Research Article

Phase-Shifted Full-Bridge ZVS DC-DC Converter with Synchronous Double Rectifiers for Battery Charging Applications

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Received 17 November 2021; Revised 2 May 2022; Accepted 11 May 2022; Published 1 June 2022

Academic Editor: N. Prabaharan

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This paper presents a phase-shifted PWM-controlled DC to DC power converter with a synchronous double rectifier. The power switches can be directed to achieve the zero-voltage switching condition using the technology of the full-bridge power converter and increase the efficiency of the converter on the secondary side of the transformer. A current doubling rectifier with low current ripple and synchronized rectifier circuits are also adopted. The secondary side of the high-frequency transformer uses the synchronous double rectifier. The synchronous double rectifier circuit converts AC voltage to DC voltage to enable high-current applications with two filtering inductors to reduce losses and dissipate heat, resulting in an efficient system. The proposed method can control the input DC voltage of the phase-shifted power converter at 400 V and achieves the required DC voltage of 24 V for battery charging applications under the zero-voltage switching condition. The results of simulations and experiments show 86.7% efficiency at 40% load condition and 91.8% efficiency at full load condition.

1. Introduction

At present, the world has seen the importance of using renewable energy to produce electricity, especially solar power generation, which has received a lot of attention. The use of photovoltaic systems can be used to replace power plants. As fossil fuel generation of electricity contributes to environmental pollution due to carbon dioxide emissions, solar energy is also popularly used to generate electricity to power used batteries [1]. Photovoltaic power generation is quite popular nowadays. It can be seen that most renewable energy plants use solar cells. Whether it is the electric vehicle industry and the electricity generation industry with renewable energy backup battery industry, the electrical system obtained from the photovoltaic system before use must be converted to the required power. The voltage, current and power are varied upon the solar intensity which had changed depend on the sunlight hitting and whether each day [2]. Such power control depends on the method of electricity generation used, such as in standalone solar power generation systems or grid-connected power generation systems. It is used to charge batteries used in electric vehicles. The design of photovoltaic systems focuses on increasing power using power converter technology with an emphasis on loss reduction. For high power capacity, the high frequency transformer was designed under the high frequency operation condition. The transformer can reduce the sizing, power loss, and good performance. This article will focus on the design of a high-frequency converter circuit using a full-bridge converter circuit with a phase shift principle connected to the primary side of the high-frequency
transformer and the secondary side of the transformer [3, 4]. High frequency uses a synchronous rectifier. The chosen power converter system is a high-frequency full-bridge power converter using a phase-shifted PWM technique that reduces losses due to voltage switching to center. Phase-shifted PWM reduces losses due to zero-voltage switching and can provide high power with a synchronous principal rectifier that converts AC voltage to DC voltage [5, 6]. Moreover, the battery charging system is both unidirectional and bidirectional in the system, increasingly used in electric vehicle applications [7–10]. The charging system uses a power converter to convert the input power to the proper charger under the proposed condition [11–14]. The proposed battery charging system consists of a PV system, a full-bridge converter, a high-frequency transformer, and a synchronous rectifier. The full-bridge converter can be designed and applied to optimal battery charging control [15–28].

Using a phase-shifted pulse width modulation (PWM) technique, a power converter circuit can reduce the power losses due to zero-voltage switching (ZVS) conditions. The energy can flow from the PV system to the battery charger by designing the output voltage at 24 volts, as shown in Figure 1.

This paper is organized as follows. Section 2 proposes the full-bridge PWM-controlled DC/DC converter. The design of the phase-shifted PWM controlled for the DC/DC converter is presented in Section 3. Section 4 presents the experimental and simulation results of the battery charging application. Finally, the conclusion and discussion are given in Section 5.

2. PWM-Controlled DC/DC Converter

The design requirements can be realized with a phase-shifted PWM-controlled converter with a high power management range. The high-frequency power converter in the phase-shifted PWM-controlled technique can require power in the switch operating range under the ZVS condition. In addition, the control is ZVS with a phase-shifted principle that reduces switching power losses. It can handle soft switching and is also suitable for high-current applications. Due to the current isolation, the high-frequency transformer can isolate the output current between the two filtering inductors.

