A Contactless Power Supply for Photovoltaic Power Generation System

Eun-Soo Kim[1], Sung-In Kang[1], Kwang-Ho Yoon[1], Yoon-Ho Kim[2]

[1]Jeonju University, 1200, Hyoja-dong, Wansan-gu, Jeonju, South Korea,   E-mail:eskim@jj.ac.kr
[2]Chung-Ang University, 221, Heukseok-Dong, Dongjak-Gu, Seoul, South Korea, E-main:yhkim@cau.ac.kr

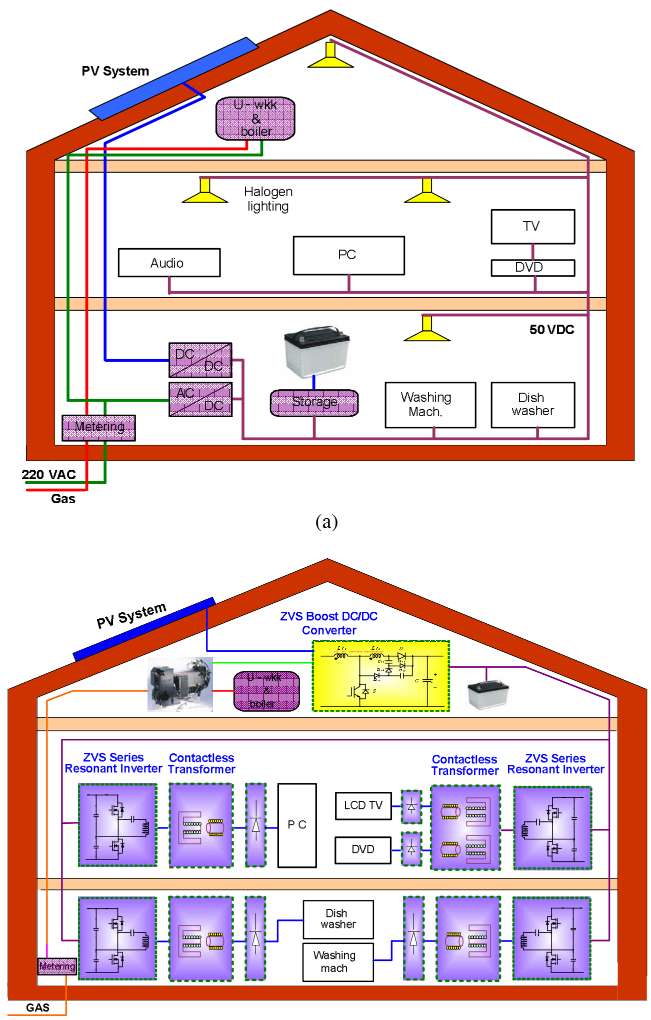
***Abstract* - Among the alternative energy sources, the solar energy is recognized as an important energy source and its application is increasing. Especially in future, the hybrid solar energy generation system with battery and fuel cell will be widely used as an independent distributed power generation system. In this paper, a solar power hybrid home generation system using a contactless power supply (CPS) that can transfer an electric power without any mechanical contact is proposed. The proposed system consists of a ZVS boost converter, a half bridge LLC resonant converter and contact-less transformer.**

I. Introduction

Among the alternative energy sources, the solar energy generation is recognized as an important energy source and its application is increasing. The solar generation system interfaced with power utility system includes DC/DC converters and inverters. Normally a boost type DC/DC converter is used to step up the input voltage. Then the inverter is used to convert dc to 60 Hz ac voltage to interface with power utility and this ac power is converted back to dc again to be interfaced with various home electric systems [1]. Recently, the solar hybrid system with battery is widely used as an independent distributed power generation system. If this solar energy is converted to the conventional utility system, then the whole energy transfer system is very complicate and inefficient. In future, as shown in Fig 1(a), it is expected that DC power service will be widely used for hybrid home power generation system using solar and fuel cell. However, such configuration of DC power service will cause the surge and spark voltage when the switch is turned on and off for connecting and disconnecting the load. To avoid surge voltage and risky situation, DC link voltage for DC power service must be limited to be used under 50VDC.

To solve these problems, in this paper, a hybrid home power generation system using contactless power supply is proposed as shown in Fig 1(b). The proposed system consists of a ZVS boost converter, a half-bridge LLC resonant converter and contactless transformer. However, since the contactless transformer has normally large air-gap, while the leakage inductance increases and magnetization inductance decreases. This causes low power conversion efficiency.

To overcome such problems, a series resonant converter is widely used [2].



