# Sinewave-PWM ZVS Inverter using High-Frequency Transformer for Utility AC Voltage Link

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**Abstract**

This paper presents a novel prototype of the utility-interfaced sinusoidal pulse width modulated (SPWM) inverter using the high-frequency flyback transformer for the small-scale solar photovoltaic power conditioner (1kW - 4kW). The proposed SPWM power conditioner circuit with a high-frequency link has a function of electrical isolation, which is vital for solar photovoltaic power conditioner systems with the viewpoint of safety and convenience. The discontinuous conduction mode (DCM) operation of the flyback transformer is also maintained to simplify the topology of the inverter circuit and control scheme. First, the operating principle of the proposed circuit is described for the understanding of the circuit parameters establishment. Then, the digitally constructed SPWM control scheme is presented. The proposed circuit is verified by the computer simulation and the prototype experiment.

**Keywords**

High-frequency flyback transformer, Sinusoidal pulse width modulation inverter, Utility-interfacing power conditioner, Zero voltage soft-switching(ZVS) .

## 1.INTRODUCTION

In the recent years, the practical costs of the solar array systems and the consumers' awareness to preserve the environment have stimulated the demands of the highly effective utility-grid connected power conditioners. The power conditioners are usually composed by the inverters which can deliver the output currents with the same phase as the utility grid voltage. So far, most of the power conditioner system is the composition of the DC-DC converter with the function of maximum power point tracking to raise the DC voltage up to the required value, the DC-AC inverter and the AC low-pass filter. The inverters, with the help of the AC low-pass filter transform the DC power into AC power and inject the energy to the AC-side connection. Eventhough the mainstream of the inverters used in the power conditioner is the non-isolated type, the type of the isolated inverters recently becomes more likely to get more attentions. In addition to the safety point of view and the convenience of installment in the place with space constraints, the cost of transformers has become lower comparing to the past. Especially, when employing the high-frequency transformer into the inverter, the downsizing of the system is realized and the component efficiency is significantly improved. However,most of the high-frequency transformers in many circuit topologies are the forward type which result in the complex circuit topologies with the difficult non-SPWM digital control schemes to achieve the standard AC output.

This paper proposes a utility-interfacing SPWM inverter with the high-frequency flyback transformer link. Its simple circuit configuration and IGBT gate pulse control scheme when applying for the use with the renewable small-scale distributed power application are described. The newly proposed circuit topology is composed of a high-frequency SPWM inverter circuit with a flyback transformer link and controlled under the condition of the discontinuous conduction mode(DCM). The DCM control scheme also results in the operation of zero current soft switching. The operation of this power conditioner is analyzed for the parameter establishment. The additional snubbers are for regenerating the currents back to the DC power source resulting in the zero voltage stand-by of the snubber capacitors. Thus, the ZVS operations are realized to reduce the power losses due to the high-frequency switching at the primary side of the transformer. Then, the experiment is conducted to verify the validation of the topology.

## 2. CIRCUIT DESCRIPTION AND ITS OPERATION

Fig.1 shows the utility-interfacing high-frequency flyback transformer linked type of the SPWM power conditioner. The three-winding high-frequency flyback transformer (*MT*) is employed in the power conditioner in purpose of isolating the renewable DC energy source from the utility power grid connection. At the primary side of the transformer, two units of IGBTs ($T_u$,$T_v$) and two sets of additional snubber (($D_{vs1}, D_{vs2}, C_{vs}, l_v$),($D_{us1}, D_{us2}, C_{us}, l_u$)) are introduced as shown in the figure to comprise the input side of the transformer winding. Both IGBTs are controlled by the SPWM gate pulses digitally constructed by the phase-locked-loop (PLL) control circuit and the micro controller. The secondary side of the transformer is comprised by two windings. The loop of the upper winding (or the negative winding), which includes one IGBT and one diode ($T_{sm}$,$D_{sm}$), is