It allows for having a small system and reducing the power loss due to the split current distribution, reducing the heat of the electronics. In addition to the power switching losses, the power rectifier must be controlled by using soft-switching operation. By converting the voltage with a synchronous rectifier with a switch controlling the flow of current through a filter inductor, the basic operation of a full-bridge circuit is to switch pairs \(S_1\) to \(S_2\) and \(S_3\) to \(S_4\), to transfer power to the primary side of the high-frequency transformer. The operation of such switches is a zero-voltage switching operation, which can reduce losses due to switching. Four different switching states make up one entire switching circuit of the phase bridge that shifts the phase-shifted full-bridge converter switch operating time at \(t_0 - t_1\), \(S_1\) and \(S_4\).

The switch operating range causes a positive voltage to appear on the primary side of the high-frequency transformer. It corresponds to the activation and deactivation of the switch \(S_2\) and the power switch, respectively. A switch \(S_1\) provides two directions of current flow through the filter inductors \(L_f\) and \(L_f'\). The current on the secondary side of the high-frequency transformer is divided into two parts. In the first part, current flows through \(L_f\), and the other part current flows through \(L_f'\), in the other half of the total independent output current until the operation of the switch \(S_2\) will load full power. During this state, the switch operating time is \(t_1 - t_2\). The switch-on operating time \(S_1\) will bring the high-frequency transformer secondary voltage to zero. At the operating range of power switches, open \(S_1\) and \(S_3\) result in the secondary side of the high-frequency transformer, and a current flowing at \(L_f\) has the same slope as the previous \(t_0 - t_1\) state, while the \(L_f'\) current changes to the linear slope. It is negative because of the voltage drop across \(L_f'\). It becomes negative for both \(L_f\) and \(L_f'\) that are rotating independently. It is important to note that since there is no voltage in the current transformer. It does not change between this state of \(t_2 - t_3\), when \(S_3\) and \(S_2\) are open. The operation allows the negative voltage range to appear on the secondary input of the high-frequency transformer, which corresponds to the operation of the \(S_1\) power switch open and \(S_2\) switch operation closed. The secondary-side current of the high-frequency transformer is equal to the current flowing through the filter inductor \(L_f'\), which is half.

![Figure 1: Phase-shifted PWM-controlled DC/DC converter with synchronous rectifier.](image-url)
of the output current of the secondary side of all high-frequency transformers. Another half of the high-frequency transformer secondary-side current flows through the $L_f$, filter inductor freewheel through switch operation $S_2$. The full load current in this state $t_3 - t_4$ is $t_0$, which is the switch operation. Open $S_2$ and $S_4$ cause the voltage across the transformer to be zero on the secondary side. $S_1$ and $S_2$ switch operation is also on, where the current in the filter inductor $L_f$ has a slope equal to the $t_3 - t_4$ state. At the same time, the current in the filter inductor $L_f$, changes the slope to negative when the voltage drop across $L_f$, becomes negative. Both $L_f$ and $L_f$, alternately work independently, which is similar to the $t_1 - t_2$ state as the voltage of the high-frequency transformer is again zero. The magnetizing current does not change during this state. Four main requirements affect the topology selecting the main power stage for this application. The requirement designs of this application are the an output power of 1kW and input voltage of 400 V. These requirements narrow the topology.

Choosing a double-end topology with ZVS for good results requires a power transformer. The fourth requirement is constant frequency operation to minimize switching losses due to the 400 V input. Fixed frequency pulse width modulation is preferred over frequency modulation using the control plans for sound and military applications in sensitive areas. The phase-shifted full-bridge topology requirements are selected because they can enhance the filtering performance required by sensitive system components based on these four principles. They are capable of achieving ZVS [29, 30].

The duty cycle loss range switch operation mode is from $t_0$ to $t_1$. Transistors $S_1$ and $S_4$ are conducted at primary, where current flows from $S_1$ to $S_4$ positive current. The energy is transferred from primary to secondary power [31]. The value of this primary current $i_p$ increases in the interval $t_0 - t_1$, which is given by

$$i_p(t_1) - i_p(t_0) = \frac{V_{dc} - nV_{out}}{n^2L_f}, \quad (1)$$

where $n^2L_f + L_s$ is the sum of the inductances crossed by the current brought back to the primary. On the secondary side, $Q_2$ is open, where all current flows through it. Unlike the current flowing through $L_f$, the current flowing through the filtering inductor $L_f$, increases.

