Isolated DC to Single-phase AC Converter with Active Power Decoupling Capability for Battery Storage System

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Abstract—This paper proposes a new active power decoupling topology circuit, which does not require any additional passive components and switching devices for battery storage systems. This converter operates as the bidirectional isolated DC to single-phase AC converter with the power decoupling capability using the coupled inductor. The pulse density modulation (PDM), which achieves zero voltage switching (ZVS) is applied for the secondary side converter using a matrix converter (MC) in order to reduce the switching losses. This paper mentioned that the proposed circuit reduces the double-line frequency power ripple on the input current to 10.3% by the experiment. In addition, the output voltage THD is lower than 3.0% overwide load range.

Keywords—Battery Storage System; Electronic Vehicle; Single-phase converter; Power ripple compensation

I. INTRODUCTION

Recently, the research of Electric Vehicle (EV) and Plug-in Hybrid Electric Vehicle (PHV) have been rapidly expanded [1]. An isolated DC to single-phase AC converter is the main component of a battery storage system for these vehicles in order to achieve a safe connection.

The converter topologies for the battery storage system have been studying for following requirements; (i) long lifetime, (ii) high efficiency, (iii) small volume, (iv) high reliability, (v) galvanic isolation. The EV/PHV with the battery storage system become increasingly popular to meet the all following conditions. However, in the conventional topologies, the large electrolytic capacitor is required to absorb a double-line frequency power ripple, which is caused by instantaneous power mismatch between DC and the AC grid side. As a result, the using large electrolytic capacitor is brought to limit the lifetime and results in low reliability of the conventional converter.

As one of the solution, active power decoupling topologies, leading to the elimination of the bulky electrolytic capacitors in the DC-link have been studying [2-6]. These active power decoupling topologies charge and discharge the buffer capacitor by the additional switching devices and passive components in order to compensate the double-line frequency power ripple. It is possible to ensure the reliability and the life-time compared to the conventional method by the buffer capacitor, which enable to use of film or ceramic capacitor instead of the bulky electrolytic capacitor. The problems of almost conventional active power decoupling topologies and control methods are the switching losses due to hard switching of an entire converter and additional switching devices for active power decoupling capability. However, these additional components prevent the high efficiency, high reliability and the downsizing of the converter system.

This paper proposes a new active power decoupling topology for an isolated DC to single-phase AC converter based on matrix converter (MC). The originality of this proposed active power decoupling topology is not require any additional components, owing to the employment of the coupled inductor. The coupled inductor assumes the boost operation and the power decoupling operation without additional magnetic component in the proposed converter. Furthermore, in order to reduce the converter losses, MC is applying to the secondary side. MC is achieved to reduce in the number of the conversion from two stages to one stage compared to a typical converter configuration as a rectifier and a full bridge converter, In addition, a pulse density modulation (PDM) is applied to MC in order to achieve the zero voltage switching (ZVS). This paper presents the validity of the proposed method by experiment.

II. CIRCUIT CONFIGURATION

A. Conventional circuit

Figure 1 shows an isolated DC to single-phase AC converter with the conventional power decoupling circuit. This power decoupling circuit is applied at the primary side in order to eliminate the bulky electrolytic capacitor. In the conventional power decoupling method, the buffer capacitor voltage is actively fluctuated in order to absorb the power ripple. Therefore, the DC-link capacitance is achieved to minimize the comparison with that in \( C_{dc} \) as shown in Fig. 1 because the buffer energy is ensured by the capacitor voltage. However, the conventional power decoupling method
requires the additional switching devices and magnetic components. In addition, the conventional converter configuration has a number of the four stages power conversion including the active power decoupling method. Consequently, this method increases the volume of the cooling system and the converter loss.

