Experimental Verification of Reducing Power Loss under Light Load Condition of a Bi-Directional Isolated DC/DC Converter for a Battery Charger–Discharger of Electric Vehicle

Ryota Kondo∗ Member, Yusuke Higaki∗ Non-member Masaki Yamada∗∗ Member

J-STAGE Advance published date : March 26, 2021

This paper proposes a bi-directional isolated DC/DC converter for the battery charger and discharger of Electric Vehicle to reduce the power loss under light loads. The proposed DC/DC converter consists of two full-bridge inverters, an isolated transformer, and a boost reactor, and provides bi-directional transmission, buck-boost conversion, zero-voltage-switching and reactive power suppression. Two power semiconductors of the inverter in the rectification side are turned off to block a reactive current, which increases the power loss under light loads. The phase shift amount in the two full bridge inverters are controlled continuously and simultaneously seamless power transmission. The 400 V–3.5 kW experimental system exhibits stable bi-directional buck-boost conversion and seamless transition between the charging and discharging modes, while suppressing the reactive power. Moreover, the proposed DC/DC converter reduces power loss by 67.5 W under light loads (240 W), compared with the conventional control.

Keywords: bi-directional isolated DC/DC converter, phase-shift control, zero-voltage switching, battery, EV

1. Introduction

In recent years, there has been increasing attention given to smart houses in which grid power is connected to renewable power sources such as photovoltaic cells, storage batteries and fuel cells(1)–(5). Smart houses optimize household power flow to save energy, and supply these renewable power sources to house during emergencies(6). Photovoltaic (PV) and storage batteries are among the most popular; and increasingly there are cases in which electric vehicle (EV) batteries are being used as storage batteries. Figure 1 shows an example of system configuration of a smart house(7). It consists of a PV power conditioner (PV-PCS) for connecting PV and grid, and an EV power conditioner (EV-PCS) for connecting EV batteries and grid.

Here, an EV-PCS provides a bi-directional isolated DC/DC converter in order to satisfy the following three requirements(8)–(11).

• Galvanic isolation for EV batteries and grid
• Bi-directional operation for charging and discharging mode of EV batteries
• Both boost conversion and buck conversion in response to differences in battery voltage due to vehicle type and the charging-discharging status of each cell (SOC: State of Charge).

DAB (Dual-Active-Bridge) converters for bi-directional power transmission by adjusting phase differences in the output voltage of two full-bridge inverters(12)(13) have been proposed for bi-directional isolated DC/DC converters like that mentioned above, and since that time, studies have been conducted focusing upon SPS (Single Phase Shift) modulation(14)–(16) and TPS (Tri phase shift) modulation(19)–(23).

In the past, the authors proposed a control scheme for synchronizing the gate pattern of individual legs of both full-bridge inverters in TPS modulation, and then continuously controlling only the phase-shift amount of either full-bridge inverter according to the charging-discharging power reference(24)(25). This proposed control scheme is capable of adjusting charge-discharge power seamlessly while simplifying control parameters to one parameter. However, the problem is that peak value and effective value of the isolation

a) Correspondence to: Ryota Kondo. E-mail: Kondo.Ryota@db.MitsubishiElectric.co.jp
* Advanced Technology R&D Center, Mitsubishi Electric Corporation
8-1-1, Tsukaguchi-Honmachi, Amagasaki 661-8661, Japan
** Himeji Works, Mitsubishi Electric Corporation
840, Chiyodami-cho, Himeji 670-8677, Japan

© 2021 The Institute of Electrical Engineers of Japan. 377
transformer’s current are increased due to the influence of reactive power when it is transmitting power during light loads, resulting in increased conduction loss. With the bi-directional isolated DC/DC converter shown in Fig. 1, the light load operating time to compensate for differential power between PV generated power and electric consumption in house cannot be ignored. This poses the risk of worsening operating efficiency of the entire system due to increased loss of the bi-directional isolated DC/DC converter during light load operation.

Therefore, the authors propose a control scheme for suppressing reactive power\(^{(20)}\). This proposed control scheme adds the following two new operating modes to conventional phase-shift control\(^{(20),(21)}\).

- Diode rectifier mode in rectification side inverter
- Synchronized phase shift mode in transmission side inverter and rectification side inverter

In this paper, we explain the operating specifications and operating principle of the above proposed control scheme. Then, we perform experimental verification to realize the reduction of loss during light load operation by designing and building a 400 V–3.5 kW experimental system.

