Design and Implementation of Full Bridge Bidirectional Isolated DC-DC Converter for High Power Applications

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Keywords

«Power semiconductor device», «Power quality», «High frequency power converter», «Voltage Source Inverters (VSI)»

Abstract

This paper proposes the design and implementation of a high power full bridge bidirectional isolated DC-DC converter (BIDC) which comprises of two symmetrical voltage source converters and a high frequency transformer. In the proposed BIDC, a well-known PI controller based single phase-shift (SPS) modulation technique is used in order to achieve high power transfer. Besides, different phase shift methods such as extended phase-shift (EPS) and double phase-shift (DPS) are compared with SPS. Both simulation and experimental results are caried out to verify PI controller based simple phase-shift controlled BIDC prototype that is designed for 300-V 2.4-kW and operating at 20 kHz.

Introduction

Bidirectional isolated DC-DC converters (BIDC) have recently received a lot of attention due to the increasing need for systems with the capability of bidirectional energy transfer between two DC buses. Apart from traditional application in dc motor drives, new applications of BIDC include energy storage in renewable energy systems, fuel cell energy systems, custom power devices, hybrid electric vehicles (HEV) and uninterruptible power supplies (UPS) [1]. A main motivation is to replace line-frequency transformers with high-frequency transformers, in which galvanic isolation is indispensable between the two sets of dc terminals [2].

Various BIDC topologies have been proposed except from full bridge as reviewed in [3] such as dual flyback [4, 5], dual-Cuk [6] Zeta Sepic [7], forward-flyback [8], dual push-pull [9], push-pull-forward [10], push-pull-flyback [11] and dual half bridge [12].

In this paper, full-bridge phase shifted converters are preferred in the proposed BIDC topology because of their high power handling capability as it is stated in [13]. The full-bridge BIDC is designed, constructed and tested for bidirectional power transfer capability within a 300-V 2.4-kW laboratory system that satisfies the effectiveness of the configuration. The experimental results show that the dc capacitors in both sides can be charged from zero to the rated voltages without any external precharging or starting-up circuit.

The rest of this paper is organized as follows: System description and power circuit topology of the proposed BIDC system is presented in Section 2. The phase shift control strategy is introduced in Section 3. Simulation and experimental results are provided in Section 4 and 5 respectively. Conclusions of the study are given in Section 6.

Proposed BIDC System

The proposed BIDC system, which composes two symmetrical single phase full bridge voltage source converters (VSCs), two dc capacitors (C_{dc1} and C_{dc2}), auxilary reactors (L_{dc1} and L_{dc2}) and an high frequency (HF) transformer, is illustrated in Fig. 1. The HF transformer provides the required galvanic isolation and the auxiliary inductor serves as the instantaneous energy storage device. As it can be seen from Fig. 1, V_{dc1} and V_{dc2} are the DC voltages, D_0-D_7 are the antiparallel diodes of the main switching elements S_0-S_7 and n is the transformer turn ratio respectively. The BIDC has an optimal operating point where the voltage ratio between the high-voltage side and the low-voltage side is equal to the transformer turns ratio [14].

