A Star-Connected Rectifier Employed by the Three-Phase Interleaved LLC Resonant Converter used by the High-Efficiency Isolated AC–DC Converter

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Abstract: The power conversion efficiency of an isolated ac–dc converter is a dominant factor in the overall efficiency of dc distribution systems. To improve the power conversion efficiency of the dc distribution system, a three-phase interleaved full-bridge LLC resonant converter employing a Y-connected rectifier is proposed as an isolated ac–dc high-frequency-link power-conversion system. The proposed Y-connected rectifier has the capability of boosting the output voltage without increasing the transformer’s turn ratio. Especially, the frequency of the rectifier’s output ripple is six times higher than the switching frequency, thereby reducing the output capacitor and the secondary transformer’s RMS current. However, the tolerance of the converter’s resonant components in each primary stage causes the unbalance problem of output ripple current. It cannot be solved using fuzzy logic control technique. To solve the current unbalance problem, a current balancing with fuzzy logic controller method is proposed for the output rectifying current. The performance of the proposed converter and the current balancing method of a 10 kW (300 V/33.3 A) prototype converter verified using MATLAB/SIMULINK software.

Keywords: Fuzzy logic controller, Current balancing method, high-frequency power interface, LLC resonant converter, three-phase interleaved, Y-connected rectifier.

I. INTRODUCTION

In modern times, a tremendous growth in telecommunication and data storage systems has resulted in the installation of millions of internet data center (IDC) around the globe. As the volume of data centers and servers has grown, the overall amount of electricity consumption also increased. Power distribution systems in a typical data center consist of several power conversion stages. Especially, electrical power is delivered using an ac grid system that goes through multiple power conversions between ac and dc. Each power conversion increases the power conversion loss caused by the reverse recovery current which increases the power loss. In order to reduce this power loss of the CC M PFC rectifier, the reverse recovery current of the rectifying diode should be reduced. To solve this reverse recovery problem, various soft switching techniques using additional passive or active snubber circuits have been proposed [12]. However, those methods require relatively large numbers of passive or active components which increase the production cost of the system. Moreover, the complex structure of the rectification circuit with many switching components decreases the reliability of the overall power conversion system.

An alternative method to minimize those drawbacks is the use of SiC diodes instead of conventional diodes in the rectification circuit [7], [8]. The SiC diode has very small reverse recovery current. Therefore, it can reduce the power loss caused by the reverse recovery current. Conventional full-bridge diodes used on the front side of the PFC circuit also
increase conduction losses. Various bridgeless PFC topologies have been proposed for eliminating the full-bridge diode rectifier [9]. Those topologies can get rid of the line-current path and can decrease the conduction loss caused by the full-bridge diode. The power density of an isolated dc–dc converter for the dc power distribution systems is one of the significant performance indicators, since the size of the desired system is limited. Therefor, multiple medium power converters connected in parallel, which share load current to increase the amount of power con-version is proper rather than a single large converter employing parallel switching devices with a big isolation transformer. A full-bridge phase shift converter is a frequently selected topol-ogy for high power dc–dc applications [25]–[27]. In order to increase the converter’s rated power using parallel operations, the parallel connection methods for the output stages using mul-tiple phase-shift converters have been proposed [28], [29]. However, these topologies cannot accomplish zero-voltage switching (ZVS) under light load conditions and additional filter inductors for the output rectifier are required.

The LLC resonant converter is another popular topology because of its outstanding performance such as high-power conversion efficiency, high power density, and its ZVS capability over the entire load range. Multiphase LLC resonant converters have also been developed to reduce the output ripple current[3]. Since an interleaved operation for the LLC resonant converter has been adopted, the output ripple current and the size of the filter capacitors could be reduced. However, those conventional studies have concentrated on the low output voltage and high-output current applications using a center-tapped transformer. The number of turns in the secondary winding used for the center-tap structure is twice the turn number required for the full-bridge structure [35]. Since the output voltage needed for the dc distribution system is relatively high (e.g., 300 to 400 V), the center-tap structure is not suitable for high-output voltage applications. A three-phase interleaved LLC resonant converter employing a Y-connected rectifier is proposed in this paper.

The proposed converter consists of three full-bridge LLC resonant converters whose output stage is composed of Y-connected three-phase full-bridge diode rectifiers for each secondary transformer winding. It has ZVS capability over the entire load range similar to the conventional LLC resonant converter. In addition, the proposed Y-connected rectifier can boost the output voltage without in-creasing the transformer’s turn ratio. Especially, the frequency of the rectifier’s output ripple is six times higher than the switching frequency, thereby reducing the output capacitor and the RMS current of the transformer’s secondary winding. Therefore, the proposed converter is suitable for high-power and high-output voltage applications. However, the imbalance of resonant net-works in the LLC resonant converters can cause the unbalance phenomena of output rectifying current. It cannot be solved using conventional control techniques since the structure of the three-phase interleaving has the limitation of individual control capability for each converter. In this paper, the high efficiency isolated ac–dc converter will be discussed to improve the performance of the dc distribution system. The proposed isolated ac–dc converter is composed of the high-efficiency bridgeless PFC rectifier with the SiC diodes, and the three-phase interleaved full-bridge LLC resonant converter with the Y-connected rectifier. In addition, an output current balancing method for the three-phase interleaved LLC resonant converter will be proposed. The performance of the proposed ac–dc high-frequency-link power-conversion system will be experimentally verified using a 10 kW prototype converter. The three-phase interleaved LLC resonant converter employing the Y-connected rectifier is required to compensate the unbalanced current. The detail description of the proposed current balancing algorithm using a reference control circuit will be presented in the next Section.

