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A Load Adaptive Control Approach for Zero Voltage Switching Dcdc Converter Used For Electric Vehicles

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Abstract:

This paper presents a load adaptive control approach to optimally control the amount of reactive current required to guarantee zero-voltage switching (ZVS) of the converter switches. The proposed dc/dc converter is used as a battery charger for an electric vehicle (EV). Since this application demands a wide range of load variations, the converter should be able to sustain ZVS from full-load to no-load condition. Which guarantees ZVS at turn-on times? The proposed control scheme is able to determine the optimum value of the reactive current injected by the auxiliary circuit in order to minimize extra conduction losses in the power MOSFETs, as well as the losses in the auxiliary circuit. In the proposed approach, the peak value of the reactive current is controlled by controlling the switching frequency to make sure that there is enough current to charge and discharge the snubber capacitors during the dead time. In addition, some practical issues of this application (battery charger for an EV) are discussed in this paper. Experimental results for a 2-kW dc/dc converter are presented. The results show an improvement in efficiency and better performance of the converter.

Index Terms—Current balancing method, high- frequency power interface, *LLC* resonant converter, three-phase interleaved, Y-connected rectifier

1.INTRODUCTION

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 power losses, which wastes energy, produces heat, and requires a data center's heavy cooling system. The conventional several power delivery architectures which use ac or dc voltage have been presented.

A conventional ac power distribution system of the IDC consists of four power conversion stages with a traditional online uninterrupted power supply (UPS), which employs an ac–dc–ac double conversion. Compared with the ac distribution system, the dc distribution system does not need several power conversion stages such as the online UPS and the individual power factor correction (PFC) circuit in front of each power supply unit (PSU) Therefore, the dc distribution system for the data centers can reduce the power conversion loss caused by redundant power stages.

The galvanic isolation in the power conversion stage is not more popular than the isolation of the server level; however, it is one of interesting research topics of isolation applications .

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II. PROPOSED AC–DC HIGH-FREQUENCY-LINK POWER-CONVERSION SYSTEM

The proposed ac–dc high-frequency-link power-conversion system is composed of three bridgeless PFC rectifiers and a three-phase interleaved *LLC* resonant converter. Fig. 1 shows the schematic of the proposed isolated ac–dc converter. To improve power conversion efficiency, the CCM bridgeless boost PFC rectifier using the SiC diodes has been designed. The input power source of the proposed ac–dc converter is three-phase four-wired ac. Each of the rectifier is controlled by a commercial analog controller. In addition, the three-phase interleaved full-bridge *LLC* resonant converter using the Y- connected rectifier is proposed for high efficiency dc–dc power conversion and galvanic isolation. The Proposed converter is controlled by a single digital signal processor (DSP). The proposed current balancing algorithm is also implemented by the same DSP. The detailed circuit operations of the proposed converter will be discussed in this Section.

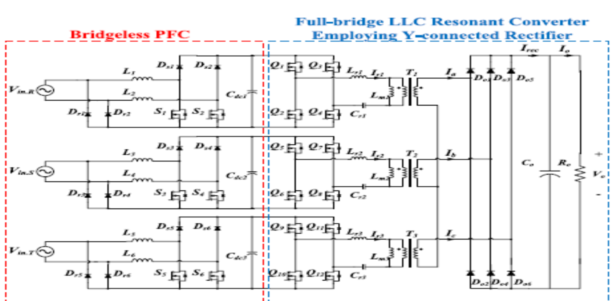

Fig.1. Circuit diagram of the proposed isolated ac–dc high-frequency-link Power-conversion system

A. Bridgeless PFC

As shown in Fig. 1, a bridgeless PFC with a dual boost method is used for the first stage of the proposed system. The topology is the best choice in medium-to-high power applications since it has a simple current-sensing circuit, low conduction loss, and small EMI noise. In addition, two power switches can be driven using the same PWM signal.