2. Circuit Configuration and Operating Principle

2.1 Circuit Configuration As shown in Fig. 1, a bi-directional isolated DC/DC converter is connected between an EV battery and a DC/AC inverter connected to grid. Figure 2 shows the circuit configuration of the proposed bi-directional isolated DC/DC converter. Respective full-bridge inverters are provided on the EV battery side and the side of the DC link with the DC/AC inverter. The EV battery side is defined as the primary side, and the DC link side as the secondary side. Power flow from the secondary side to the primary side is the charging direction, and power flow from the primary side to the secondary side is the discharge direction. Lossless snubber capacitors \(C_{11}\) to \(C_{24}\) are connected in parallel to semiconductor elements \(Q_{11}\) to \(Q_{24}\) constituting the full-bridge inverters. High-frequency reactors \(L_1\) and \(L_2\) are connected to each end of an isolation transformer \(Tr\). During battery charging mode, \(L_1\) and \(L_2\) act as reactors for zero-voltage switching (ZVS) of the secondary side inverter \((Q_{21}\) to \(Q_{24}\)), while \(L_1\) and \(L_2\) act as a boost reactor of the primary side inverter \((Q_{11}\) to \(Q_{14}\)). Conversely, during battery discharging, \(L_1\) and \(L_2\) act as reactors for ZVS of the primary side inverter \((Q_{11}\) to \(Q_{14}\)), and \(L_1\) and \(L_2\) act as a boost reactor of the secondary side inverter \((Q_{21}\) to \(Q_{24}\)).

Figure 3 shows the gate specification of \(Q_{11}\) to \(Q_{24}\). Figure 3(a) shows the gate specification during charging mode, and Fig. 3(b) shows the gate specification during discharging mode. In both Fig. 3(a) and Fig. 3(b), a dead time \(\theta_{dd}T\) is provided for each leg \((Q_{11}\) and \(Q_{12}\), \(Q_{13}\) and \(Q_{14}\), \(Q_{21}\) and \(Q_{22}\), \(Q_{23}\) and \(Q_{24}\)). In addition, the ON period for \(Q_{11}\) to \(Q_{24}\) is the period subtracting only dead time \(\theta_{dd}T\) from all half-cycles \(T/2\). During the charging mode shown in Fig. 3(a), when \(Q_{11}\) and \(Q_{12}\) are completely off, they operate as a diode. Then, by fixing the phase of \(Q_{21}\) and \(Q_{22}\), phase of \(Q_{13}\) and \(Q_{14}\) are shifted by \(\theta_1\) relative to that of \(Q_{21}\) and \(Q_{22}\), and phase of \(Q_{23}\) and \(Q_{24}\) are shifted by \(\theta_2\) relative to that of \(Q_{21}\) and \(Q_{22}\). During the discharging mode shown in Fig. 3(b), \(Q_{21}\) and \(Q_{22}\) are completely OFF and operate as a diode. Then, by fixing the phase of \(Q_{11}\) and \(Q_{12}\), phase of \(Q_{13}\) and \(Q_{14}\) are shifted by \(\theta_1\) relative to that of \(Q_{11}\) and \(Q_{12}\), and phase of \(Q_{23}\) and \(Q_{24}\) are shifted by \(\theta_2\) relative to that of \(Q_{11}\) and \(Q_{12}\). The phase-shift amounts \(\theta_1\) and \(\theta_2\) are standardized by one cycle \(T\), and are thus dimensionless. Figure 4 shows the operating specifications and four operating modes of phase-shift amounts \(\theta_1\) and \(\theta_2\). The minimum value of \(\theta_1\) and \(\theta_2\) is \(\theta_{dd}\), which is necessary for ZVS, while the maximum value is \(0.5\cdot\theta_{dd}\). Under conditions of \(\theta_1 = \theta_2 = 0.5\cdot\theta_{dd}\), power transmission is 0 with no voltage applied to the isolation transformer \(Tr\). That is, this is the origin point at which charging mode and discharging mode switch, and is the boundary condition of Mode 2 and Mode 3. This boundary condition of
Mode 2 and Mode 3 is expressed by the following equation.