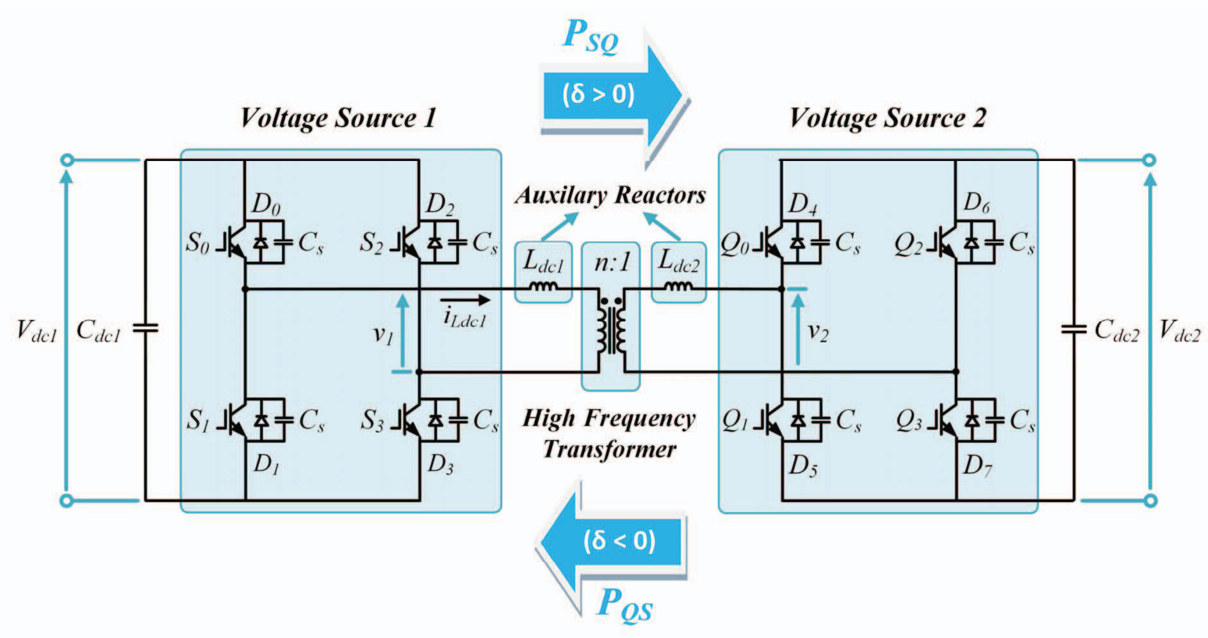

Fig. 1: Full bridge bidirectional isolated dc-dc converter topology

Phase Shift Controller

The most widely used control method for the BIDC is single phase-shift (SPS) modulation in which high power transfer capability can be achieved [15]. Alternative phase shift techniques such as extended-phase-shift (EPS), dual-phase-shift (DPS), triple-phase-shift (TPS) and some other modulation techniques such as the trapezoidal and the triangular that require complex computations were discussed in [3] and [16, 17] respectively. However, SPS is more advantageous in terms of small inertia, high dynamic and ease of realizing soft-switching control [3]. The main waveforms of the BIDC with SPS control is shown in Figure 2. The primary bridge (Voltage Source 1) is composed by S_0, S_1, S_2 and S_3 while the secondary bridge (Voltage Source 2) is composed by Q_0, Q_1, Q_2 and Q_3 gate signals. The gate signals of S_1-S_2, S_0-S_3, Q_1-Q_2 and Q_0-Q_3 are identical square wave signals with 50% duty ratio [18].