$$V_s = mV_{dc}, \quad (2)$$

where $V_s$ is the secondary voltage of the transformer, given by

$$iL_f(t_1) - iL_f(t_0) = \frac{mV_{dc} - V_{out}}{L_f}, \quad (3)$$

The switch $S_1$'s ZVS mode is $t_1 - t_2$. This operation mode is the independent mode with ZVS operation at time: $t_1$, $t_2$. The $S_3$ and $S_2$ were operated at ZVS, providing zero voltage to their terminals. The primary current circulates between $S_1$ and $S_4$ which is open at secondary level. The voltage applied to $S_2$ and the current through it are zero. The total load current flows through it, where $S_4$ is the current flowing through the two inductors.

$$\frac{iL_f(t_1)}{t_1 - t_0} - iL_f(t_0) = \frac{mV_{dc} - V_{out}}{L_f}, \quad (4)$$

The freewheeling mode is $t_3 - t_4$ which corresponds to the dead time between $S_1$ and $S_4$ at time $t_3$, $S_4$ is blocked, $C_2$ starts to discharge, and $C_4$ charges due to a current flowing through it during this time. The voltage at the primary changes signal becomes negative. When $C_2$ is discharged, the voltage between the terminals is zero. The Diode $D_2$ is conductive according to the initialization condition of $S_2$ to ZVS. Considering the change in signal for the voltage at the primary, the current $I_{Q2}$ decreases, and $I_{Q1}$ increases. The change is not instantaneous due to the leakage inductance, which is in series with the transformer. The two MOSFETs $Q_1$, $Q_2$ are conductive, and the secondary transformer is short-circuited, which can cause problems when the secondary side short-circuited the power. Capacitor required to discharge $C_2$ and charge $C_4$ is the only energy stored in the transformer leakage inductance. As a result, there may not be enough energy to discharge $C_2$ and $S_2$ cannot be initiated at ZVS. The power to discharge $C_2$, depends on the value of the current or the load conditions.

![Figure 2: Diagram of current and voltage of the phase-shifted full-bridge ZVS DC-DC converter with synchronous double rectifiers.](image)

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**Note:** The content provided is a natural reading of the image, taking into account the visible symbols and mathematical expressions. The diagram is not transcribed but mentioned for context. The text includes a detailed explanation of the operation modes and the mathematical expressions used to describe the behavior of the high-frequency transformer in the context of ZVS operation. The diagram likely represents the transition between various states and currents, but the specific details of the diagram are not transcribed due to the complexity and visual nature of the information.
The switch $S_2$’s ZVS mode is $t_4 - t_5$ converter working mode. During this phase, the secondary voltage remains zero, where the current passed $Q_1$. It is believed that $Q_2$ decreased. Figure 2 shows the signal used to control the switches $S_1$-$S_4$, $Q_1$-$Q_2$ in operation of the phase shift signal and diagram of current and voltage of the phase-shifted full-bridge ZVS dc-dc converter with synchronous double rectifiers. The hardware implementation of phase-shifted full-bridge ZVS dc-dc converter with synchronous double rectifiers was used in the experimental operation as shown in Figure 3.

$$\frac{i_p(t_5) - i_p(t_4)}{t_5 - t_4} = \frac{V_{dc}}{L_r}$$

$$\frac{IL_{f_1}(t_5) - IL_{f_1}(t_4)}{t_5 - t_4} = -\frac{V_{out}}{L_{f_1}}$$

$$\frac{IL_{f_2}(t_5) - IL_{f_2}(t_4)}{t_5 - t_4} = -\frac{V_{out}}{L_{f_2}}$$

The switch $S_2$’s ZVS mode is $t_4 - t_5$ converter working mode. During this phase, the secondary voltage remains zero, where the current passed $Q_1$. It is believed that $Q_2$ decreased. Figure 2 shows the signal used to control the switches $S_1$-$S_4$, $Q_1$-$Q_2$ in operation of the phase shift signal and diagram of current and voltage of the phase-shifted full-bridge ZVS dc-dc converter with synchronous double rectifiers. The hardware implementation of phase-shifted full-bridge ZVS dc-dc converter with synchronous double rectifiers was used in the experimental operation as shown in Figure 3.