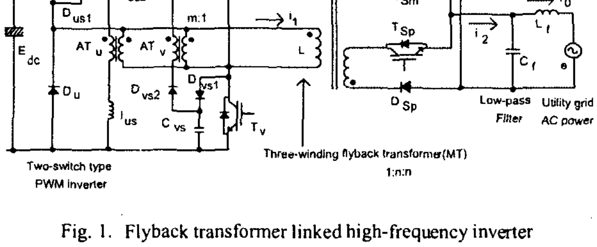
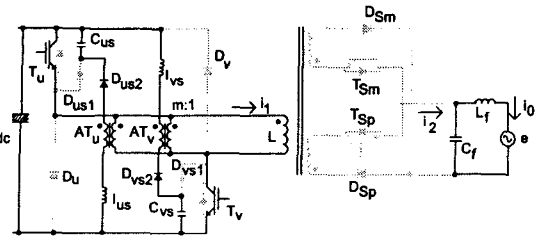
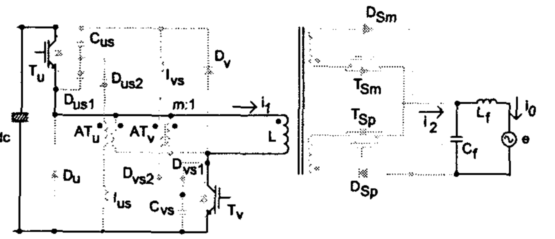



Fig. 1. Flyback transformer linked high-frequency inverter




a. The primary-side active power switches are on and the snubber capacitors are discharging




b. The primary-side active power switches are on and the snubber capacitors are completely discharged

Fig. 2. Operating modes and equivalent circuits when the primary-side active power switches are on (Energy storing mode)

conducted only when the utility grid voltage is negative. On the other hand, the loop of the lower winding (or the positive winding), which also includes one IGBT and one diode ($T_{sp}$,$D_{sp}$), is conducted only when the utility grid voltage is positive. Hence, both windings are used for polarity selection in order to deliver the AC output currents into the utility side through the low-pass AC filter, which is constructed by $L_f$ and $C_f$.

As mentioned above, the inverter is operated under the condition of discontinuous conduction mode. The current $i_1$ flows through the IGBT legs of the input side only when the switches are turned on by the SPWM gate signals. The turn-on time ($T_{on}$) of each switching period $T_s$ is determined by comparing the sinusoidal waveform (modulated by modulation rate $M$), which is synchronous to the utility voltage, to the sawtooth signal with specified frequency $f_s$ (in this paper, 16 kHz). According to the characteristics of the flyback transformer, after the input-side switches are turned off in each switching period, the discontinuous triangular current $i_1$ is suddenly absorbed to the secondary side of the flyback transformer and the current $i_2$ start to flow. At the secondary side, the current $i_2$ flow to either the upper winding or the lower winding in accordance with the polarity of the utility voltage. Then, the polarity-selected triangular current $i_2$ passes through the AC low-pass filter, which smooths the current into the grid utility.

Fig. 2(a), Fig. 2(b) and Fig. 3 illustrates the operating modes of the proposed inverter circuit when the active power switch $T_u$ and $T_v$ is turned on and off and the polarity of the utility voltage $e$ is positive. In case of the negative grid voltage, the operating modes can be described similarly. For the output current $i_2$ to be able to flow in the positive loop, $T_{sp}$ is turned on for every positive cycle of the grid voltage.

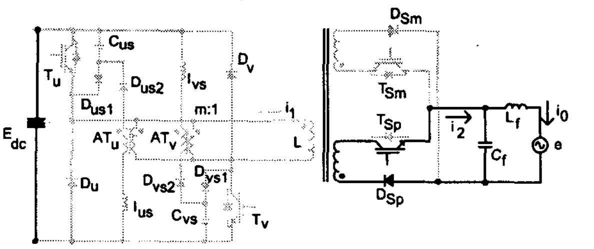



Fig. 3. Operating modes and equivalent circuits when the primary-side active power switches are off (Energy releasing mode)

■ Energy Storing Mode ($T_0 \leq t \leq T_0 + T_{on}$)