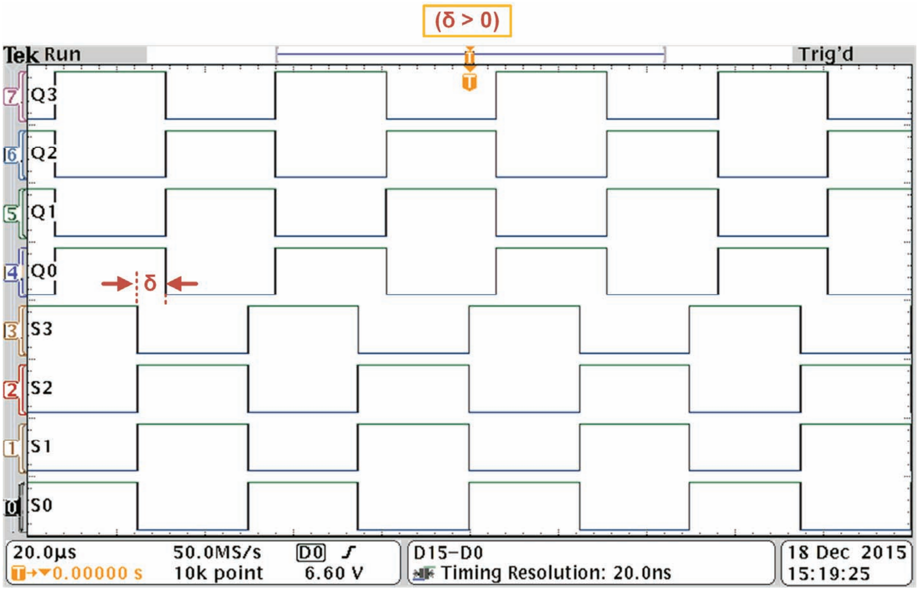

Fig. 2: Full bridge bidirectional isolated dc-dc converter topology

The diagonal switching pairs in each converter are controlled with constant duty cycle 50% (ignoring the small dead time) and with 180 degrees phase shift between two legs to provide a nearly square wave ac voltage across transformer terminals ($\pm v1$ and $\pm v2$) [1]. Considering the presence of auxilary reactors and the leakage inductance of the transformer, with a controlled and known value, the two square waves can be appropriately phase shifted to control the power flow from one dc-source to the other in order to achieve bidirectional power transfer [18]. The phase shift between two ac voltages, denoted by δ, is a significant parameter specifying the direction and amount of power transfer between dc buses.

In order to transfer power from side "S" to side "Q", the transformer secondary voltage "v_2" should lead the transformer primary voltage "v_1" and "δ" is considered as positive. On the contrary, the power transfer from side "Q" to side "S" may be possible when the transformer primary voltage "v_1" leads the transformer secondary voltage "v_2" where the phase shift angle "δ" is considered as negative. This leading or lagging phase shift is simply implemented by proper timing control of converter switches.

The dc–dc converter allows bidirectional power transfer by means of controlling the phase-shift angle δ [rad] between square voltages v_1 and v_2 as follows [15];

$$P_{SQ} = \frac{V_{dc1} . V_{dc2} . n}{\omega \mathrm{Ls}} \delta \left(1 - \frac{|\delta|}{\pi} \right) \tag{1}$$

where V_{dc1} and V_{dc2} are the two side DC link voltages, n is the transformer turn ratio, ω is the angular switching frequency and Ls is the total inductance (37 µH) which is the sum of transformer leakage inductance (7µH) and auxilary inductances (L_{dc1} = 12 µH and L_{dc2} = 18µH). L_s is an important element that determines the maximum amount of transferable power with given switching frequency. Therefore, apart from other practical limitations, it is possible to reach a high power density converter with a low leakage transformer [1].

Simulation Results

The proposed BIDC and its associated phase shift controller are tested and evaluated with simulation results obtained by using PSCAD/EMTDC with 1µs solution time step. Fig. 3 shows two different cases with respect to the phase shift angle being positive or negative.