The duty cycle loss mode is $t_5 - t_6$ during this period. $S_2$ and $S_3$ are open. The power is transferred from primary current to secondary current which evolves and increases as follows. In Table 1, a summary of the results of the analysis and comparison between FB-LLC and PSFB shows differences, advantages, and disadvantages in the range of values over the operating range. In summary, PSFB are highly efficient over the zero voltage switching range on both primary and secondary sides due to active switching devices.

$$\frac{i_p(t_5) - i_p(t_6)}{t_5 - t_6} = \frac{V_{dc}}{n^2L_{f_2} + L_r}$$

On the secondary side, all currents through $S_5$ and $S_6$ are blocked. The current $IL_{f_1}$ increases, unlike the decreasing $IL_{f_1}$, which is given by

$$\frac{IL_{f_1}(t_5) - IL_{f_1}(t_4)}{t_5 - t_4} = \frac{mV_{dc} - V_{out}}{L_{f_1}}$$

$$\frac{IL_{f_2}(t_5) - IL_{f_2}(t_4)}{t_5 - t_4} = \frac{-V_{out}}{L_{f_2}}$$

When the power delivery mode is $t_6 - t_7$, the period is the dead time between $S_1$ and $S_3$ at time $t_5$, $S_3$, which is blocked. On the primary side, the capacitor $C_3$ discharges until it reaches the zero voltage. $C_3$, unlike $C_1$, is charged. Where the terminal $C_1$ is terminated, $D_3$ becomes conductive, modulating the ZVS soft-switching conditions for closing $S_4$ and switch $S_3$. Mode: $t_5$ to $t_6$, this period corresponds to the ZVS operation between power switches. There is the voltage applied to the transformer. As soon as $t_7$,
$S_1$ and $S_8$ are initiated with a zero voltage at the primary side terminal, current flows through $S_1$ and $S_2$ on the secondary side, voltage and current through $Q_1$ are zero, and all current flows through $Q_4$.

The current at the filtering inductor level $i_{Lf_1}$ and $i_{Lf_2}$ decreases, which is provided by

$$\frac{i_{Lf_1}(t_8) - i_{Lf_1}(t_7)}{t_8 - t_7} = \frac{-V_{out}}{L_{f_1}}$$

$$\frac{i_{Lf_2}(t_8) - i_{Lf_2}(t_7)}{t_8 - t_7} = \frac{-V_{out}}{L_{f_2}}.$$

(8)

The freewheeling mode is $t_8 - t_9$. This interval corresponds to the dead time between $S_2$ and $S_4$. At time $t_8$, $S_2$ is blocked and $C_2$ is discharged. The voltage at the terminals decreases until the zero voltage is reached. It charged $C_1$ and $C_2$, which leads to a change in the sign voltage at the primary transformer. When $C_4$ is become to zero, the operation of $D_4$ adjusts to the soft-switching condition of $S_3$. On the secondary side, the current $IQ_1$ through $Q_4$ decreases while through $Q_2$, $IQ_2$ increases. The secondary transformer is short-circuited to $Q_1$ and $Q_2$ in the range of $t_9$ to $t_{10}$, which is the maximum dead time value between $S_2$ and $S_4$.

The switch $S_1$’s ZVS mode is $t_9 - t_{10}$ at time $t_9$, and $S_4$ starts at zero voltage. The current on the primary side and the current flowing through the filter inductors $i_{Lf_1}$ and $i_{Lf_2}$ are written in the forms:

$$\frac{i_p(t_{10}) - i_p(t_9)}{t_{10} - t_9} = \frac{V_{dc}}{L_r}$$

$$\frac{i_{Lf_1}(t_{10}) - i_{Lf_1}(t_9)}{t_{10} - t_9} = \frac{-V_{out}}{L_{f_1}}.$$

$$\frac{i_{Lf_2}(t_{10}) - i_{Lf_2}(t_9)}{t_{10} - t_9} = \frac{-V_{out}}{L_{f_2}}.$$

(9)

3. Design of Phase-Shifted PWM-Controlled Converter

This design is for a phase-shifted full-bridge converter with an input voltage of 400 V. The output voltage is 24 V at a device switching frequency of 200 kHz. The switching operation at various modes and high-frequency transformer are designed, including the synchronous rectifiers and filtering inductors and capacitors.

3.1. Transformer Design. The high-frequency transformer is designed to determine the input voltage of the high-frequency transformer, the output voltage of the high-frequency transformer, and full load conditions. This reduces losses for efficient power distribution. The voltage gain is used in the calculations to determine the inductance $L_r$ which is equal to 10 $\mu$H, and the phase angle shift rate is $\phi_{eff}$, which equals 0.4 at the input voltage, given by [31]

$$\frac{V_o}{V_{in}} = N_1^2 \times \phi_{eff} - I_o \left( \frac{N_2}{N_p} \right)^2 \times \frac{L_r}{V_{in}} \times f_s.$$  

(10)