B. Proposed circuit

Figure 2 presents the proposed isolated DC/AC converter, which is composed by a matrix converter and a full-bridge inverter with the coupled inductor. The third-winding $N_3$ of the coupled inductor is galvanic isolation between the primary side. In particular, the buffer capacitor $C_{buf}$ absorbs the double-line frequency power ripple by charging and discharging it, whereas full-bridge inverter controls the buffer capacitor voltage. In the secondary-side, MC is employed to eliminate the DC-link smoothing capacitors. Furthermore, the MC is achieved to reduce the number of the power conversion from two stages to one stage in the secondary side compared to a general configuration of a rectifier and a full-bridge inverter. Thus, MC as a secondary converter contribute the improvement of the power density of the converter system and the converter efficiency.

Figure 3 shows the operation modes of full-bridge inverter with the coupled inductor. The proposed inverter has four operation modes which generate a phase shift between the switching of each arm. Fig. 3 (a) and (b) is power transfer operation mode to secondary side. On the other hand, Fig. 3 (c) and (d) is power decoupling operation mode in order to charge and discharge the buffer capacitor. A leakage inductor of the coupled inductor is utilized as the boost inductor $L_{boost}$. Note that the main power from the battery to the AC grid is controlled by the differential mode, whereas the power ripple component is absorbed by controlling the common mode. The inductance of the boost inductor in worst case, which ripple ratio is maximum is calculated by

$$L_{boost} = \frac{d_{com,max} V_{dc}}{2 \Delta i_{dc} f_{sw}} \tag{1}$$

$$\Delta i_{ripple} = \frac{i_{ripple,pp}}{2} \tag{2}$$

where $\Delta i_{dc}$ is the allowable current ripple ratio, $i_{ripple,pp}$ is the peak to peak value of the input current $i_{dc}$, $V_{dc}$ is a DC input voltage and $f_{sw}$ is the switching frequency. Note that the $d_{com,max}$ is the maximum reference of the common mode in a one period, which is explained in next section.

C. Principle of power decoupling

If both the grid current and voltage are sinusoidal, the buffer capacitor voltage $V_{buf}$, which necessary to compensate the power ripple is calculated based on the energy of the buffer capacitor. First, the energy of the buffer capacitor $W_{buf}$ is expressed by

$$W_{buf} = \int_{t_1}^{t_2} V_{buf}^2 dt = \int_{t_1}^{t_2} C_{buf} \frac{dV_{buf}}{dt} dt$$

$$= \int_{t_1}^{t_2} P_{av} \cos(2\omega_t \tau) d\tau$$

where $P_{av}$ is the average power and $\omega_t$ is the grid angular frequency.
where $i_{\text{buf}}$ is the current of $C_{\text{buf}}$, $P_{\text{ave}}$ is the average power of the output-side and $\omega_0$ is the grid-side angular frequency. From (3), the voltage of the buffer capacitor $v_{\text{buf}}$ for the compensation of the power ripple is presented by

$$v_{\text{buf}} = \sqrt{V_{\text{cc}}^2 + \frac{P_{\text{ave}}}{\omega_0 C_{\text{buf}}}(\sin(2\omega_0 t) - \sin(2\omega_0 t_0))}$$

$$= \sqrt{V_{\text{cc}}^2 + \frac{P_{\text{ave}}}{\omega_0 C_{\text{buf}}}(\sin(2\omega_0 t))}$$

(4)

where $V_{\text{cc}}$ is the buffer capacitor voltage at a start time $t_0$.

III. CONTROL STRATEGY

In the control of the differential mode operation as a power transfer, the three-winding voltages of the coupled inductor are controlled into a three-level wave form by operation modes as shown in Fig. 3 (a) and (b). On the other hand, the common mode operation is controlled to absorb the power ripple. In particular, the power ripple component occurs in the buffer capacitor voltage because the input current is regulated into a constant value in the proposed power decoupling method.