(a)

(b)

Fig. 1 Hybrid Photovoltaic power generation system for DC power service
(a) The conventional DC power service using hybrid power generation system
(b) The proposed hybrid photovoltaic power generation system using contactless power supply

However, the series resonant converter for the contactless power supply generally operates with higher switching frequency than resonant frequency to achieve soft switching under continuous resonant current mode. In this case, the main

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switches can achieve zero voltage switching (ZVS), but it has disadvantage that the secondary side diode converter cannot achieve zero current switching. Furthermore, due to the higher switching frequency operation than resonant frequency, it has low voltage gain and high power loss since a large primary side circulating current flows.

Thus, in this paper, a contactless power supply using contactless transformer and half-bridge LLC resonant converter that achieves ZVS operation of main switches and ZCS operation of secondary side diodes is proposed. Since the proposed contactless power supply using LLC converter operates with lower switching frequency than the resonant frequency, it can achieve high voltage gain, which, in turn, offers low turns ratio for the transformer and high efficiency due to discontinuous resonant current.

Based on the theoretical analysis and simulation results, the 80W prototype is built and applied to the solar power generation system. The final experimental results are described.

II. Characteristic Analysis of Half-Bridge LLC Resonant Converter

The conventional series resonant inverter that is applied to the contactless transformer generally operates with higher switching frequency than the resonant frequency. However, in this paper, the resonant converter that operates with lower switching frequency than the resonant frequency is proposed for the contactless power supply. In this case, it has advantages that the problems of the conventional series resonant converter can be improved and high system efficiency can be obtained. Fig. 2(a) shows a structure of the contactless transformer that is applied to the half-bridge LLC converter. The primary side is a magnetic core but secondary side is an air-core. Large air-gap is made between the two sides. The large air-gap transformer has smaller magnetizing inductance and lower coupling coefficient (k) due to increase of primary and secondary side leakage inductances. In this type of transformers, it has some difficulty in transferring energy from primary side to secondary side due to the large magnetization current. Fig. 2(a) shows main circuits of a half-bridge resonant LLC converter and Fig. 2(b) shows its equivalent circuit. In Fig. 2(b), V_{ab} is the terminal voltage of the half-bridge converter. C and L_{l1} are primary side series capacitor and series leakage inductance respectively, L_m is magnetization inductance, and L_{l2} and R_{eq} are secondary side leakage inductance and equivalent load resistance converted to the primary side respectively. The equivalent load resistance (R_{eq}) includes rectifier diode, capacitor filter and resistance.

$$R_{eq} = \frac{8}{\pi^2} R_L \tag{1}$$

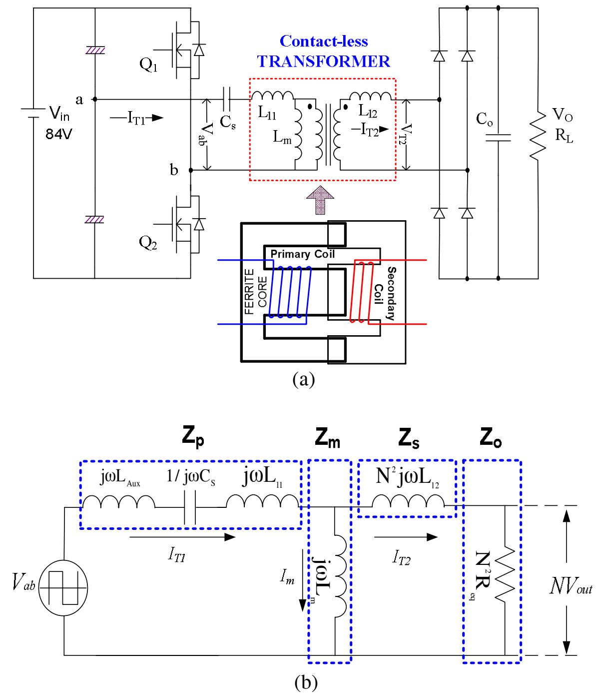


Fig. 2 Half-bridge LLC resonant converter using a contactless transformer (a) and its equivalent circuit (b)

In this paper it is assumed that the winding turns-ratio ($N = n_1/n_2$) is equal to '1'. From Fig. 2(b), resonant frequency (f_r) when equivalent load resistance (R_{eq}) is in short and corner frequency (f_o) when it is open, can be obtained.

$$f_r = \frac{1}{2\pi\sqrt{L_{eq} \cdot C}} \tag{2}$$

$$f_o = \frac{1}{2\pi\sqrt{(L_{l1} + L_m) \cdot C}} \tag{3}$$

When an equivalent load resistance (R_{eq}) is in short, the equivalent leakage inductance (L_{eq}) is expressed as

$$L_{eq} = \frac{L_{l1}(L_m + L_{l2}) + L_{l2}L_m}{L_{l2} + L_m} \tag{4}$$

Normalized frequency ($f_n = f_s/f_r$) is a ratio between switching frequency (f_s) and resonant frequency (f_r).