\[ \theta_1 = \theta_2 = 0.5 - \theta_{\text{sl}} \]  

(1)

The boundary condition of Mode 1 and Mode 2 is expressed by the following formula. Two modes are present during charging mode from the origin point at which \( \theta_1 \) and \( \theta_2 \) are 0.5 - \( \theta_{\text{sl}} \): Mode 2 in which \( \theta_1 \) and \( \theta_2 \) are changed by the same value, and Mode 1 in which \( \theta_2 \) is fixed at \( \theta_{\text{sl}} \) and \( \theta_1 \) is changed.

\[ \theta_1 = \theta_2 = \theta_{\text{sl}} \]  

(2)

In the interval from the origin point to Mode 2, \( \theta_1 \) and \( \theta_2 \) are reduced towards \( \theta_{\text{sl}} \), and furthermore, \( \theta_1 \) is increased from boundary condition \( \theta_1 = \theta_2 = \theta_{\text{sl}} \) towards 0.5 - \( \theta_{\text{sl}} \) according to equation (2) in Mode 1, continuously increasing charging power. Similarly during discharging mode, there exists two modes from the origin point at which \( \theta_1 \) and \( \theta_2 \) are 0.5 - \( \theta_{\text{sl}} \): Mode 3 in which \( \theta_1 \) and \( \theta_2 \) are changed by the same value, and Mode 4 in which \( \theta_1 \) is fixed and \( \theta_2 \) is changed. The boundary condition of Mode 3 and Mode 4 is similar to equation (2). \( \theta_1 \) and \( \theta_2 \) are reduced to \( \theta_{\text{sl}} \) during the interval from the origin point in Mode 3, and furthermore, by increasing \( \theta_2 \) towards 0.5 - \( \theta_{\text{sl}} \) in Mode 4 from boundary condition \( \theta_1 = \theta_2 = \theta_{\text{sl}} \) in equation (2), continuously increasing discharging power.

### 2.2 Operating Principle for Suppressing Reactive Power

Figure 5 is a chart of operating waveforms for \( v_{\text{br}} \), \( v_{\text{br}} \), and \( i_{\text{br}} \). For Mode 1 to Mode 4 with voltage condition \( V_1N_2 > V_2N_1 \) in switching half-cycle 0 to \( T/2 \). The voltage condition \( V_1N_2 > V_2N_1 \) is a light load condition under which \( i_{\text{br}} \) is a discontinuous mode and reactive power is generated. The explanation of ZVS operation during dead time periods is omitted in order to focus on the principles behind power conversion and reactive power suppression.

In Mode 1, the positive output periods for \( v_{\text{br}} \) in order to fix \( \theta_1 \) at minimum value \( \theta_{\text{sl}} \), the output periods for \( v_{\text{br}} \) are 2\( \theta_{\text{sl}}T \) to \( T/2 \) as shown in Fig. 5. On the other hand, the ON period for \( Q_{13} \) is 0 to \( \theta_1T \), so during the 2\( \theta_2T \) to \( \theta_1T \), the \( Q_{11} \) parasitic diode and \( Q_{13} \) conduct, \( L_1 \) and \( L_2 \) are excited, and \( i_{\text{br}} \) increases positively. Thus, from \( \theta_1T \) when \( Q_{13} \) turns OFF, the \( Q_{14} \) parasitic diode conducts, \( L_1 \) and \( L_2 \) exciting current is transmitted to the primary side via the \( Q_{11} \) parasitic diode and \( Q_{14} \), and \( i_{\text{br}} \) decreases from voltage condition \( V_1N_2 > V_2N_1 \). With conventional control system, after \( i_{\text{br}} \) reaches 0 A when \( Q_{11} \) is turned ON, it turns negative, and reactive power is generated, but in the proposed control system, \( Q_{11} \) acts as a diode, \( i_{\text{br}} \) remains at 0 A without a switch of polarity, so it is possible to prevent generation of reactive power. The periods of \( T/2 \) to \( T \) are also ones in which \( i_{\text{br}} \) remains at 0 A.