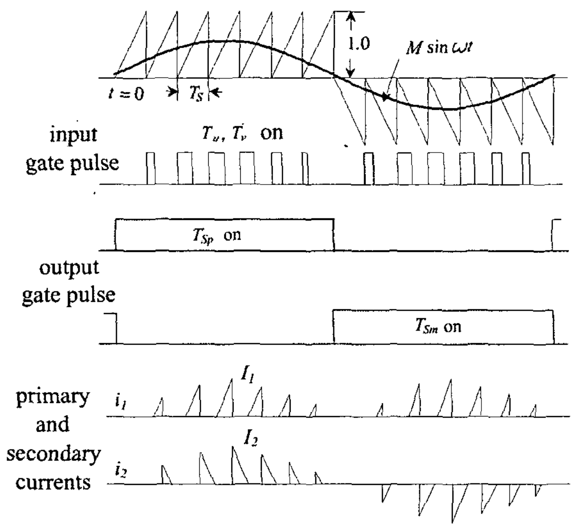
Fig. 2 illustrates the equivalent circuit of the energy storing mode at the beginning time ($T_0$) of the switching time ($T_s$). The switches $T_u$ and $T_v$ are simultaneously turned on by SPWM gate pulse signals. Due to the fact that the DCM condition is maintained by the control scheme, both switches are always turned on under the zero-current soft-switching commutation. The current $i_1$ increases linearly because of the transformer magnetizing inductance. According to the characteristics of the flyback transformer, the secondary current $i_2$ is supposed to flow from the dot of the secondary-side lower loop winding but it is blocked by the diode $D_{sp}$. Hence, the energy from the DC source is forced to stored into the flyback transformer as the magnetic energy in this operating period, which is referred as the energy storing mode. This mode ends when both switches are turned off.

At the beginning of this operating mode, the secondary windings of the auxiliary transformers ($AT_u$,$AT_v$) are magnetized by the main transformer and diodes ($D_{us2}, D_{vs2}$) start to conduct. The snubber capacitors previously charged from the turn-off operation discharge the electricity very fast through the auxiliary transformers as shown by the equivalent circuit in Fig. 2(a). The discharged currents resonate with the inductors ($l_{us}, l_{vs}$) by only half cycle because the blocking of diodes $D_{us2}$ and $D_{vs2}$. Thus, the snubber capacitors maintain the zero voltage status and wait for the next turn-off operation as shown by the equivalent circuit in Fig. 2(b).

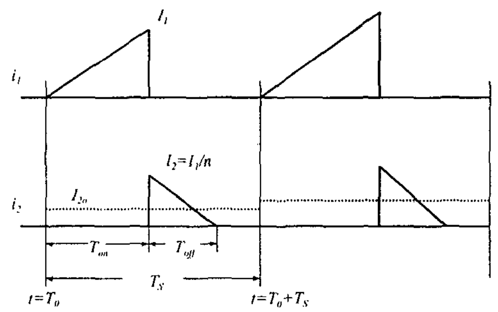
■ Energy Releasing Mode ($T_0+T_{on} \leq t \leq T_0+T_{on}+T_{off}$)

Fig. 3 illustrates the operating mode of the energy releasing mode. The operation begins after the active power switches $T_u$ and $T_v$ are turned off simultaneously. This forces the voltage across the primary side of the transformer to change its polarity and reverses the direction of the current $i_2$ to flow through the secondary-side lower loop. The magnetized energy that has been stored from previous mode is completely released and transferred into the AC filter before the end of the switching time $T_s$. The high-frequency components of the saw-tooth current waveform $i_2$ are deducted by the AC filter. Then, the sinusoidal output current waveform $i_o$ is finally achieved and injected into the utility grid connection.

Fig. 4 displays the time sequencing schemes of the SPWM gate signals and currents in the primary and the secondary side of the flyback transformer. The turn-on time




a. Timing pulse signals and sequences




b. Current waveforms in the primary side and the secondary side of the flyback transformer

Fig. 4. Control pulse sequences and current waveforms flowing through the input and output sides

($T_{on}$) of the SPWM control signal, which is the time for turning on the input side switches $T_u$ and $T_v$, is constructed by comparing the saw-tooth signal of the desired frequency to the modulated sinusoidal waveform.The modulation ratio $M$ is typically determined by referring to the required output current. At the secondary side, the positive loop (or the lower winding) is selected to allow the current $i_2$ to flow through by the polarity selecting signals, which turn the primary-side active power switche ($T_{Sp}$) on every positive half-cycle of the utility grid voltage. Otherwise, the secondary-side active power switch ($T_{Sm}$) is turned on. Fig. 4(b) depicts and magnifies the current waveforms of the primary side ($i_1$) and the secondary side ($i_2$) of the flyback transformer. As thoroughly mentioned in the following section, the circuit parameters are properly designed so that the current $i_2$ completely reaches zero within the switching period $T_S$, which is also the sampling time of the saw-tooth carrier signal. $I_{2o}$ is the average value of $i_2$ during the period $T_S$ and equivalent to the output current of the low-pass filter in the utility AC side.