Then, the common mode operation of the proposed method is employed for the remaining period after the differential mode operation. Therefore, the duty ratio of the common mode operation is calculated by the following:

$$d_{\text{com,c}} = (1 - d_{\text{diff}}) \frac{v_{\text{com}}^*}{v_{\text{buf}}}$$

(5)

where $d_{\text{diff}}$ is the duty ratio of the differential mode, whereas $d_{\text{com,c}}$ is the duty ratio of the common mode as shown in Fig. 5(c) and $v_{\text{com}}^*$ is a command of the common voltage. This common mode voltage command $v_{\text{com}}^*$ is output by a PI control of the DC input current as explained in the next section. In addition, $d_{\text{diff}}$ is decided to the maximum value of the relationship between the input and output voltage.

Figure 4 shows a relationship among each command, the triangle carrier and the switching pattern of the primary converter in the proposed system. The differential mode voltage of each duty ratios as shown in Fig. 3(a) and (b) in a carrier period is equal in order to suppress a DC biased magnetization of the coupled inductor, especially. The comprising signals A and B is generated by comprised duties which the sum of “$d_{\text{com,c}}$ and $d_{\text{diff}}$” and only $d_{\text{com,c}}$ and a triangle carrier as shown in Fig. 4. Thus, the desired operation in each duties of the primary converter is actualized as described previously. The primary converter of the proposed system achieves the power decoupling operation and the transfer power to the secondary side at the same time without the additional passive components and the switching devices.

Figure 5 shows the control block diagram of the proposed system with the power decoupling capability. The DC input current control, which absorbs the power ripple component, is control by using PI controller. The actively fluctuated value of the buffer capacitor voltage command is calculated by (4). Furthermore, the pulse pattern conversion outputs the each gate signal using carrier and signals A and B as shown in Fig. 4.

IV. MODULATION METHOD OF MATRIX CONVERTER

Figure 6 shows the signal generation block of the proposed PDM based on the delta-sigma conversion [6]. In this PDM method, the output grid voltage waveform is generated by using the input voltage pulses of MC as the minimum unit. PDM allows MC to switch at the zero voltage period of the third-winding of the coupled inductor. Moreover, the distortion of the grid voltage, which influences on the output voltage quality of MC is achieved to become low. A delta-sigma conversion generates the inverse voltage pulses in order to cancel the quantization error. Consequently, MC with this PDM method achieves the decrease of the switching loss and the low output voltage THD.

V. EXPERIMENTAL RESULT

Table 1 shows the experimental conditions and Figure 7 demonstrates the experimental waveforms of the proposed converter with/without the power decoupling method at R-L.
Voltage fluctuation is small because the ripple is low because the pulse is applied without power decoupling method. However, a small ripple component to 10.3% in maximum. It is verified from the analysis result in Fig. 2 that the power pulsation are compensated by the active power decoupling capability. In contrast, the proposed method actively fluctuates the input current of the proposed converter. This proposed converter configuration is chosen because of the following advantages:

(i) Boost operation is achieved without additional $L$,
(ii) Elimination of bulky electric capacitors in the circuit,
(iii) The buffer capacitor using a low capacitance,
(iv) No additional component for the power decoupling,

**VI. CONCLUSION**

This paper has proposed a new DC to single-phase AC isolated converter with the power decoupling capability by using the coupled inductor. This proposed converter configuration is chosen because of the following advantages:

- Boost operation is achieved without additional inductance
- Elimination of bulky electric capacitors in the circuit
- The buffer capacitor using a low capacitance
- No additional component for the power decoupling
(v) Low output voltage THD.

A prototype was constructed to validate the power decoupling method and fundamental operation in experiment. As a result, the power ripple component of a secondary-order harmonics was reduced by 79.2% in comparison to the case without the proposed power decoupling method. The result with applying the PDM based on the delta-sigma conversion is verified to achieve ZVS operation in MC and low output voltage THD, which is lower than 3.0% within the entire output power range.

In future work, we will analyze the loss distribution of the proposed converter.

REFERENCES