In Mode 2, \( \theta_1 \) and \( \theta_2 \) change equally, and the output periods for \( v_{\text{br}} \) and \( v_{\text{br}} \) are \( \theta_2T + \theta_{\text{sl}}T \) to \( T/2 \) similar to those shown in Fig. 5(b). However, the \( Q_{11} \) parasitic diode does not conduct due to the voltage condition \( V_1N_2 > V_2N_2 \), so \( i_{\text{br}} \) becomes a constant 0 A. That is, under voltage condition \( V_1N_2 > V_2N_1 \), the amount of power transmission in Mode 2 is 0 W. During charging mode under voltage condition \( V_1N_2 > V_2N_1 \), charging power is 0 W in Mode 2. It is increased as increasing \( \theta_1 \) in Mode 1 from boundary condition \( \theta_1 = \theta_2 = \theta_{\text{sl}} \).

In Mode 3, \( \theta_1 \) and \( \theta_2 \) change equally similar to Mode 2. According to Fig. 5(c), the output periods of output voltage \( v_{\text{br}} \) from the primary side inverter, which is the transmission side, are \( \theta_2T + \theta_{\text{sl}}T \) to \( T/2 \). Due to voltage condition \( V_1N_2 > V_2N_1 \), the \( Q_{21} \) parasitic diode conductions and generation of reactive power is suppressed based on the operating principle explained in equation (2). Even if in \( T/2 \) to \( T \), \( i_{\text{br}} \) remains at 0 A. In Mode 3, \( i_{\text{br}} \) further increases as \( \theta_1 \) and \( \theta_2 \) are increased, so discharging power is increased. Conversely, if \( \theta_1 \) and \( \theta_2 \) reach 0.5 - \( \theta_{\text{sl}} \), then discharging power becomes 0 W.

In Mode 4, in order to fix \( \theta_1 \) at minimum value \( \theta_{\text{sl}} \), the output periods for \( v_{\text{br}} \) are 2\( \theta_{\text{sl}}T \) to \( T/2 \) as shown in Fig. 5(d). On the other hand, the ON period for \( Q_{23} \) is 0 to \( \theta_2T \), so during the periods 2\( \theta_{\text{sl}}T \) to \( \theta_2T \), the \( Q_{21} \) parasitic diode and \( Q_{23} \) conduct, \( L_1 \) and \( L_2 \) are excited, and \( i_{\text{br}} \) increases negatively. Thus, from \( \theta_2T \), when \( Q_{23} \) turns OFF, the \( Q_{24} \) parasitic diode conduct, the \( L_1 \) and \( L_2 \) exciting current is transmitted to the secondary side via the \( Q_{12} \) parasitic diode and \( Q_{24} \), and \( i_{\text{br}} \) decreases towards 0 A. \( Q_{21} \) acts as a diode, so even if \( i_{\text{br}} \) reaches 0 A, \( i_{\text{br}} \) remains at 0 A without a switch of polarity, and it is possible to prevent generation of reactive power. Even during the periods \( T/2 \) to \( T \), \( i_{\text{br}} \) remains at 0 A. In Mode 4, \( i_{\text{br}} \) is further increased as \( \theta_2 \) is increased, increasing discharging power. That is, during charging mode in Mode 3, \( \theta_1 \) and \( \theta_2 \) are increased, and discharging power is continuously increased as \( \theta_2 \) is increased in Mode 4 from boundary condition \( \theta_1 = \theta_2 = \theta_{\text{sl}} \).

Under voltage condition \( V_1N_2 < V_2N_1 \), reactive power is suppressed based on the operating principle explained in Fig. 5(d) for Mode 1, Fig. 5(c) for Mode 2, Fig. 5(b) for Mode 3, and Fig. 5(a) for Mode 4 from the symmetry. Under voltage condition \( V_1N_2 = V_2N_2 \), in Mode 2 and Mode 3, no difference is produced in the voltage applied to both transformer ends, so there is no power transmission. During charging mode, charging power is increased by increasing \( \theta_1 \) from \( \theta_{\text{sl}} \) in Mode 1, and during discharging mode, discharging power is increased by increasing \( \theta_2 \) from \( \theta_{\text{sl}} \) in Mode 4. Similar to voltage conditions \( V_1N_2 > V_2N_1 \) and \( V_1N_2 < V_2N_1 \), reactive power is suppressed in Mode 1 and
Mode 4 due to the same operating principle as in both voltage conditions.