## 3. PRINCIPLES OF CIRCUIT OPERATION

Since the switching frequency of the implemented saw-tooth carrier signal is high enough, the utility grid voltage is fixed at $e = E_m \sin\omega T_0$ when $T_0$ is the beginning time of each switching cycle. It is also approximated to be the same as the voltage across the filter capacitor $C_S$. Based on these approximations, at any switching period, the peak of the input current $i_1$ denoted as $I_1$ is calculated as follows;

$$I_1 = T_{on}E_{dc}/L. \tag{1}$$

The AC utility grid voltage is also approximately constant during any operating cycle $T_S$, the turn-on time is expressed as

$$T_{on} = T_S M \sin\omega T_0, \tag{2}$$

when, $\omega$ is the angular frequency. After the primary-side active power switches of the flyback transformer are turned off. The current of the transformer magnetizing inductance starts to flow. Finally, in the secondary side, the peak of the current $i_2$ denoted as $I_2$ can be found as

$$I_2 = T_{off} E_m \sin\omega T_0/n^2 L, \tag{3}$$

when $T_{off}$ is the turn-off time of the switches at the input side and $E_m$ is the approximated utility voltage in each switching cycle. Moreover, since it is given that $I_2 = I_1/n$. The average value of the output current ($I_{2o}$) over the switching cycle $T_s$ is derived as

$$I_{2o} = \frac{T_S E_{dc}^2}{2LE_m} M^2 \sin\omega T_0, \tag{4}$$

when $E_{dc}$ and $L$ are the DC source voltage and the transformer inductance, respectively. Obviously, the output current is smoothed by the AC low-pass filter into the sinusoidal form. Its amplitude is in proportion with $M^2$, which is demanded by the system controller;for example:the MPPT algorithm. It is noted that the output current can be easily controlled to meet the desired value of the output current by detecting the DC voltage $E_{dc}$ and the AC voltage amplitude $E_m$ and adjusting the modulation ratio $M$ properly based on the rms value of $I_{2o}$, which is obtained by

$$I_{2orms} = \frac{T_S E_{dc}^2}{2\sqrt{2}LE_m} M^2. \tag{5}$$

Furthermore, under the DCM condition ($T_{on} + T_{off} < T_S$), the operating constraint is given as shown below;

$$M(1 + nE_{dc}/E_m) < 1 \tag{6}$$

and

$$I_2/I_{20} > 2(1 + E_m/nE_{dc}). \tag{7}$$

Then, to preserve the DCM condition, all energy passed from the primary side of the flyback transformer in each switching cycle is required to be completely transferred to the utility grid connection as shown in the mode of Fig. 3, the condition that $nE_{dc} > E_m$ needs to be included in Equation 6 and Equation 7. As a result, the sinewave modulation ratio $M$ becomes less than 0.5 in usual operation.

## 4. IMPLEMENTATION OF CONTROL SCHEME

Fig.5 illustrates the control block diagram of the SPWM utility-interfacing inverter circuit with the high-frequency flyback transformer link. The modulation ratio $M$ is calculated directly by inputting the given output current $I_{2orms}$ into (5). A small part of the grid voltage $e$ is also used as the source of the reference sinusoidal waveform to be compared with the saw-tooth carrier signal, which is generated by PLL (Phase Locked Loop) circuit. Most parts of the signal computation are achieved by software programming of the microcontroller board. The SPWM digital signal is obtained and transformed into the gate switching signal used for turning on and off the transformer primary-side active power switches in the proposed inverter circuit. It is noted that the secondary-side switching signals for secondary-side active power switches synchronized with the utility voltage frequency for selecting the polarity of the output current are also needed seperately.