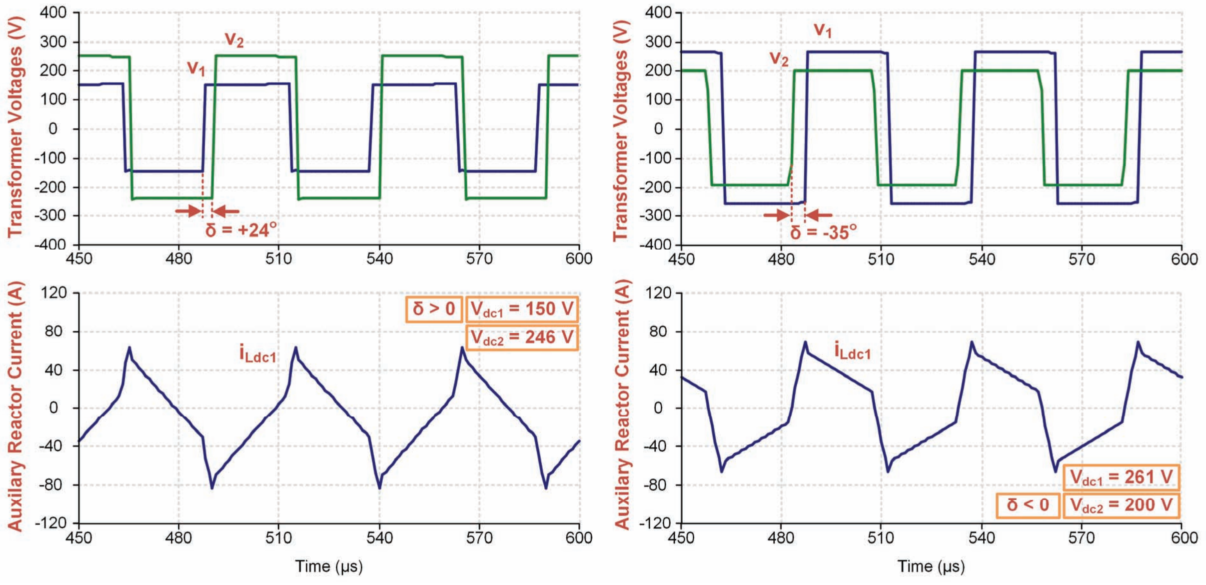

Fig. 3: Simulation results of BIDC operation

As it can be seen from the Fig. 3, when V_{dc1} is 150 V and with the positive 24° phase shift angle, V_{dc2} reaches to 246 V. With a negative 35° phase shift, V_{dc1} reaches to 261 V where V_{dc2} is supplied with constant 200 V. The maximum power transfer may be reached at $|\delta|$=90 degrees. Thus, the converter full range of bidirectional power transfer can be gained by controlling phase shift in -90 to +90 range.

Experimental Results

In this section, the performance of the phase shift control and bidirectional power transfer capability of the proposed BIDC system is investigated with experimental results. Experimental studies of the proposed BIDC system is realized with laboratory prototype as shown in Fig. 4. The power circuit parameters of the proposed 300-V 2.4-kW BIDC are provided in Table 1.