3. Experimental Verification

Figure 6 shows a 400 V–3.5 kW experimental system. Table 1 shows the experimental specification. The rated battery charging-discharging current $I_1$ is 12 A, and the range of battery voltage $V_1$ is 290 to 400 V. Rated charging-discharging power $P_1$ is 3.5 kW. Assuming charging from the secondary side to the primary side to be the positive direction, charging power is positive, and discharging power is negative. The turn ratio of isolation transformer is designed to be 1:1. Inductance, $L_1$ and $L_2$ are set to equal. In order to transmit power seamlessly and bi-directionally, regenerative voltage source loads $V_{s1}$ and $V_{s2}$ are provided. In addition, the switching frequency $f_{sw}$ for $Q_{11}$ to $Q_{24}$ is set to 20 kHz. Figure 7 shows the control block diagrams for a bi-directional isolated DC/DC converter. The bi-directional isolated DC/DC converter provides constant current control to control $I_1$, and constant voltage control to control $V_2$. An externally input current reference $I_{11}^*$ is selected as a battery current reference value $I_1^*$ during constant current control with a multiplexer (MUX), and a current reference $I_{12}^*

Table 1. Experimental specification of the bi-directional DC/DC converter

| Parameter                        | Specification |
|----------------------------------|--------------|
| EV Battery-Side voltage          | $V_1$        |
| EV Battery-Side rated current    | $I_1$        |
| Power rating                     | $P_1$        |
| DC Link-Side Voltage             | $V_2$        |
| Switching frequency              | $f_{sw}$     |
| Transformer turn ratio           | $N_1 : N_2$  |
| Boost and soft switching inductor| $L_1, L_2$   |
| Snubber Capacitor                | $C_{11, 12}$ |
| Snubber Capacitor                | $C_{21, 22}$ |
during constant voltage control generated with constant voltage control is selected as a $I_1$ during constant voltage control $I_{12}$ is generated by PI control from deviation between a DC link voltage reference value $V_2$ and actual voltage $V_2$. Then, a phase-shift amount $\theta_C$ is generated by PI control from the deviation between $I_{11}$ and $I_1$. $\theta_1$ and $\theta_2$ are calculated from $\theta_C$ with a control processor. Figure 8 shows the calculating specification of the control processor. Mode 1 to Mode 4 defined in Fig. 4 are determined according to the value of $\theta_C$ by the control processor. Thus $\theta_1$ and $\theta_2$ are calculated from $\theta_C$ according to the transformation formula shown in Table 2. The gate specification for $Q_{11}$ to $Q_{22}$ based on $\theta_1$ and $\theta_2$ are as shown in Fig. 3. As for determination of charging mode and discharging mode, when $I_{11}$ is detected, charging means $Q_{11}$ and $Q_{12}$ are OFF as in Fig. 3(a) if $I_{11}$ is positive, and discharging means $Q_{21}$ and $Q_{22}$ are OFF as in Fig. 3(b) if $I_{11}$ is negative.