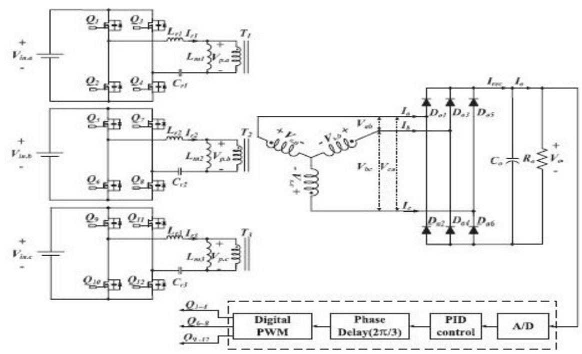

Fig.2.Schematic of the proposed three-phase interleaved *LLC* resonant converter with DSP control

B. Three-Phase Interleaved LLC Resonant Converter Employing the Y-Connected Rectifier

Fig. 2 shows the schematic of the proposed dc–dc power conversion stage. The proposed converter has 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. Due to these advantages, the proposed converter is suitable for high power and high-output voltage applications. The proposed converter can be controlled in the same manner as the conventional single-phase full-bridge *LLC* converter. The converter's output voltage can be controlled using a conventional pulse frequency modulation (PFM) technique, however, the phase difference for each converter's switching signal is $2\pi/3$. The steady-state equation of the output voltage ,V_{out} , can be derived as follows:

$$V_{out} = 2MnV_{in} \quad (1)$$

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where n is the turn ratio of the transformer as $n = N_1/N_2$ and M is the resonant gain, respectively. From (1), the output voltage of the proposed converter can be doubled due to the Y-connected rectifier, compared with the input–output voltage ratio of the single-phase *LLC* resonant converter Fig. 3 shows the theoretical operating waveforms of the proposed converter in a steady state. The operation of the proposed converter can be divided into 12 operating modes. In this paper, representative operation modes such as *Mode* 1 (t_0 -t_1) and *Mode* 2 (t_1 -t_2) will be explained. In *Mode* 1, the master converters' switches Q_1 and Q_4 turn ON under the ZVS condition and the magnetizing current I_{m1} increases in the positive direction. In addition, the slave converter's switches Q_6 , Q_7 , Q_9 , and Q_{12} continue in their ON state and their resonances are still in progress. During this period, the rectifying diodes D_{o1} , D_{o4} , and D_{o5} turn ON and all of the primary side's energy in the three converters is transferred to the secondary rectifying stage. In *Mode* 2, when the primary current, I_{r3} ,meets the magnetizing current I_{m3} , the resonance in the primary stage ends and the energy is transferred from the primary to the secondary stage. At this time, D_{o5} is turned OFF, while D_{o1} and D_{o4} remain ON. During this periods, only two converters transfer their energy in the primary stage to the output. The other operations can be explained as the same manner as *Mode* 1 and 2. *Mode* (1, 2) repeats to *Mode* (3, 4), *Mode* (5, 6), *Mode* (7, 8), *Mode* (9, 10), and *Mode* (11, 12) with different switches and rectifier diodes.

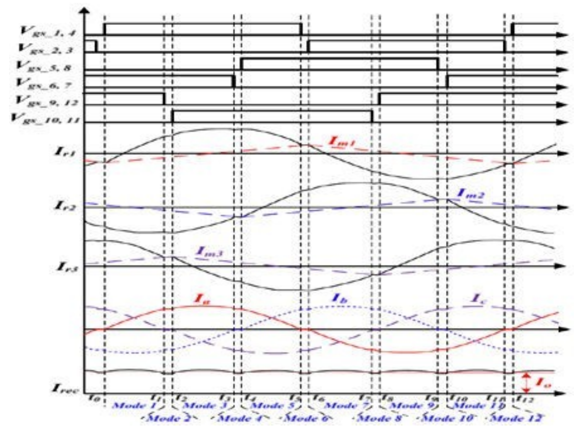

Fig.3. waveforms of the proposed converter

III. UNBALANCE PHENOMENA OF RECTIFYING

As aforementioned, the output voltage of the proposed *LLC* resonant converter can be controlled by using the conventional PFM method. It means that the switching frequencies of the three converters are all the same because of the phase-shifted switching operation at the same frequency. In addition, the switching operation is controlled by a single DSP. The phase difference among each converter's switching signal is $2\pi/3$ for the interleaved operation. Due to this control strategy, the proposed converter has the limitation of the individual control capability of the output voltage for each converter. If the resonant components of the primary stages of the proposed converter have some tolerance,. The resonant component of the three *LLC* resonant converters under the balanced condition are designed to L_m = 470 μH, L_r = 120 μH, and C_r = 141nF, respectively. The series resonant frequency, f_r ,can be calculated using the following equation:

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (2)$$

In order to analyze the tendency of the gain variation due to the tolerance of the resonant components, the

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resonant inductance, Lr , is changed to±10%. If the series resonant frequency is changed by the variation of the resonant inductance at the same output load condition, the resonant gain located at the operating frequency will be changed. Using (2), fr 132 μH is lower than fr 120 μH because Lr is 10% larger than the original resonant inductance. The overall gain curve at the resonant inductance Lr 132 μH is shifted to the left side of the original gain curve. Therefore, the overall resonant gain curve in the operating frequency region of Lr 132 μH is decreased. In the same way, fr 108 μH is higher than fr 120 μH

IV. 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 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.

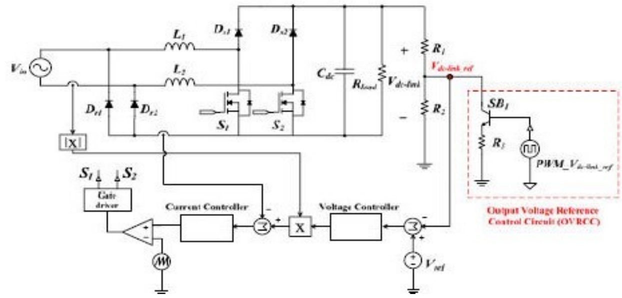

Fig.4 Schematic of PFC rectifier with the control circuit of output voltage reference

Fig.4. 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 a 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. 4, 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. When the duty ratio of PWM $V_{dc\text{-link ref}}$ is zero,

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the maximum voltage of $V_{dc\text{-}link\ ref}$ can be derived as following the equation:

$$V_{dc\text{-}link\ ref} = R_1/R_2 \times V_{dc\text{-}link}. \quad (3)$$

From (3), the output voltage of PFCs is limited to the minimum voltage. When the duty ratio of PWM $V_{dc\text{-}link\ ref}$ is maximum, $V_{dc\text{-}link\ ref}$ falls to the minimum voltage as shownnext

$$V_{dc\text{-}link\ ref} = R_1/R_2//R_3 \times V_{dc\text{-}link}. \quad (4)$$

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

B. Algorithm Implementation Using DSP-Based Control System

Figs. 5 and 6 show the proposed current balancing algorithm and the control scheme of the algorithm, respectively. The current balancing algorithm is implemented using the DSP controller which also controls the output voltage of the proposed dc–dc converter. According to the magnitude of the peak value of the rectifier current, the proposed current balancing circuit changes each output voltage of the PFC circuits. As shown in Fig. 5, if the difference among the sensed rectifying currents of each converter is over a specific threshold, the middle value

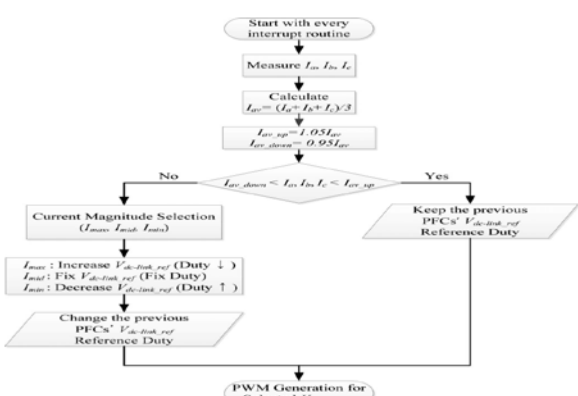


Fig.5. Proposed current balancing algorithm

Among the output rectifier currents will be selected as the reference current. In the case of the PFC side of the selected reference current, the output reference control voltage $V_{dc\text{-}link\ ref}$ is fixed. It means that the duty ratio of PWM $V_{dc\text{-}link\ ref}$ 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 coverter is higher than other converters.