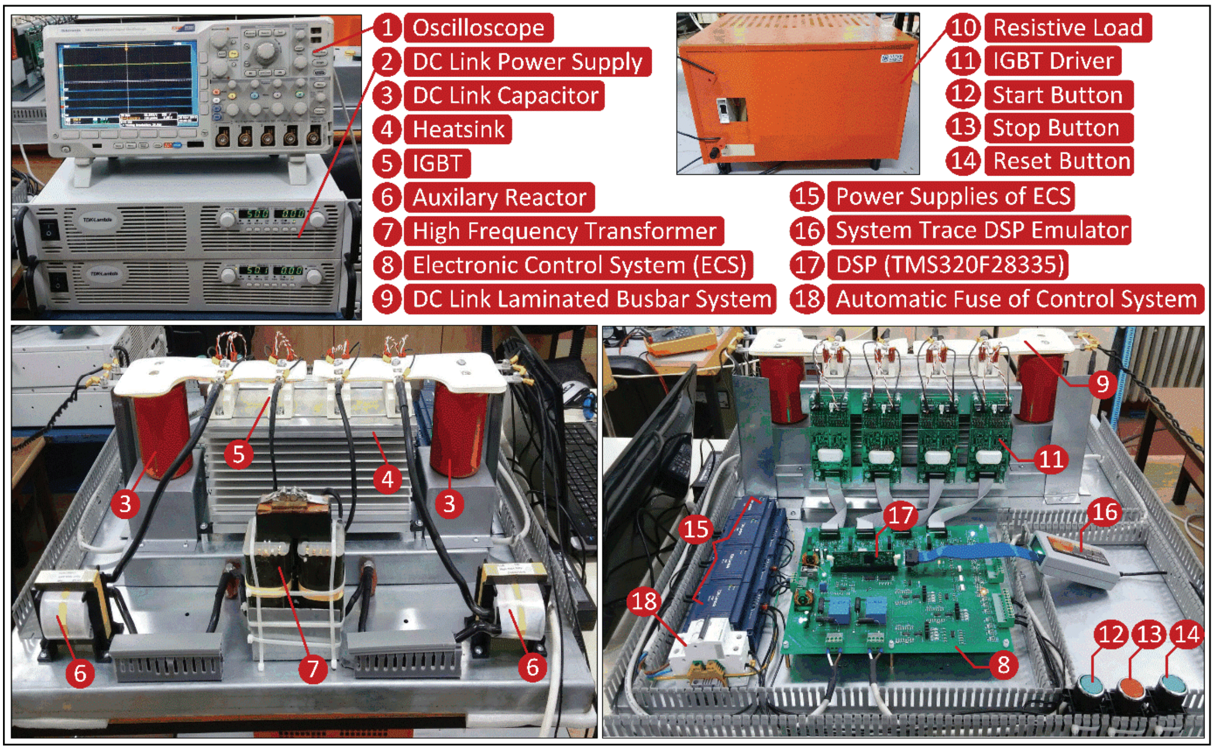

Fig. 4: Experimental prototype of 300-V 2.4-kW BIDC system

The power circuit of the two voltage source converters are constructed with Semikron SKM100GB12T4 Trench IGBT modules that are driven in 20kHz with Semikron SKYPER PRO 32 R drivers. The HF transformer is specially designed with a volume of 297 cm^3 by using UU 93 ferrite core that offers high permeability at high frequencies. Besides, iron core auxilary reactors and Itelcond AYX-HR series DC capacitors are used in the power circuit of the BIDC System. In the electronic control system of laboratory prototype, 32-bit floating-point TMS320F28335 DSP based microcontroller is used as a digital controller of system whose sampling time is assigned 50µs. Voltage measurements are realized with LEM LV-25P voltage sensors and experimental waveforms are captured with Tektronix MSO3034 oscilloscope.

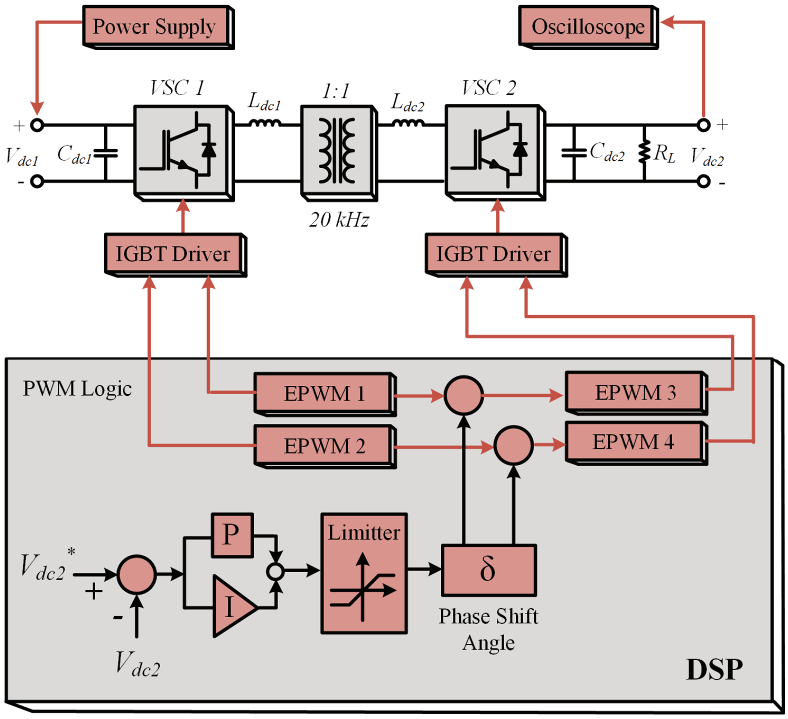

Fig. 5: Experimental Experimental implementation of control procedure

Fig. 5 illustrates the implementation of control algorithm to maintain the DC link voltage (load side) constant at desired value with a proper phase shift angle obtained by PI controller against the variations of supply voltage.