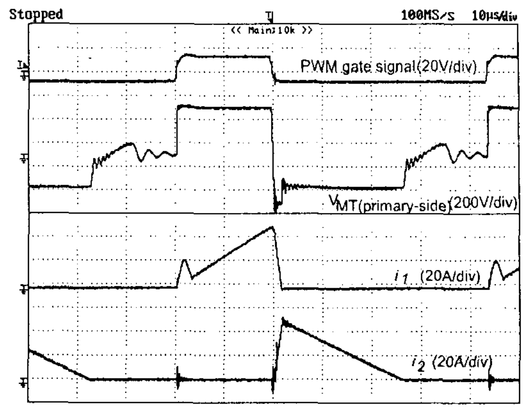



Fig. 6. The primary/secondary side current waveforms, the primary-side voltage across the main flyback transformer and the SPWM gate pulse

## 5. EXPERIMENTAL RESULTS

By referring to all principles mentioned in the previous sections, an example of the variables of the proposed utility-interfacing flyback transformer linked inverter is represented below.

- DC power source : $E_{dc} = 200V$
- grid voltage specifications : 100Vrms, 60Hz
- power output : $P$=1 kVA
- switching frequency : $f_S$=16 kHz
- winding ratio of flyback transformer : $n$=0.80
- magnetizing inductance(estimated from the primary side of the flyback transformer) : $L$=140$\mu$H
- low-pass filter : $L_S$=300 $\mu$H, $C_S$=25 $\mu$F

The computer-aided simulation of the proposed inverter under the parameters mentioned above is conducted to verify the validity of the total system of the proposed power conditioner before experimenting the prototype. The specification of IGBT switches are 75A/600V, which is enough for the maximum amplitude of the current $i_1$ and $i_2$ when the highest modulation ratio $M = 0.5$ is employed. The A-D transformation of the grid voltage for polarity notification and the control signal processings are handled by 16-bit microcontroller run by 26 MHz clock processing. The microprocessor samples the grid voltage polarity and value to build its own sinusoidal signal synchronous to the grid voltage. Then, it compare this signal to the saw-tooth signal generated inside based on the outside signal from the PLL circuit. The sampling frequency is set to 16 kHz or the sampling is done every 62.5 $\mu$s. The proposed inverter is operated by connecting the DC source fixed at 200 volt for the convenience of power efficiency investigation. The modulation ratio $M$ is adjusted manually to range from 3 to 4.5. Although the maximum operable modulation ratio $M$ is 0.5, the leakage currents do exist at the primary side of the transformer resulting in the pulse width compensation of the SPWM gate signals to raise the peak current $I_1$ and $I_2$ when the grid voltage is high. However, the leakage currents can keep flowing in the auxiliary transformer and decrease the conversion efficiency of the total power conditioner. Thus, the flyback transformer should be produced with the leakage inductance as small as possible to avoid this problem. Both of the polarity switching signals at the secondary side are the complement of each other. They are delivered by two channels of the controller board seperately from the channels of the SPWM gate signal. The experimental waveforms are shown in Fig. 6. As seen in the figure, the snubber capacitor discharges the voltage as soon as the primary-side switches are turned on. The discharged current resonate with the inductor $l_u$ (or $l_s$) in only one half cycle of a short period smaller than 3 $\mu$s. When the total switching time ($T_S$) is up to 28 $\mu$s, both snubber capacitors have plenty of time to discharge the voltage they absorb from the previous turn-off operation. The discharged current is regenerated to the DC power source and returned to overlap with the primary-side current $i_1$ as seen as the small lump in the waveform. Fig. 7 displays the waveform of the switch current and the switch voltage showing that the overlapping area of both waveforms is very small as the effect of the zero soft-switching commutation. The utility grid voltage e and the output current $i_o$ are showned in Fig.8. The efficiencies of the DC-AC power conversion measured range from 92.6% to 93.0%. The total harmonic distortions (THD) vary from 3.3% to 3.5%, which is well below 5% required by the industrial standard. The system power factor is about 0.995, resulted by the use of the low-pass LC filter.

