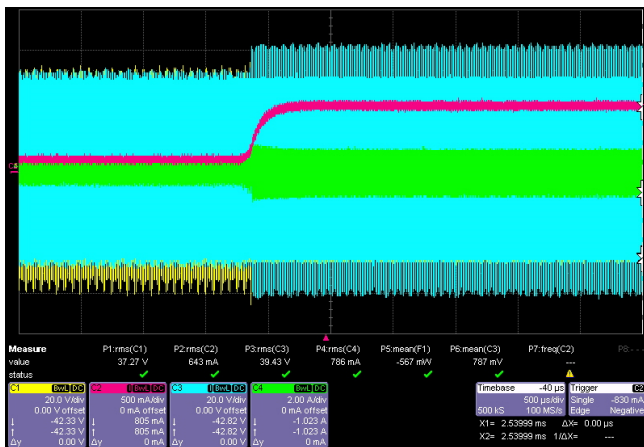


d) Regulation of the sampled current $i_{p,sampled}$ with the GSC method

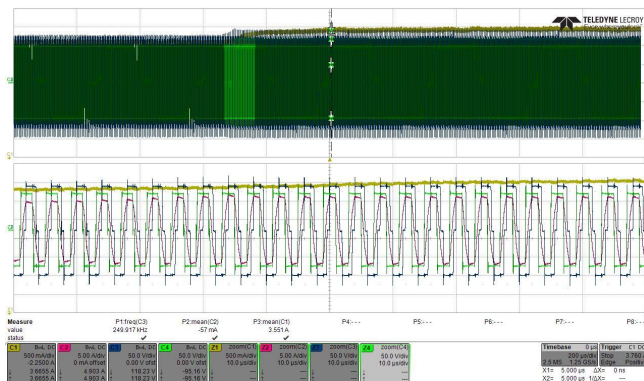
Fig. 6. Simulation results for the DHB converter

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a) Rising step load change with GSC



b) Zoom in on the rising step load change

Fig. 7. Experimental results of the proposed control scheme

A DHB prototype has been implemented to confirm experimentally the performance of the GSC method, with the specifications detailed in Table I. Figure 7a depicts the transient response of the prototype when performing a rising step load change on the system. Figure 7b enlarges the step load change to show the dynamic behavior in more details. The experimental outcomes illustrate the conclusive results obtained in simulation, and verify the superior efficiency of the Geometric-Sequence Control regarding transient performance, stability and robustness.

V. CONCLUSION

In this paper, a Dual Half-Bridge controlled by a digital Geometric-Sequence Control approach has been proposed. This current control method allows the DHB converter to operate over a wide range of running conditions, i.e. load variations and input voltage changes. Moreover, the GSC control loop shows improved stability, robustness and transient response compared to typical PI controllers.

The control system can be further improved using a more efficient modulation technique, like a variable duty-cycle method with Zero-Voltage Switching (ZVS) regions, or a variable frequency control scheme.