![Fig.1. Circuit diagram of the proposed isolated ac–dc high-frequency-link power-conversion system.](image)

![Fig2. Schematic of PFC rectifier with the control circuit of output voltage reference.](image)

**II. PROPOSED CURRENT BALANCING METHOD**

A. Rectifying Current Balancer Based on DC-Link Voltage Compensation

As explained in the aforementioned Section, the unbalance phenomena of the rectifying current in the proposed converter are influenced by the gain difference of each converters resonant network. When the input voltage of the converter is fixed, the unbalance problem cannot be solved using the
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conventional PFM controller because of the limitations of individual control capability for each converter, which means the same switching frequency for all converters. If another controller is able to control the output voltages of bridgeless PFCs, the difference of the resonant gain can be compensated by adjusting input voltages of each converter. In addition, this method can control each output rectifier current passing through the output filter capacitors in the Y-connected rectifier. Fig. 8 shows the propose control strategy of the bridgeless PFC using the control circuit of output voltage reference. The control circuit is a hybrid voltage controller based on a conventional analog voltage controller of PFCs with digital control signal generated from a DSP. If all of the bridgeless PFC converters can be controlled by the DSP controller, the balancing algorithm will be easily implemented because the controller has an advantage of easily adjustable output voltage reference. However, this method requires additional voltage and current sensing circuits, which convert analog signals to isolated digital signals for the DSP using the proposed three-phase interleaved Y-connected LLC resonant converter with Y-connected rectifier. In addition, this method also increases the computational burden of the DSP controller and the production cost of the ac–dc high-frequency-link power-conversion system.

As shown in Fig. 8, the proposed bridgeless PFC circuit is controlled by an analog PFC controller. In order to adjust the output voltage of the bridgeless PFC, an output voltage reference control circuit (OVRCC) is proposed. It is simply composed of a bipolar junction transistor, a resistor, and a PWM signal, PWM $V_{dc-link\text{ ref}}$, generated from the DSP controller. When the duty ratio of PWM $V_{dc-link\text{ ref}}$ increases, the OVRCC decreases $V_{dc-link\text{ ref}}$; consequently, the analog PFC controller will increase the output voltage of the bridgeless PFC. On the other hand, the voltage controller will decrease the output voltage of the bridgeless PFC when the duty ratio of PWM $V_{dc-link\text{ ref}}$ decreases for reducing the reference voltage. Using OVRCC, the output voltage of PFCs, which is the input voltage of the proposed LLC resonant converter, can be controlled by the DSP controller. In order to prevent unstable and uncontrollable conditions in the output voltage of PFCs, it is limited by a hardware protection circuit as resistors $R_1$, $R_2$, and $R_3$, which determined the output voltage reference $V_{dc-link\text{ ref}}$. When the duty ratio of PWM $V_{dc-link\text{ ref}}$ is zero, the maximum voltage of $V_{dc-link\text{ ref}}$ can be derived. The output voltage of PFCs is limited to the mini-mum voltage. When the duty ratio of PWM $V_{dc-link\text{ ref}}$ is max-imum, $V_{dc-link\text{ ref}}$ falls to the minimum voltage as shown next.

Therefore, the output voltage of PFCs is limited to the mini-mum voltage. Actually, the variation of the PFCs’ output voltage under overall load variation is enough about ±5% from the experimental results. Therefore, the minimum output voltage of PFCs is limited to 360 V. In addition, the maximum output voltage of PFCs is limited to 400 V. The proposed LLC resonant converter is designed to be able to accommodate the change of input voltage about ±20 V. In addition, the proposed LLC resonant converter and the proposed bridgeless PFC rectifier are controlled independently. Therefore, the unstable condition caused by the proposed balance methods can be prevented. For controlling output rectifier current, the peak value of the output rectifier current should be measured. Fig. 9 shows the peak current sensing circuits of the proposed converter using current transformers (CTs). Using CTs in the secondary stage of the Y-connected rectifier, the amplitude of each output rectifier current can be measured. These sensing signals are transferred to the DSP controller to calculate the peak value of each output rectifier current.

