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Bidirectional DC/DC Converters using ZVS Technique

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ABSTRACT:

This paper proposes a zero voltage switching (ZVS) technique for bidirectional dc/dc converters. The dc/dc unit considered consists of two distinct bidirectional dc/dc cells paralleled at both input and output and whose two input bridges are coupled by means of passive inductive branches. A multiangle phase-shift modulation method is proposed which simultaneously achieves bidirectional power control, power sharing, and ZVS of all the electronic devices over the full power range without the need for auxiliary switches. Simulation and experimental results are reported for a 2.4 kW dc/dc unit consisting of two paralleled 1.2 Kw bidirectional dual-bridge series resonant converter cells.

Index Terms—***Bidirectional dc/dc converters, resonant conversion, zero voltage switching (ZVS).***

INTRODUCTION:

IN dc/dc converters intended for bidirectional power control soft switching of all the active devices is mandatory to ensure high efficiency, high power density, and reliability. The task is especially challenging in the presence of wide I/O voltage variations or in applications requiring programmable output voltage levels, as soft switching must be ensured over an extended operating range. Topological modifications relying on auxiliary hardware as well as modulation-based approaches [12]–[17] have been presented in the literature for soft-switching enhancement. Criticalities of power and thermal design are often reduced when multiple dc/dc subcells are employed in power-sharing mode to form the single dc/dc unit. In these cases, zero voltage switching (ZVS) operation on the input side can be achieved by coupling the cells in a two-by-two fashion through passive circuitry so that they mutually assist each other. In such scenarios, it becomes of strong practical interest to formulate advanced modulation strategies which, applied to the overall dc/dc unit, enable ZVS operation of the output devices as well, hence eliminating the need for additional semiconductor devices altogether.

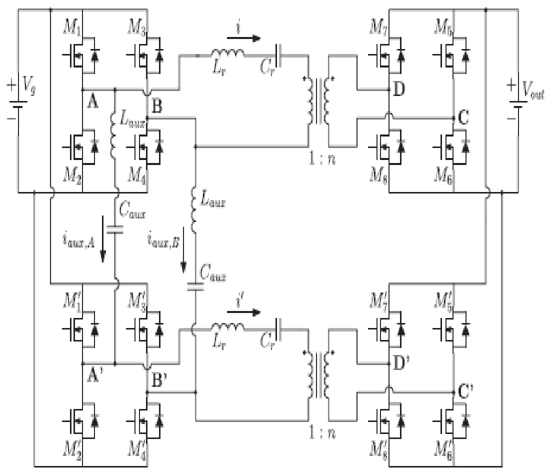

Fig. 1. DC/DC unit consisting of two paralleled DBSRC cells.

Existing System:

Operation of the proposed technique can be summarized as follows. Each DBSRC cell in Fig. 1 is modulated using a three-angle phase-shift modulation in which legs A, B, C, and D are phase shifted one with respect to the other, as detailed in Fig. 2. Three independent angles exist per cell, namely ϕAB, ϕAD, and ϕDC, ϕXY denoting the phase lag between legs Y and X. Control vectors **v**ϕ = (ϕAB, ϕAD, ϕDC) and **v**_ ϕ = (ϕA_B_ , ϕA_D_ , ϕD_C_) are generated so as to achieve the desired power flow and to ensure ZVS

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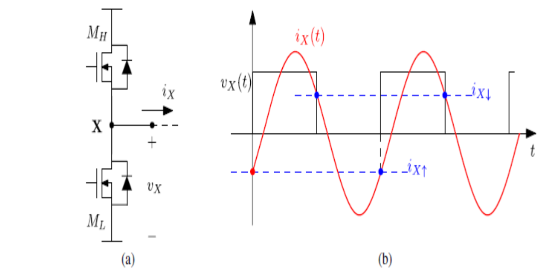
operation of output devices $M5 \ldots M8$ and$M5$ _. . . $M8$ _, i.e., legs C/D andC_/D_. Power sharing between the cells is ensured by driving the two converters with the same control commands: $\phi AB = \phi A\_B\_$, $\phi AD = \phi A\_D\_$ and $\phi DC = \phi D\_C\_$, whereas $\mathbf{v}\phi = \mathbf{v}\_\ \phi = (\phi AD, \phi AB, \phi DC)$ is selected so as to yield the desired amount of active and reactive power (P,Q) through the tank. Such *trajectory control* of $\mathbf{v}\phi$ for ZVS operation of legs C/D and C_/D_ is treated in Section II-B.



Generic leg X (a) and main associated waveforms (b).

Proposed System:

While the trajectory control approach allows exploitation of the degrees of freedom provided by multiangle modulation to achieve full ZVS of the output devices, it exposes input devices $M1 \ldots M4$ and$M1$ _. . . $M4$ _ to hard switching over certain power levels. Let us start by observing that minimization of the total reactive power $|Qtank| = |QA + QB + QC + QD|$ results in $QD = QC = 0$, as discussed above, but does not imply $|Qtank| = 0$. The resonant tank is in fact an inherently reactive element, which must exchange a minimum amount of reactive power with the rest of the circuit. Hence, QA and QB in general do not vanish even on theMCT. Furthermore, QA _= QB except when $\phi AB = 180◦$. For a more general study, input turn-off currents $iA\downarrow(\mathbf{v}\phi)$ and $iB\downarrow(\mathbf{v}\phi)$ need to be evaluated along the ZVS trajectories defined by (7). For example, Fig. 8 reports leg B turn-off current $iB\downarrow(\mathbf{v}\phi, \text{ZVS}(\Pi o\ ,\ \alpha))$ normalized to the full-power amplitude of the tank current versus the normalized active power level and for the same trajectories $\alpha = 0$, 0.6, 0.9, and 2 already considered in Fig. 7. Existence of a $iB\downarrow < 0$ power interval for $\alpha = 0$, 0.6, and 0.9 implies hard-switching of devices $M3$ and $M4$ in the corresponding power levels. On the other hand, the $\alpha = 2$ trajectory implies ZVS of leg B across the full power range. However, since the corresponding trajectory in Fig. 7 folds around .