Table I: Power Circuit parameters of the proposed BIDC system

Rated Power (P_D)	2.4 kW
DC Voltages (V_{dc1}, V_{dc2})	260 V (Constant) 100-300V (Variable)
DC Capacitors (C_{dc1}, C_{dc2})	2.2 mF
Auxilary Reactors (L_{dc1}, L_{dc2})	12 µH, 18 µH
Snubber Capacitor (C_s)	100 nH
HF Transformer Switching Frequency (f_{sw})	20 kHz
HF Transformer Leakage Inductance (L_{tr})	7µH (2 %)

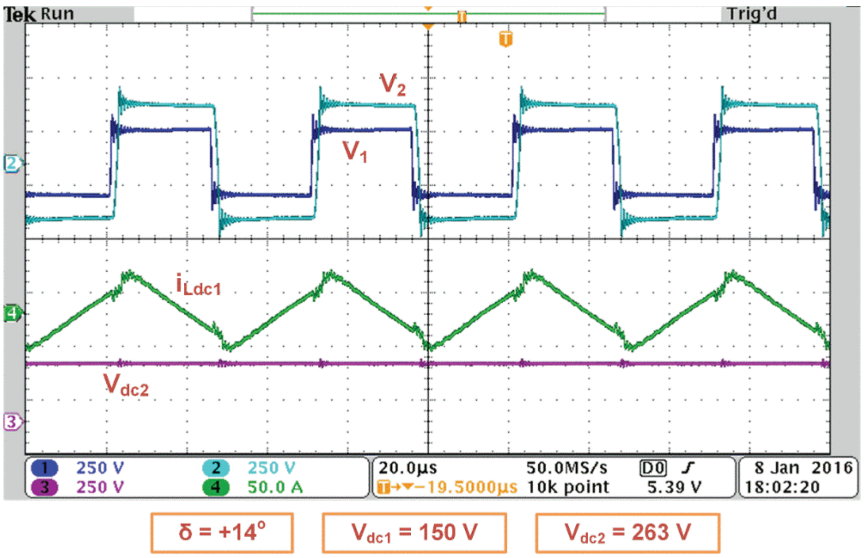

Fig. 6: Experimental waveforms for positive single phase-shift

Fig. 6 presents the experimental waveforms when V_{dc1} is 150 V while V_{dc2} is 264 V at positive 18° phase shift angle that allows the power transfer P_{SQ} = 2.4 kW. Here, "*S*" side dc link voltage V_{dc1} is supplied with a constant 150 V and "*Q"* side dc link voltage V_{dc2} is charged from zero volt up to 264 V without needing any external precharging or starting-up circuit.