Figure 9 shows measured waveforms $v_{tr1}$ and $i_{tr2}$ of the proposed control system and conventional control system \[250,255\]. Load power $P_1 = -240 \text{ W}$ measured on the secondary side with voltage conditions $V_1 = 290 \text{ V}$ and $V_2 = 380 \text{ V}$ during discharging mode are assumed to be light load conditions. The waveforms are acquired with a Yokogawa oscilloscope (DL2054) with 12.5 MS/s sampling. In the conventional control system shown in Fig. 9(a), polarity of $i_{tr2}$ is switched in the output period of $v_{tr1}$, and reactive power is generated. On the other hand, in the proposed control system shown in Fig. 9(b), $i_{tr2}$ decreases and reaches to 0 A in the output period for $v_{tr1}$, but $i_{tr2}$ is remained as a constant 0 A, and reactive current is suppressed due to the diode mode in secondary side. Figure 9(a) and (b) confirm that the peak value of $i_{tr2}$ in the proposed control system decreases from 15 A to 8.1 A, and the effective value of $i_{tr2}$ decreases from 7.3 $A_{\text{rms}}$ to 2.3 $A_{\text{rms}}$. Thus, decreased conduction and switching loss by semiconductor elements ($Q_{11}$ to $Q_{22}$) and decreased conduction loss by the transformer (Tr) and high-frequency reactors ($L_1$, $L_2$) is expected. Figure 10 and Fig. 11 are measured waveforms of discharging mode with the proposed control system. The voltage condition in Fig. 10 and Fig. 11 is the lower limit value for battery voltage specifications, which is $V_1 = 290 \text{ V}$. According constant current control by the control system, $P_1$ for current command value $I_{tr1}$, in Fig. 10 measured on the primary side assumes a target value of $-0.8 \text{ kW}$, while $P_1$ for current command value $I_{tr1}$ in Fig. 11 assumes a target value of rated $-3.5 \text{ kW}$. In Fig. 10, the operating condition is Mode 1, and adjusting $\theta_2$. During the period that $v_{tr2} = 0 \text{ V}$, $I_1$ and $L_2$ are excited and $i_{tr2}$ increases. Thereafter, during the output period that $v_{tr2} = 380 \text{ V}$, power is transmitted from the primary side to the secondary side, and $i_{tr2}$ is decreasing. After $i_{tr2}$ reaches 0 A and becomes constant, reactive power is suppressed. In addition, $I_1$ is controlled with a constant $-3.6 \text{ A}$. In Fig. 11, similar to Fig. 10, the operating condition is also Mode 1, and $\theta_2$ is adjusted. However, since power transmission increases compared to Fig. 10, $\theta_2$ is also increased, and the period that $v_{tr2} = 0 \text{ V}$ increases. Similar to Fig. 10, during the period that $v_{tr2}$ is 0 V, $L_1$ and $L_2$ are excited and $i_{tr2}$ increases. Thereafter, during the output period of $v_{tr2}$, $i_{tr2}$ decreases. As a result, $I_1$ is controlled at a constant $-12 \text{ A}$, and favorable discharging control is realized. The operating conditions in Fig. 11 show load power increasing in contrast to Fig. 10, so $i_{tr2}$ during the output period of $v_{tr2}$ is in continuous mode, and thus reactive current is not suppressed. That is, suppressing effect of the reactive power with the proposed control scheme is generated.
Experimental Verification of Reducing Power Loss under Light Load Condition

Ryota Kondo et al.

Fig. 10. Experimental waveforms in boost discharging mode ($V_2 = 380\, \text{V}$, $V_1 = 290\, \text{V}$, $I_{i1}^* = -3.6\, \text{A}$, and $P_2 = -1.0\, \text{kW}$)

Fig. 11. Experimental waveforms in boost discharging mode ($V_2 = 380\, \text{V}$, $V_1 = 290\, \text{V}$, $I_{i1}^* = -12\, \text{A}$, and $P_2 = -3.5\, \text{kW}$)

Fig. 12. Experimental waveforms at the transition from discharging mode to charging mode of $I_1$ control mode ($V_2 = 380\, \text{V}$, $V_1 = 350\, \text{V}$ and $I_{i1}^* = -5\, \text{A} \sim 5\, \text{A}$)

Efficiency characteristics during discharging mode. The voltage conditions are $V_1 = 290\, \text{V}$ and $V_2 = 380\, \text{V}$. The operating waveforms shown in Fig. 9 are waveforms measured under conditions of minimum load ($P_2 = -240\, \text{W}$) shown in Fig. 13. According to the loss comparison results in Fig. 13(a), measured values of both control scheme are largely equal under power conditions of $-3.5\, \text{kW} < P_2 < -2\, \text{kW}$. Under conditions of increased $P_2$ as described above, during the $v_{v2}\text{out}$ output period, $i_{v2}$ does not enter discontinue mode, and no diode mode suppressing reactive current is generated, so no loss difference is generated. Furthermore, rated efficiency is 93.7% in both the conventional control and proposed control. On the other hand, under power conditions of $-2\, \text{kW} < P_2 < 0\, \text{kW}$, loss is decreasing in the proposed control system compared to the conventional control system. The amount of loss reduction increases as $P_2$ decreases, and this experimental scope confirms that under minimum power condition $P_2 = -240\, \text{W}$, loss is reduced from 128.6 W in a conventional control scheme to 61.1 W by 67.5 W (52%). Similarly, according to the efficiency comparison results in Fig. 13(b), under $P_2 = -240\, \text{W}$, efficiency improves from 65.5% in a conventional control scheme to 79.5%.