A is ratio between magnetization inductance (L_m) and primary side leakage inductance (L_{l1}). B is a ratio between magnetization inductance (L_m) and secondary side leakage inductance (L_{l2}). Q is a load quality factor.

$$f_n = \frac{f}{f_r} \tag{5}$$

$$A = L_{l1} / Lm \quad (6)$$

$$B = L_{l2} / Lm \quad (7)$$

$$Q = \frac{2\pi f_r L_{eq}}{R_{eq}} \quad (8)$$

Using equation (1) ~ (8), voltage gain (M) between input and output voltage can be expressed as given by

$$|M| = \left| \frac{1}{1 + A - (\frac{1}{f_n})^2 \cdot (A + \frac{B}{B+1}) + jQ(1+B)(f_n - \frac{1}{f_n})} \right| \quad (9)$$

Fig. 3 shows voltage gain characteristics with respect to f_n and Q when the A and B are 0.384 and 0.00918, respectively. Fig. 3 shows that the voltage gain characteristics of the proposed contactless power supply system are similar to that of the conventional LLC resonant converter. This means that the proposed system that operates lower switching frequency has similar voltage gain characteristics while it has advantages in achieving ZVS operation of the main switches and ZCS operation of the secondary side rectifier diodes. Thus the half-bridge LLC resonant converter applied to the contactless transformer has advantages in that it can achieve high efficiency characteristics and low output voltage noise.

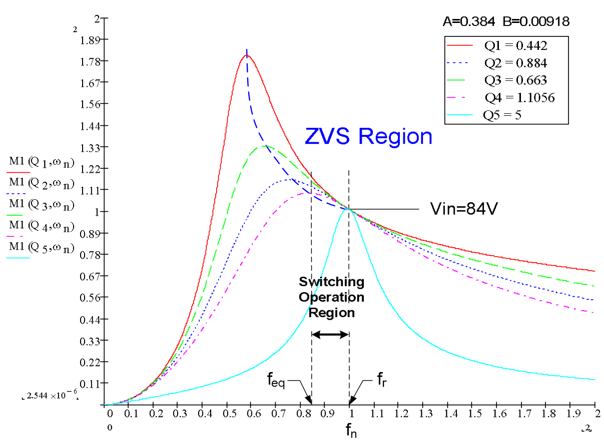


Fig. 3 Voltage gain characteristics of half-bridge LLC resonant converter using a contactless transformer

III. Experimental Results

Fig. 4 shows a main circuit of the contactless power supply for the photovoltaic home power generation system. The solar cell output voltage is boosted to constant 84VDC. The implemented LLC resonant converter is controlled to be constant 12VDC output using 84VDC output voltage of the ZVS boost converter.

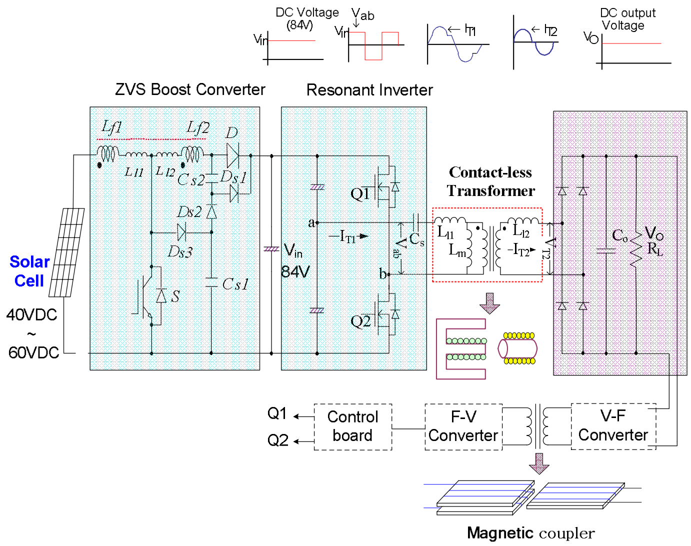
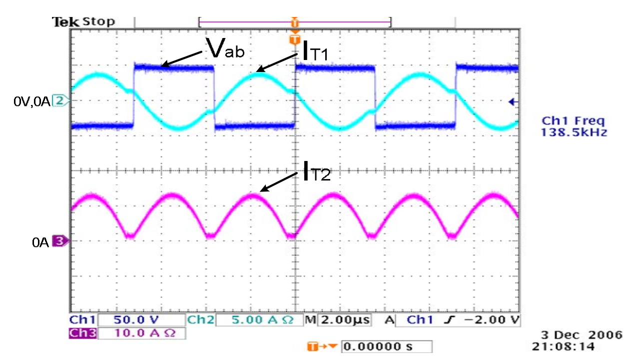


Fig. 4 Main circuit of the contactless power supply for photovoltaic power generation system