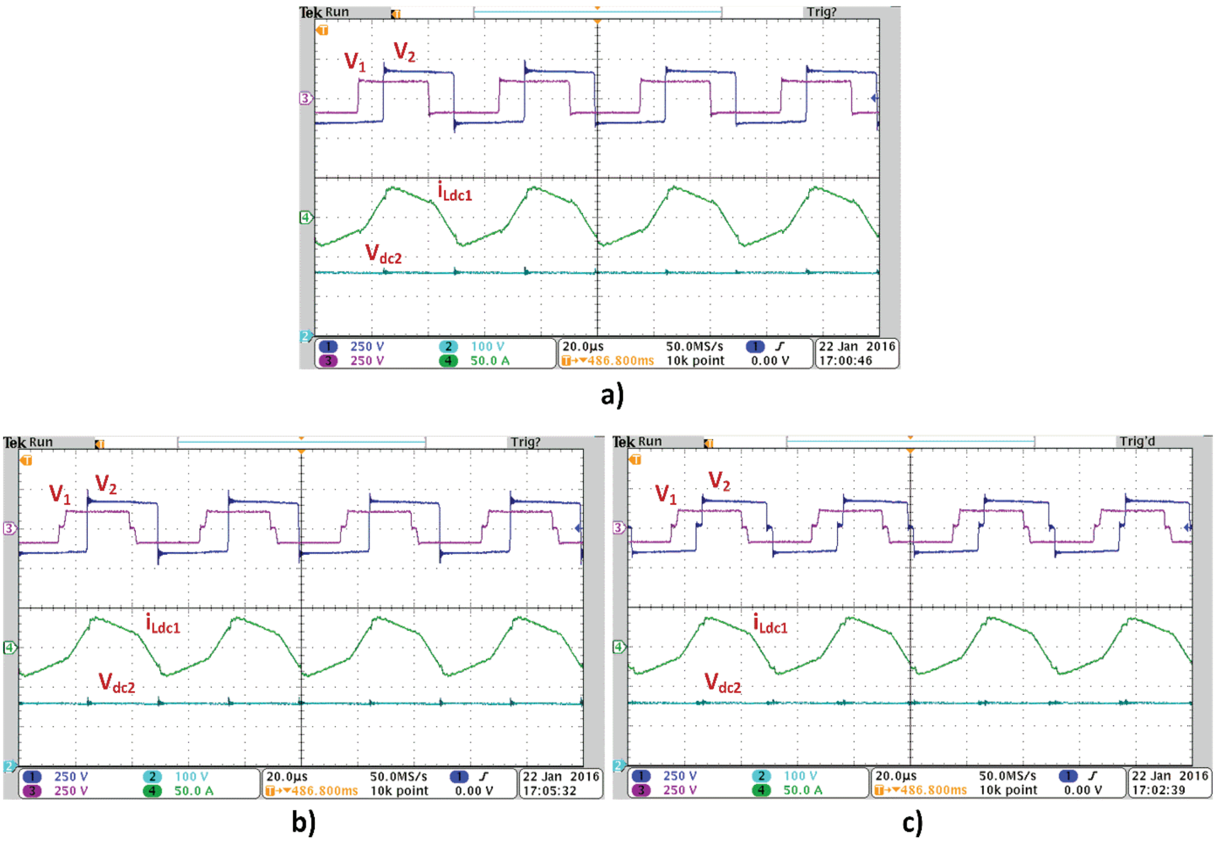

Fig. 7: Comparison of different phase-shift methods a) SPS b) EPS c) DPS

In Fig. 7, extended phase-shift (EPS) and double phase-shift (DPS) methods which are typically improved methods of SPS are compared with each other experimentally. The main difference between SPS and the improved phase shift methods (EPS and DPS) is that there is not only the outer phase shift ratio as in SPS but also inner phase shift ratios which provide decreasing circulating power. Compared with SPS method; current stress can be reduced and the efficiency of the system can be improved by expanding the ZVS operation range with EPS and DPS methods. However, SPS method is a step ahead with allowing higher range of power transfer and ease of application.

Conclusion

This paper addresses the design and implementation of a high-frequency full bridge bidirectional isolated dc–dc converter intended for high-power applications. The proposed BIDC system, consists of two symmetrical single phase full bridge VSCs, two dc capacitors, auxilary reactors and an high frequency (HF) transformer that provides the required galvanic isolation. Various phase-shift (simple phase-shift, extended phase-shift and double phase-shift) methods are applied and compared with each other. In order to obtain high power transfer, the system control is realized with an effective PI based simple phase-shift controller. The performance of the proposed system and its controller are firstly evaulated with simulation results obtained by using PSCAD/EMTDC and then verified with experimental results taken from 300-V, 2.4-kW prototype that is established in the laboratory.

References

[1] Karshenas, H.R., Daneshpajooh, H., Safaee, A., Jain P., Bakhshai, A. Bidirectional DC-DC Converters for Energy Storage Systems, Chapter 8 in Energy Storage in the Emerging Era of Smart Grids, Edited by Prof. Rosario Carbone, 2011.

[2] Jimichi, T., Fujita, H., Akagi, H. A Dynamic Voltage Restorer Equipped with a High-Frequency Isolated DC-DC Converter. IEEE Transactions on Industry Applications, vol. 47, no. 1, pp. 169-175, 2011.