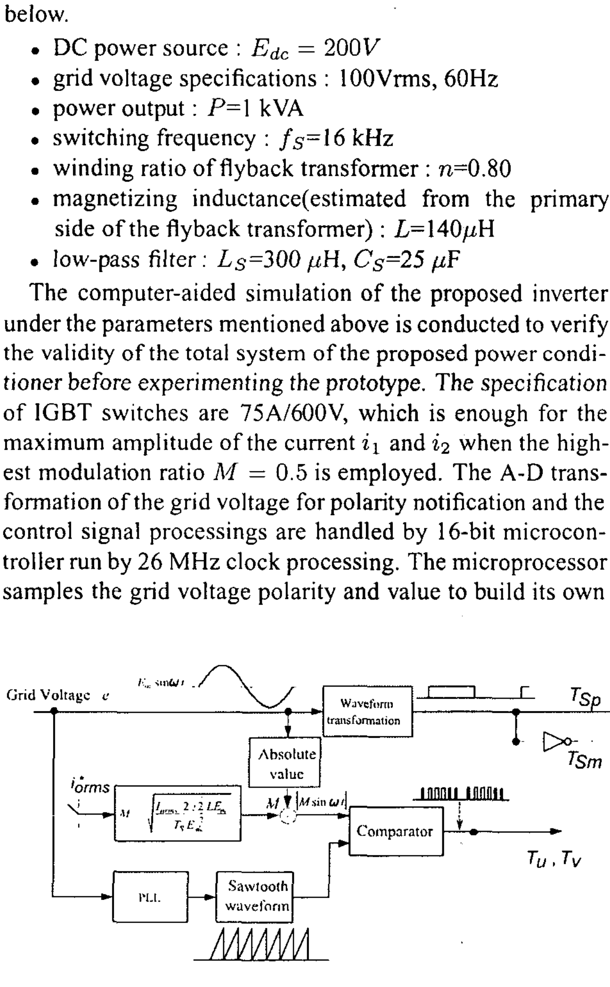



Fig. 5. Control block diagram of the SPWM utility-interfacing inverter system

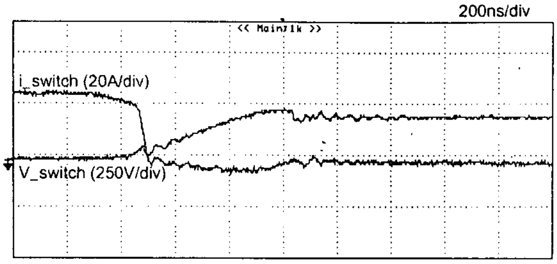



Fig. 7. The overlapping of the switch voltage and switch current at the primary side of the main transformer

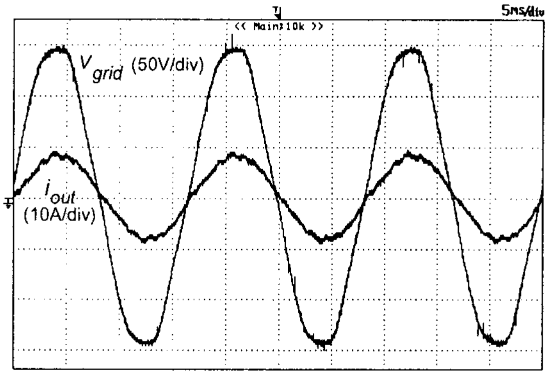



Fig. 8. The grid voltage and the output current

## 6. CONCLUSIONS

This paper has presented a novel prototype of the utility-interfaced power conditioner with the isolation link of the high-frequency flyback transformer operated under the discontinuous current mode. The proposed circuit topology can also operate with ZVS to ruduce the power losses of high-frequency switching. Although the snubber assisted circuits are added to the primary side of the main flyback transformer, the simple sinusoidal PWM signal is still applicable to the proposed circuit topology. Moreover, the efficiency of the power conversion is high and the total harmonic distortion (THD) of the output current is highly acceptable.

For the future work, the THD should be further improved by employing the close-loop control scheme to adjust the pulse width of the SPWM gate signal in the real time. The leakage inductance of the flyback transformer should be minimized as much as poosible. Then, the static and dynamic characteristics of the proposed power conditioner should be investigated.

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