The RMS current, power loss calculation, and component selection are considered the only efficient phase shift ($\phi_{eff}$) [32]. The loss of duty cycle is neglected and expressed as

$$\phi_{eff} = \frac{V_{in} \times N_p}{V_o \times N_s}.$$  

(11)

The selected transformer size and shape are primarily concerned with efficiency and temperature rise. Some transformer design requires the optimal iteration solution for selecting the most suitable core and balanced core and winding losses. We limit the maximum magnetic flux to 0.1 Tesla to calculate the number of primary cycles [33].

$$N_p = \frac{V_{in} \times \phi_{eff}}{2 \times B_{max} \times A_c \times f_s}.$$  

(12)

The maximum magnetic flux can be obtained by

$$B_{max} = \frac{V_{in} \times \phi_{eff}}{2 \times N_p \times A_c \times f_s}.$$  

(13)

The following equation can be used to calculate core losses. The current flowing in the primary through the high-frequency transformer is considered as the primary to the secondary, and the output magnetic resonance current is given by

$$I_{pri \text{rms}} = \frac{I_o}{2} \times \frac{N_2}{N_p}$$

(14)

$$P_{pri \text{rms}} = I_{pri \text{rms}}^2 \times R_{pri}.$$  

The RMS current and power of the second switching device can be obtained from

$$I_{Sec \text{rms}} = \frac{I_o}{2} \times \sqrt{2 \times \phi_{eff}}.$$  

(15)

$$P_{sec \text{ rms}} = I_{sec \text{ rms}}^2 \times R_{sec}.$$  

(16)

3.2. Filter Inductor. The filtering inductor selection depends on the maximum ripple given by the desired utilization current. The ripple value for the filtering inductor can be obtained from

$$\Delta I_{Lf_1} = \Delta I_{Lf_2} = \% \text{Ripple} \times \frac{I_o}{2}.$$  

(17)

The values of the filter inductors $L_{f_1}$ and $L_{f_2}$ and their maximum current are determined according to the current ripple of the specified inductor.

$$L_{f_1} = L_{f_2} = \frac{1}{\Delta I_{Lf_1}} \times V_o \times (1 - \phi_{eff}) \times T.$$  

(18)
3.3. Synchronous Rectifier. The optimized synchronous rectifier and efficient MOSFETs are chosen to take into account the output voltage of the high-frequency transformer. The switch phase shift is controlled relative to the face of the switch on the primary side when different load sizes are connected [34, 35]. The voltage and current stresses of MOSFETs synchronous rectifiers can be calculated by using the following equations

\[ V_{\text{SR, stress}} = \frac{V_o}{p_{\text{th}}} \]  
\[ I_{\text{SR, rms}} = I_o \sqrt{\frac{p_{\text{th}}}{2} + \frac{1}{4}} \]

3.4. Capacitor Output. The current ripple of the output capacitor is the other function. The current of multiplier rectifier phase shift can fully be canceled where the ripple current in the output capacitance in the case of \(p_{\text{th}}\) is 0.4 [36]. Output capacitor current ripple, RMS current, and ESR loss can be calculated from these equations.

\[ \Delta I_{\text{C_{out}}} = \frac{V_o}{L_{f_1}} \times T \times (1 - 2 \times p_{\text{th}}) \]
\[ I_{\text{C_{out, rms}}} = \sqrt{\frac{1}{12} \times \Delta I_{\text{C_{out}}}^2} \]
\[ P_{\text{C_{out}}} = I_{\text{C_{out, rms}}}^2 \times \text{ESR}_{\text{out}} \]

The output capacitor voltage ripple is given by

\[ \Delta V_{\text{C_{out}}} = \frac{V_o \times (1 - 2 \times p_{\text{th}}) \times T^2}{16 \times L_{f_1} \times \Delta V_{\text{C_{out}}}} \]

The filter capacitor is selected to maintain the transient voltage when there is a change in the load. The capacitor should take care when operating with no load and full load. The voltage ripple should be low during an extreme variation. The voltage filtering capacitor value of the capacitor voltage ripple value is given by

\[ C_{\text{out}} = \frac{V_o \times (1 - 2 \times p_{\text{th}}) \times T^2}{16 \times L_{f_1} \times \Delta V_{\text{C_{out}}}} \]
4. Experimental and Simulation Results

This section shows the design parameters for the phase-shifted full-bridge converter used to simulate the system operation, which will be on the primary side of the high-frequency transformer and the secondary side of the high-frequency transformer. The specific parameters of the proposed power converters are designed as shown in Table 2. High-frequency full-bridge phase-shifted converters for photovoltaic applications simulate the performance, and performance of the proposed system was selected for all functional simulations. On the high-frequency transformer operation, the resonant phenomena between the mutual inductance of proposed transformer
and outside equivalent capacitance, which operates with the phase-shifted modulation methodology, can control the power converter switches to be the ZVS switching scheme. The secondary side of high frequency transformer was directly connected to the proposed synchronous rectifier which was designed to reduce the
Figure 9: Primary and secondary voltages of the phase-shifted full-bridge ZVS DC-DC converter with synchronous double rectifiers at full load condition.