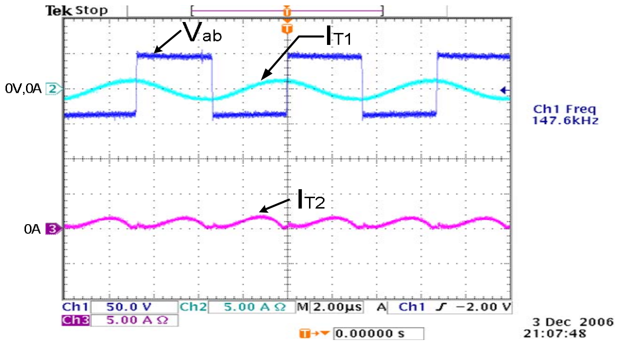
Table 1 shows the specifications and measured parameters of the designed system. Fig. 5(a) and Fig. 5(b) show experimental output waveforms with output power 80W, 7.2W respectively.

TABLE 1
Specifications and measured parameters of half-bridge LLC resonant converter using a contactless transformer

Input voltage(V_{in})	84V_{DC}	Transformer turn ratio(N)	n_1/n_2= 17/5=3.4
Output voltage(V_o)	12V_{DC}	Equivalent leakage inductance(L_{eq})	22.54uH
Output power(P_o)	80W	Resonant capacitor(C)	50nF
Resonant frequency(f_r)	150kHz	Magnetic inductance(L_m)	51.95uH
Switching frequency(f_s)	100~150kHz	Primary side leakage inductance(L_{l1})	19.74uH
Coupling coefficient (k)	0.828	Secondary side leakage inductance(L_{l2})	25.6nH



(a)



(b)

Fig. 5 Experimental waveform of the voltage (V_{ab}) and current (I_{T1}) in the primary, and of the rectified current (I_{T2}) in the secondary for the half-bridge LLC resonant converter using a contactless transformer (50V/div., 5A/div., 10A/div., 2us/div.) (a) 80W, (b) 7.2W

Fig. 5 also shows that since the primary current (I_{T1}) is lagging to the terminal voltage (V_{ab}), and the secondary side rectifier current (I_{T2}) is discontinuous, the main switches operate with ZVS and rectifier diodes operate with ZCS. Fig. 6 shows system efficiency characteristics with respect to output load variations. For the output power range of 7W~80W, the high efficiency characteristics over 80% was obtained. Fig. 7 shows the LCD TV and DVD player operating by the proposed contactless photovoltaic power generation system.

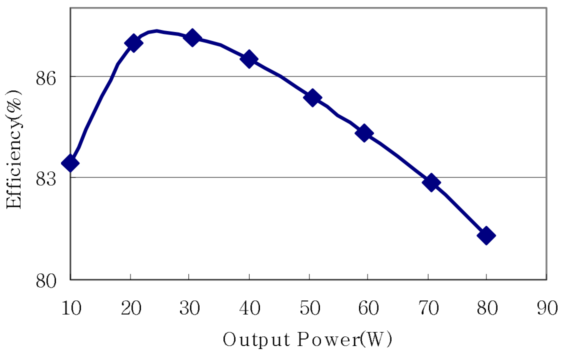


Fig. 6 Efficiency characteristics of contactless power supply

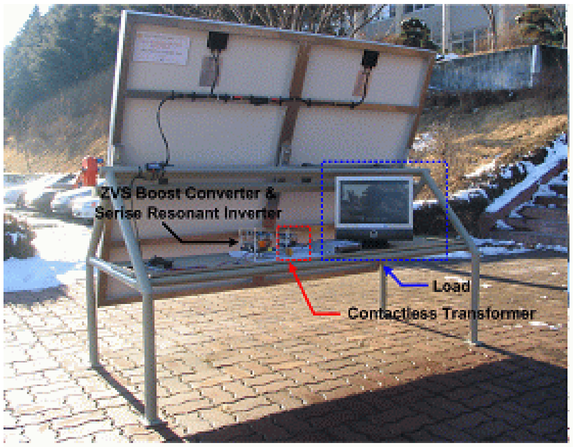


Fig. 7 prototype

IV. Conclusion

In this paper, a contactless power supply for a hybrid photovoltaic home power supply system is proposed to improve the efficiency of the conventional photovoltaic distributed power generation system. The prototype has been theoretically analyzed and then the 80W prototype has been built.

The proposed system can reduce switching stress and improve system efficiency by ZVS and ZCS operation of switches and reducing energy conversion steps. The prototype has been tested successfully. The experimental results verified an important feature that the proposed system has efficiency over 80% by ZVS and ZCS operation, and can save complicate power conversion process compared to conventional utility system by directly supplying the dc power to the home electric system.

Acknowledgment

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