[3] Zhao, B., Song Q., Liu, W., Sun, Y. Overview of Dual-Active-Bridge Isolated Bidirectional DC–DC Converter for High-Frequency-Link Power-Conversion System. IEEE Transactions on Power Electronics, vol. 29, no. 8, pp. 4091-4106, 2014.

[4] Chung, H.S.H, Cheung, W.L., Tang, K.S. A ZCS bidirectional flyback dc/dc converter IEEE Transactions on Power Electronics, vol. 19, no. 6, pp. 1426–1434, 2004.

[5] Kashif, M. Bidirectional flyback dc-dc converter for hybrid electric vehicle: Utility, working and PSPICE computer model. in Proc. Asia Pacific Conf. Postgraduate Res. Microelectron. Electron., pp. 61–66, 2012

[6] Aboulnaga, A.A, Emadi, A. Performance evaluation of the isolated bidirectional Cuk converter with integrated magnetics. in Proc. 35th IEEE Annu. Power Electron. Spec. Conf., pp. 1557–1562, 2004.

[7] Bellur, D.M., Kazimierczuk, M.K. Isolated two-transistor zeta converter with reduced transistor voltage. IEEE Trans. Circuits Syst. II: Exp. Briefs., vol. 58, no. 1, pp. 41–45, 2011.

[8] Zhang, F., Yan, Y. Novel forward-flyback hybrid bidirectional dc-dc converter. IEEE Transactions on Industrial Electronics, vol. 56, no. 5, pp. 1578–1584, 2009.

[9] Xiao H., Xie, S. A ZVS bidirectional dc-dc converter with phase shift plus PWM control scheme. IEEE Transactions on Power Electronics, vol. 23, no. 2, pp. 813–823, 2008.

[10] Zhang, Z., Thomsen, O.C., Andersen, M.A.E. Optimal design of a push-pull-forward half-bridge (PPFHB) bidirectional dc-dc converter with variable input voltage. IEEE Transactions on Industrial Electronics, vol. 59, no. 7, pp. 2761–2771, 2012.

[11] Souza, E.V., Barbi, I. Bidirectional current-fed flyback-push-pull dc-dc converter. Brazilian Power Electronics Conference, pp. 8–13, 2011.

[12] Li, H., Peng, F.Z., Lawler, J.S. A natural ZVS medium-power bidirectional dc-dc converter with minimum number of devices. IEEE Transactions on Industrial Applications, vol. 39, no. 2, pp. 525-535, 2003.

[13] Cheng, K.W.E., Ho, S.L., Wong, K.P., Cheung, T.K., Ho, Y.L. Examination of Square-Wave Modulated Voltage Dip Restorer and Its Harmonics Analysis. IEEE Transactions on Energy Conversion, vol. 21, no. 3, pp. 759-766, 2006.

[14] Tan, N.M.L, Abe, T., Akagi, H. Topology and Application of Bidirectional Isolated DC-DC Converters. 8th International Conference on Power Electronics - ECCE Asia, May 30-June 3, Korea, 2011.

[15] Tan, N.M.L, Abe, T., Akagi, H. Design and Performance of a Bidirectional Isolated DC–DC Converter for a Battery Energy Storage System. IEEE Transactions on Power Electronics, vol. 27, no. 3, pp. 1237-1248, 2012.

[16] Krismer, F., Round, S. Kolar, J.W. Performance optimization of a high current dual active bridge with a wide operating voltage range. IEEE Power Electron. Specialist Conf. (PESC), June 2006, pp. 1–7.

[17] Wang, Y., Haan, S.W.H., Ferreira, J.A. Optimal operating ranges of three modulation methods in dual active bridge converters. IEEE Power Electron. and Motion Control Conf., pp. 1397–1401.

[18] Alonso, A.R., Lamar, D.G., Vazquez, A. Sebastian, J., Hernando, M.M. An overall study of a Dual Active Bridge for bidirectional DC/DC conversion. IEEE Energy Conversion Congress and Exposition, 2010.