4. Conclusion

In this paper, we conducted experimental verification of a bi-directional isolated DC/DC converter suppressing reactive current. We established the operating principle of a diode mode in which the semiconductor elements on one arm of full-bridge inverter in a rectification side are turned OFF, and a synchronized phase shift mode in which the phase-shift amounts of full-bridge inverters in both transmission side and

under only light load conditions in which $i_{v2}$ is in discontinuous mode. Figure 12 shows the experimental waveforms at the transmission from discharging mode to charging mode during constant current control. $I_{i1}$, shown in Fig. 7 switches from $-5\, \text{A}$ to $+5\, \text{A}$ in steps under voltage conditions of $V_2 = 380\, \text{V}$ and $V_1 = 350\, \text{V}$. $I_{i1}$ is switched seamlessly from $-5\, \text{A}$ to $+5\, \text{A}$ at about 200 ms. In addition, $V_{gs-Q12}$ reaches off voltage $-5\, \text{V}$ during discharging mode ($I_1 < 0\, \text{A}$) according to gate measured waveforms $V_{gs-Q12}$ and $V_{gs-Q22}$ for Q12 and Q22, but $V_{gs-Q12}$ switches to $-5\, \text{V}$ during charging mode ($I_1 > 0\, \text{A}$). That is, switches between the diode modes for charging and discharging mode in Fig. 3 are realized.

Figure 13 shows the measured loss characteristics and
rectification side are synchronized for continuous changing. Then, 400 V–3.5 kW experimental system realized reactive current suppression effects during light loads, rated charging-discharging operation and seamless power transition between charging mode and discharging mode. Furthermore, we realized loss reduction by 67.5 W (52%) during light loads ($P_2 = -240$ W) according to efficiency characteristics.

References

(1) M. Angelo, A. Pedrasa, T.D. Spooner, and I.F. MacGill: “Coordinated Scheduling of Residential Distributed Energy Resources to Optimize Smart Home Energy Services”, IEEE Trans. Smart Grid, Vol.1, No.2, pp.134–143 (2010)

(2) M. Pippattanamsoporn, M. Kuslu, and S. Rahman: “An Algorithm for Intelligent Home Energy Management and Demand Response Analysis”, IEEE Trans. Smart Grid, Vol.3, No.4, pp.2166–2173 (2012)

(3) K. Ogami, K. Tanaka, K. Uchida, A. Yona, T. Senju, and T. Funabashi: “Optimum operation planning of controllable loads in smart house”, Power Electronics and Drive Systems, 2012 IEEE 4th International Conference on Cloud Computing Technology and Science, pp.141–146 (2012)

(4) H. Omori, Y. Iga, N. Kimura, T. Morizane, and Y. Nakamura: “A Study of the Specification of a Smart-House Based on Analysis of Domestic Electric Power Consumption”, JIASC2012, IEEE Japan, No.4, pp.83–84 (2012) (in Japanese)

(5) N. Yamaguchi: “Approaches and Models of Household Sector in Smart Community”, 2014 National Convention Record, IEEE Japan, No.1, pp.25–26 (2014) (in Japanese)

(6) METI Journal, No.10-11, p.9 (2011)

(7) M. Kawakubo and N. Tsuchimoto: “PV Inverter and EV Charger—Discharger Linked by AC Power Line”, Mitsubishi Denki Gihō, Vol.86, No.10, pp.20–23 (2012)

(8) F. Krismer, J. Biela, and J.W. Kolar: “A Comparative Evaluation of Isolated Bi-directional DC/DC Converters With Wide Input and Output Voltage Range”, in Proc. Industrial Applications Conference (IAS), pp.599–606 (2005)

(9) D.C. Erb, O.C. Onar, and A. Khaligh: “Bi-Directional Charging Topologies for Plug-in Hybrid Electric Vehicles”, in Proc. Applied Power Electronics Conference and Exposition (APEC), pp.2066–2072 (2010)

(10) Y.C. Wang, Y.C. Wu, and T.L. Lee: “Design And Implementation Of A Bidirectional Isolated Dual – Active – Bridge – Based DC/DC Converter With Dual – Phase – Shift Control For Electric Vehicle Battery”, in Proc. 2013 IEEE Energy Conversion Congress and Exposition, pp.5468–5475 (2013)

(11) M. Kwon, S. Jung, and S. Choi: “A High Efficiency Bi-directional EV Charger with Seamless Mode Transfer for V2G and V2H Application”, in Proc. 2015 IEEE Energy Conversion Congress and Exposition (ECCE), pp.5394–5399 (2015)