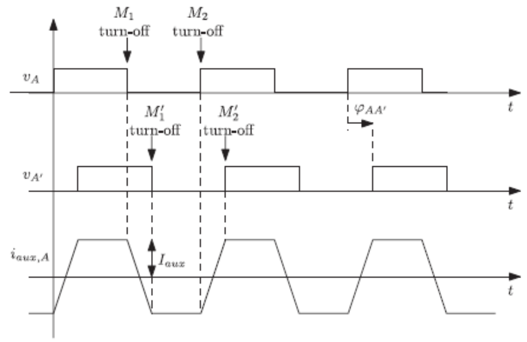


Fig. 9. Input ZVS operation via phase-shift between the two DBSRC cells: main waveforms.

SIMULATION RESULTS

A. Output ZVS and Trajectory Control Accuracy

The trajectory control theory developed in Section II relies on two main hypotheses. Apart from the already mentioned fundamental approximation, the other less evident but equally important assumption was the implicit hypothesis that legs A. . .D are driven with zero dead time, and that the corresponding voltages resemble the one depicted in Fig. 2. Nonzero dead times practically required to accommodate the finite switching times of the semiconductor devices introduce a distortion in which the behavior of the switching node voltage during the dead time interval depends on the instantaneous current level outsourced by the node itself. Computer simulations have been performed in order to assess how close the theoretical predictions are to the behavior of the DBSRC cell when a finite dead time Td is introduced in the gate driving signals. The simulation model, developed inMATLAB/PLECS as a good compromise between accuracy and simulation time, allowed to draw positive conclusions regarding the accuracy of the theory presented so far. The simulated DBSRC cell is a 1.2-kW converter switched at 100 kHz and operating between $Vg = 500$ V and $Vout = 400$ V nominal voltages. Tank parameters are $Lr = 440\ \mu$H, $Cr = 14$ nF, while the transformer turns ratio is $n = 0.8$ so as to yield $M = 1$ under nominal operating voltages.

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Simulations were performed under nonnominal operating conditions.

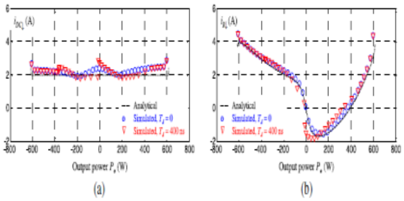

Fig. 11. Simulated steady-state turn-off currents of the output devices (a) and input leg B (b) as the control vector is swept along an $I_{ZVS} = 2$ A trajectory.

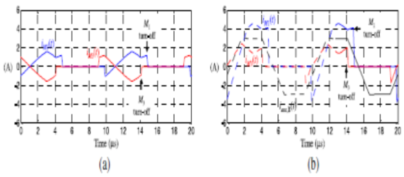

Fig. 12. Simulated currents through M_1 and M_3 without (a) and with (b) the proposed input ZVS assistance provision at a light load operating point.

EXPERIMENTAL RESULTS

A 2.4-kW dc/dc unit consisting of two paralleled 1.2-kW DBSRC cells was prototyped with the purpose of validating Each DBSRC cell was designed with a split resonant inductor on the primary side with the purpose of reducing the criticality of the magnetics design by allowing a smaller air gap. Similarly, with the purpose of having symmetrical common-mode voltage stresses on the transformer and on the resonant capacitor, the transformer primary winding was split as well and the entire.

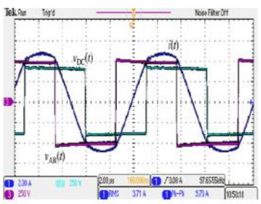

Fig. 14. Experimental waveforms at 1.1-kW forward power, $V_g = 500$ V, $V_{out} = 400$ V, $M = 1$; voltage scale: 250 V/div; current scale: 2 A/div; time scale: 2 μs/div.

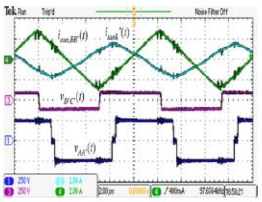

Fig. 15. Experimental waveforms for full ZVS operation with the proposed technique, $P_{test} = 110$ W; voltage scale: 250 V/div; current scale: 2 A/div; time scale: 2 μs/div.

CONCLUSION

This paper presents a zero voltage switching (ZVS) technique for bidirectional dc/dc converters consisting of two or more modules operating in parallel. The technique employs a multiangle phase-shift modulation combined with passive inductive coupling between the two input bridges of the DBSRC cells in order to enable full ZVS operation of all the electronic devices over the entire power range and without the need for additional semiconductor devices. The approachwas evaluated experimentally on a 2.4-kW dc/dc unit consisting of two 1.2-kW paralleled dual-bridge series resonant converters, demonstrating marked efficiency improvement over a one-angle modulation strategy.

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