III. PROPOSED CURRENT BALANCING METHOD with FLC

As explained in the aforementioned Section, the unbalance phenomena of the rectifying current in the proposed converter are influenced by the gain difference of each converter’s resonant network. When the input voltage of the converter is fixed, the unbalance problem cannot be solved using the conventional PFC controller because of the limitations of individual control capability for each converter, which means the same switching frequency for all converters. If another controller is able to control the output voltages of bridgeless PFCs, the difference of the resonant gain can be compensated by adjusting input voltages of each converter. In addition, this method can control each output rectifier current passing through the output filter capacitors in the Y-connected rectifier. Fig 2 shows the propose control strategy of the bridgeless PFC using the control circuit of output voltage reference. If all of the bridgeless PFC converters can be controlled by the DSP controller, the balancing algorithm will be easily implemented because the controller has an advantage of easily adjustable output voltage reference. However, this method requires additional voltage and current sensing circuits, which convert analog signals to isolated digital signals for the DSP using the proposed three-phase interleaved-connected LLC resonant converter with Y-connected rectifier. In addition, this method also increases the computational burden of the DSP controller and the production cost of the ac–dc high-frequency-link power-conversion system.

As shown in Fig 2, the proposed bridgeless PFC circuits controlled by an analog PFC controller. In order to adjust the output voltage of the bridgeless PFC, an output voltage reference control circuit (OVRCC) is proposed. It is simply composed of a bipolar junction transistor, a resistor, and a PWM signal, PWM $V_{dc-link\text{ ref}}$, generated from the DSP controller. When the duty ratio of PWM $V_{dc-link\text{ ref}}$ increases, the OVRCC decreases $V_{dc-link\text{ ref}}$; consequently, the analog PFC controller will increase the output voltage of the bridgeless PFC when the duty ratio of PWM $V_{dc-link\text{ ref}}$ decreases for reducing the reference voltage. Using OVRCC, the output voltage of PFCs, which is the input voltage of the proposed LLC...
resonant converter, can be controlled by the DSP controller. In order to prevent unstable and uncontrollable conditions in the output voltage of PFCs, it is limited by a hardware protection circuit as resistors R1, R2, and R3, which determined the output voltage reference Vdc−link ref. When the duty ratio of PWM Vdc−link ref is zero, the maximum voltage of Vdc−link ref can be derived as following the equation

\[ V_{dc-link\_ref} = V_{dc-link} \times \frac{R_3}{R_1 + R_2} \]  

(1)

From (1), the output voltage of PFCs is limited to the minimum voltage. When the duty ratio of PWM Vdc−link ref is maximum, Vdc−link ref falls to the minimum voltage as

\[ V_{dc-link\_ref} = V_{dc-link} \times \frac{R_3}{R_2} \]  

(2)

Therefore, the output voltage of PFCs is limited to the maximum voltage.

![Fig3. Current Control method employing with fuzzy logic.](image)

![Fig4. Fuzzy logic inputs & output.](image)

In the case of the PFC side of the selected reference current, the output reference control voltage Vdc−link ref is fixed. It means that the duty ratio of PWM Vdc−link ref maintains the previous duty ratio. In the case of the maximum rectifier current, the output voltage of the PFC should be decreased because the resonant gain of this full-bridge LLC resonant converter.

![Fig5. Surface of the rule base.](image)

![Fig6. Prototype of the proposed 10 kW isolated ac–dc high frequency-link power-conversion system.](image)

![Fig7. Output voltage in (v) & current.](image)
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**Fig 8. Detailed Output Current & Output Voltage.**

**Fig 9. Transformer Secondary Currents In Amps.**

**Table I. Design Specifications of the Prototype Bridgeless PFC Converter**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage ($V_{in}$)</td>
<td>AC 220V</td>
</tr>
<tr>
<td>Output Voltage ($V_{out}$)</td>
<td>DC 380V</td>
</tr>
<tr>
<td>Rated Power ($P_{out}$)</td>
<td>3.3kW × 3</td>
</tr>
<tr>
<td>PFC Control IC</td>
<td>L4981</td>
</tr>
<tr>
<td>Main Switch ($S$)</td>
<td>IXKR47N60C5</td>
</tr>
<tr>
<td>Rectifier Diode ($D_r$)</td>
<td>DSE12X101-06</td>
</tr>
<tr>
<td>Boost Diode ($D_s$)</td>
<td>C3D20060D</td>
</tr>
<tr>
<td>Boost Inductance ($L_1 = L_2$)</td>
<td>800 μH</td>
</tr>
</tbody>
</table>

**V. CONCLUSION**

To improve the power conversion efficiency for the dc distribution system, the high efficiency isolated ac–dc high frequency-link-power-conversion system is proposed. The proposed system is composed of the bridgeless PFC rectifier with Sic diodes and the three-phase interleaved full-bridge LLC resonant converter with the Y-connected rectifier. In addition, the output current balancing method for the three-phase interleaved LLC resonant converter is proposed. From the mat lab simulation of 10-kW (300 V/33.3 A) prototype converter, the validity and effectiveness of the proposed converter and the current balancing method using FLC have been verified. Under the 10% unbalanced condition of the proposed dc–dc converter, the proposed balancing method can reduce the peak-to-peak ripple current about 41% at 1 kW and 29% under 8-kW load conditions. The proposed dc–dc converter shows high-power conversion efficiency at the rated load of 10 kW.

**VI. REFERENCES**


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