(12) R.W. De Doncker: “A Three-Phase Soft-Switched High-Power Density DC-DC Converter for High-Power Applications”, IEEE Trans. Industry Applications, Vol.27, No.1, pp.63–73 (1991)

(13) M.H. Kheraluwala and R.W. Gascoigne: “Performance Characterization of a High-Power Dual Active Bridge DC-DC Converter”, IEEE Trans. Industry Applications, Vol.28, No.6, pp.1294–1301 (1992)

(14) H.L. Chan, K.W.E. Cheng, and D. Sutanto: “A Novel Square-Wave Converter with Bidirectional Power Flow”, in Proc. Power Electronics and Drive Systems, 1999. '99. Proceedings of the IEEE 1999 International Conference on, Vol.2, pp.966–971 (1999)

(15) F.Z. Peng, H. Li, G.-J. Su, and J.S. Lawler: “A new ZVS bi-directional dc-dc converter for fuel cell and battery application”, IEEE Trans. Power Electronics, Vol.19, No.1, pp.54–65 (2004)

(16) S. Inoue and H. Akagi: “A bidirectional dc-dc converter for an energy storage system with galvanic isolation”, IEEE Trans. Power Electronics, Vol.22, No.6, pp.2289–2306 (2007)

(17) S. Inoue and H. Akagi: “A bidirectional isolated dc-dc converter as a core circuit of the next-generation medium-voltage power conversion system”, IEEE Trans. Power Electronics, Vol.25, No.2, pp.535–542 (2007)

(18) Y. Xie, J. Sun, and J.S. Freudenberg: “Power Flow Characterization of a Bidirectional Galvanically Isolated High-Power DC-DC Converter Over a Wide Operating Range”, IEEE Trans. Power Electronics, Vol.25, No.1, pp.54–66 (2010)

(19) G. Guidi, A. Kawamura, Y. Sasaki, and T. Imakubo: “Dual Active Bridge Modulation with Complete Zero Voltage Switching Taking Resonant Transitions into Account”, Power Electronics and Applications (EPE2011), pp.1–10 (2011)

(20) K. Wu, C.W. Silva, and W.G. Dunford: “Stability analysis of isolated bidirectional dual active full bridge DC-DC converter with triple phase-shift control”, IEEE Trans. Power Electronics, Vol.27, No.4, pp.2007–2017 (2012)

(21) G.E. Sfakianakis, J. Everts, H. Huisman, and E.A. Lomonova: “ZVS Modulation Strategy for a 3-5 Level Bidirectional Dual Active Bridge DC-DC Converter”, in Proc. 2016 Eleventh International Conference on Ecological Vehicles and Renewable Energies (EVER), pp.1–9 (2016)

(22) A.F. Martinez, S.B. Monge, J.N. Apruzzese, and J. Bordonau: “Operator–ing Principle and Performance Optimization of a Three-Level NPC Dual-Active-Bridge DC-DC Converter”, IEEE Trans. Industrial Electronics, Vol.63, No.2, pp.678–690 (2016)

(23) H. Zhou and A.M. Khambakonde: “Hybrid modulation for dual-active-bridge bidirectional converter with extended power range for ultracapacitor application”, IEEE Trans. Industry Applications, Vol.45, No.4, pp.1434–1442 (2009)

(24) R. Kondo, Y. Higaki, and M. Yamada: “Proposition and Experimental Verification of a Bi-Directional Isolated dc-dc Converter for Battery Charger-Discharger of Electric Vehicle”, IEEE Trans. IA, Vol.135, No.1, pp.61–70 (2016) (in Japanese)

(25) R. Kondo, Y. Higaki, and M. Yamada: “Proposition and Experimental Verification of a Bi-Directional Isolated dc-dc Converter for Battery Charger-Discharger of Electric Vehicle”, in Proc. Applied Power Electronics Conference and Exposition (APEC), pp.1713–1720 (2016)

(26) R. Kondo, Y. Higaki, and M. Yamada: “Experimental Verification of a Power Loss Reduction by Suppressing a Reactive Power of a Bi-Directional Isolated DC/DC Converter of Battery Charger – Discharger for Electric Vehicle”, JIASC2016, IEEE Japan, No.1, pp.269–274 (2015) (in Japanese)