Figure 10: Waveforms of the current doubler rectifier on filters 1 and 2 and primary current and secondary current of the phase-shifted full-bridge ZVS DC-DC converter with synchronous double rectifiers.

Figure 11: Efficiency of the prototype test of the phase-shifted full-bridge ZVS DC-DC converter with synchronous double rectifiers.
switching power loss and improve the heat dissipation, as shown in Figure 1.

The simulation results show that the input voltage of the phase-shifted circuit is 400 V, and the designed output voltage is controlled at 24 V with the zero-voltage switching principle. The primary side of the high-frequency transformer combines the synchronous switching rectifiers to convert them to DC voltage, as shown in Figure 4. Figure 5 shows the simulation results of the phase-shifted circuit comparing the primary and secondary currents connected to the high-frequency transformer compared to the zero-voltage switching condition period. The electric current is flown through the two filtering inductors. Figure 6 shows the simulation of the primary electrical current and voltage connected to a high-frequency transformer obtained by a phase-shifted switch $S_1 - S_4$ during zero-voltage switching. Figure 7 shows the simulation of the secondary voltage currently connected to the high-frequency transformer obtained by the phase shift switches $S_1 - S_4$ during zero-voltage switching. Figure 8 shows the experiment of primary and secondary voltages of the phase-shifted full-bridge ZVS DC-DC converter with synchronous double rectifiers at 40% load condition. Figure 9 shows the experiment of primary and secondary voltages of the phase-shifted full-bridge ZVS DC-DC converter with synchronous double rectifiers at full load condition. Figure 10 shows the waveforms of the current doubler rectifier on filters 1 and 2 and primary current and secondary current of the phase-shifted full-bridge ZVS DC-DC converter with synchronous double rectifiers. Figure 11 shows the efficiency of the prototype test of the phase-shifted full-bridge ZVS DC-DC converter with synchronous double rectifiers.

The proposed power converter operation was controlled by phased-shifted PWM switching scheme that can control the output power as requirement. This results in easy control of wide range power on both the secondary side of the high-frequency transformer and the conversion of AC voltage to DC voltage using active devices with double rectifiers. In addition to this, the proposed circuit can be applied to phase shift control with zero-voltage switching (ZVS), and it is also possible to split the current in two with a synchronous rectifier through it. The two filter inductors reduce wastage and dissipate the heat of the device.

5. Conclusion

This paper has proposed the high-frequency full-bridge power converter in photovoltaic applications using the phase-shifted PWM technique with synchronous double rectifiers. The simulation results show the voltage produced by a photovoltaic at 400 V can be controlled by a high-frequency full-bridge power converter by 24 V with the phase-shifted PWM characteristics that make the switch operation ZVS condition. It can control the power on the primary side of the high-frequency transformer as designed. The secondary side of the high-frequency transformer converts AC voltage to DC voltage using synchronous double rectifiers, where two-way current divides flow through filtering inductors to reduce conductivity losses with phase shift switching. The zero-voltage switching condition that occurs during the phase switching can reduce the losses due to the switch and provide an efficient system.

Data Availability

No data were used to support this study.

Disclosure

This research work was developed from conference paper in “24th International Conference on Electrical Machines and Systems (ICEMS2021)” held at Gyeongju City, South Korea, in 2021: https://ieeexplore.ieee.org/document/9634358.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Krischonme Bhumkittipich was responsible for conceptualization, visualization, and supervision. Wasan Phetphimoon was responsible for formal analysis, original draft preparation, methodology, and software. Yuttana Kongjeen and Preecha Yupapin were responsible for validation and investigation. Krischonme Bhumkittipich, Yuttana Kongjeen, and Preecha Yupapin were responsible for review and editing. All authors have read and agreed to the published version of the manuscript.

Acknowledgments

We would like to acknowledge the Power System Research Center, Rajamangala University of Technology Thanyaburi (RMUTT).

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