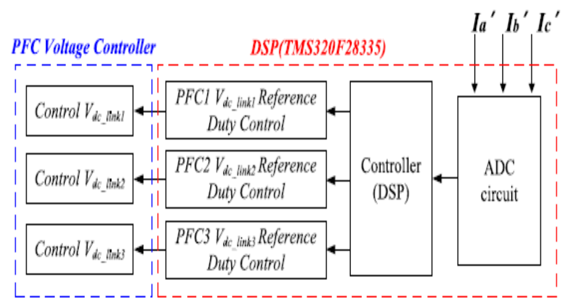


Fig.6 Control strategy of the proposed current balancing algorithm using analog and DSP controllers

In the case of the minimum rectifier current, the PFC' output voltage should be increased because the resonant gain of this converter is lower than other converters. Using the proposed balancing algorithm, the difference of the resonant gain among *LLC* resonant converters can be compensated. As a result, the unbalanced output rectifier current can be regulated.

V. SIMULATION RESULTS

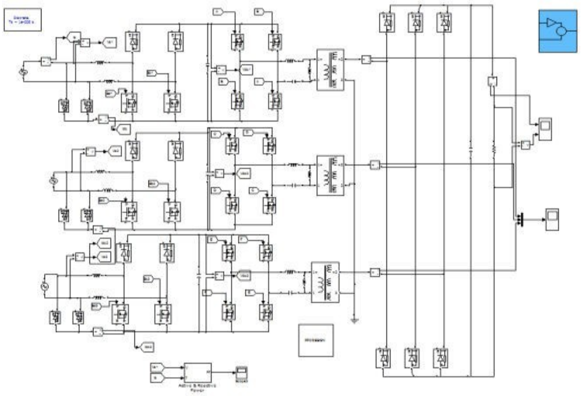


Fig 7 simulation circuit of proposed converter

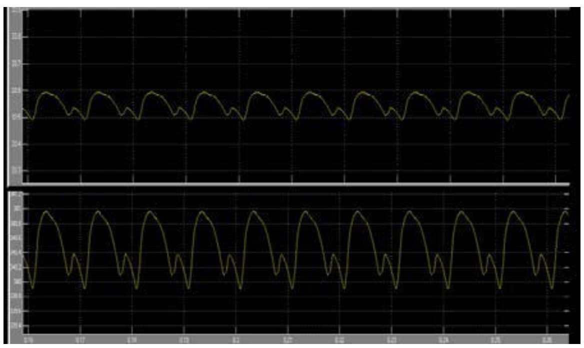
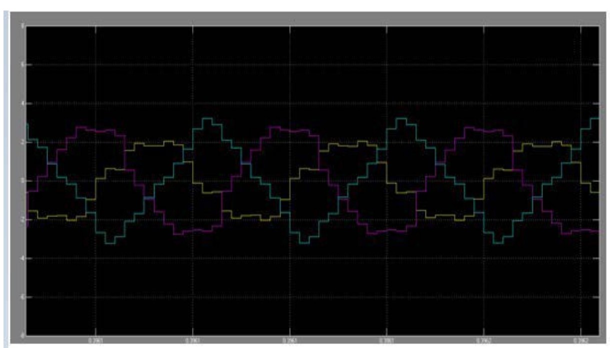


Fig.8 Output voltage & current



VI. CONCLUSION

The high efficiency isolated ac–dc high frequency-link-power-conversion system is proposed to improve the power conversion efficiency for the dc distribution system. 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 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 of 97.88% at the rated load of 10 kW. Consequently, the power conversion efficiency of the proposed ac–dc high-frequency-link power conversion system is 95.53% at the rated load and it is improved 0.13% using the proposed current balancing method.

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